AN ABSTRACT OF THE THESIS OF

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Title: Examining Effectiveness of Oregon's Forest Practice Rules for Maintaining Warm-Season Maximum Stream Temperature Patterns in the Oregon Coast Range

Abstract approved:

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Stream temperature, as an important component of stream ecosystems, can be affected by forest harvesting through removal of riparian shade and changes in hydrology. Riparian Management Areas (RMAs), as implemented through the current Oregon Forest Practice Rules, are designed, in part, to maintain stream temperature following forest harvesting. However, effectiveness of RMAs in achieving this outcome is uncertain. The objective of this research was to examine effectiveness of RMAs, as outlined by the current Oregon Forest Practices Act and the Northwest State Forests Management Plan, in maintaining warm-season temperature patterns of streamwater. Twenty-two headwater streams, on either private- or state-owned forestlands in the Oregon Coast Range that encompassed a range of RMA widths and harvest prescriptions, were evaluated for effectiveness of RMAs on stream temperature. A Before-After-Control-Impact/Intervention design was used, and each stream had an upstream control and a downstream treatment reach. Temperature probes were placed 1) at the top of the control reach, 2) at the boundary between the control and treatment reaches, and 3) at the bottom of the treatment reach from June to September for four years starting in 2002. All but one stream have at least two years of pre-

harvest temperature data, and one year of post-harvest temperature data. Selected stream and riparian characteristics were collected every 60 m within the control and treatment reaches once prior to and once following harvest. I hypothesized that RMAs would be effective if pre-harvest warm-season maximum temperature patterns were maintained following harvest treatments. Comparisons of temperature patterns between control and treatment reaches both pre- and post-harvest indicate that my hypothesis should be rejected because warm-season maximum temperature patterns were not maintained when mean values in treatment reaches across all study streams were considered. Difference in temperature gradients between control and treatment reaches averaged 0.6°C, based on two years of pre-harvest and one year of post-harvest data. This indicates that more warming or less cooling occurred in treatment reaches than occurred in control reaches when pre-harvest and post-harvest periods were compared, suggesting that current RMAs for small- and medium fish-bearing streams of the Oregon Coast Range are not effective for maintenance of warm-season maximum temperature patterns.

Examining Effectiveness of Oregon's Forest Practice Rules for Maintaining Warm-Season Maximum Stream Temperature Patterns in the Oregon Coast Range

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jennifer Marie Fleuret, Author

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Chapter I

Introduction

1.1. Introduction

Stream temperature is an important component of a stream ecosystem that can be influenced by timber harvesting through alteration of heat and energy delivery. Many factors influence stream temperature, including hyporheic exchange, solar radiation, shade, air temperature, channel substrate, discharge, and wind speed (Poole and Berman 2001). Removal of riparian canopy and shade through forest harvest has been documented to increase stream temperature (e.g. Johnson and Jones 2000, Story et al. 2003) to levels that are detrimental for some aquatic species (Beschta et al. 1987). Effects of increased stream temperature on fish and other aquatic organisms are well-documented (e.g. Beschta et al 1987, Newbold et al. 1980). Studies detailing impacts on freshwater fish occurred as early as the 1920s (e.g. Titcomb 1926). Increased stream temperature can result in reduced concentrations of dissolved oxygen, which can lead to changes in metabolic rates, spawning success, and disease incidence (Beschta et al. 1987). Increased stream temperature can also result in increased biomass of both periphyton and certain macroinvertebrates, which can increase the productivity of the system (Boothroyd et al. 2004, Newbold et al. 1980).

Many studies have examined the role that riparian vegetation plays by influencing stream temperature through obstruction of insolation. For example, solar radiation can account for more than 95% of the heat input during summer in Oregon Coast Range streams (Brown 1970). Implementation of Riparian Management Areas (RMAs) can reduce the potential for increased temperatures following harvest by retaining riparian vegetation. Although required by law in some states, effectiveness of specific RMAs in maintaining stream temperature patterns is uncertain. Assessing effectiveness of RMAs can be difficult, considering the many factors that influence stream temperature, and the difficulty in obtaining a large sample size. However, my research is designed specifically to determine effectiveness of Oregon's rules for RMAs in maintaining warm-season maximum temperature patterns in streams following harvest.

1.2. Literature Review

1.2.1. Factors Affecting Stream Temperature

Many factors contribute to heating and cooling processes in streams, including incoming solar radiation, hyporheic exchange, discharge, channel substrate composition, convection, and conduction (Poole and Berman 2001). Atmospheric and stream heat exchanges occur in several ways, including inputs of heat through short- and longwave radiation, loss of heat through longwave radiation and evaporation, and heat convection exchanges of energy across the air-water interface (Sinokrot and Stefan 1993). A general formula for heat gains and losses into and out of a stream follows:

$$\Delta H = N + T + B + E + S \qquad [1]$$

where ΔH is change in temperature, N is net radiation, T is heat added or lost by tributary and groundwater inflows, B is heat exchange between the water and streambed (conduction), E is heat exchange from evaporation or condensation, and S is heat exchange between the air and stream surface (convection) (Hewlett and Fortson 1982). These values may be positive (indicating heat gain) or negative (indicating heat loss), and are influenced by various factors, including riparian shade, upland vegetation, precipitation, air temperature, wind speed, solar angle, cloud cover, humidity, groundwater temperature, and tributary temperature and inflows (Poole and Berman 2001). Although conduction, evaporation, and convection are important processes, their relative contributions to stream heating are small when compared to the heat contributed by solar radiation (Brown 1970, Sinokrot and Stefan 1993, Johnson 2004).

The temperature of phreatic groundwater is thought to be the origin of surface water temperature, and the temperature of surface water has been generalized to increase (moves towards atmospheric temperature) as it flows downstream from its source (Vannote et al. 1980). Changes in stream temperature are moderated by the presence of insulating and buffering processes (Poole and Berman 2001).

Insulating processes affect the rate of heat delivery into and out of a stream, and include channel width and riparian vegetation structure, encompassing proximity to the channel, height, and density (Poole and Berman 2001). Channel width determines the surface area of the stream, with a wider stream having a larger surface area available for heat exchange than a narrow stream. Smaller volumes of water will also heat more quickly than streams with a greater volume of water (Moore and Miner 1997).

Buffering processes may contribute to heating and cooling processes by releasing and storing heat (Poole and Berman 2001). Hyporheic flow is probably the most important modifier of stream temperature, and the hyporheic zone is an ecotone between the surface and groundwater through which significant exchanges of water, nutrients, and organic matter occur (Boulton et al. 1998). The magnitude of hyporheic flow is affected by channel morphology, streambed heterogeneity, streamflow variability, as well as groundwater and tributary inflows and outflows (Poole and Berman 2001). Heat exchange with the hyporheic zone was found to have a cooling effect during the daytime in streams in British Columbia, and this effect accounted for more than 25% of the net radiation input into the stream (Moore et al. 2005a).

Thermal heterogeneity within streams comes from a number of sources including the interaction of surface-, hyporheic-, and deep groundwater flow. This interaction and resultant heterogeneity helps create thermal refugia for aquatic organisms. Solar radiation contributes to thermal stratification, and removal of shade can change the presence and location of cold water patches (Ebersole et al. 2003). Additionally, there are longitudinal and seasonal patterns of thermal heterogeneity, which are influenced by lateral and vertical hyporheic exchange, as well as channel substrate, discharge, and riparian vegetation. Groundwater inflows also function to moderate maximum temperatures and dampen diurnal changes (Danehy et al. 2005).

Effects of channel substrate on stream temperature are largely unstudied, and are thought to be relatively minor by some researchers and relatively important by others. For example, bedrock has been postulated to both increase and buffer temperature (Johnson 2004, Brown 1969), and it is possible that effects of bedrock and alluvial substrates are more important in affecting stream temperature than are generally recognized. Heat transfer between water and substrate is much faster than between water and air, and if hyporheic exchange is occurring, a potentially large amount of water is in contact with substrates. Direct solar radiation may heat up substrates during the day, resulting in the conduction of heat to streamwater during the night (Johnson and Jones 2000). Sinokrot and Stefan (1993) also suggest that streambeds can act as an energy sink during the day and a source at night, but that as streams increase in size, streambed heat conduction becomes less important. Also, smaller inputs of solar radiation (such as in heavily shaded streams) allow streambed heat conduction to play a relatively greater role in moderating stream temperature (Story et al. 2003).

There is evidence that upland microclimate influences stream temperature. Upland soil water temperatures were closer to stream temperatures than nearby riparian zone soil water temperature after a harvest in western Washington, which suggests that these streams receive a significant portion of their water from upland preferential flowpaths (Brosofske et al. 1997). Air temperature, as well as relative humidity, cloud cover, and wind speed, also possibly influence streamwater temperature in streams of western Oregon (Zwieniecki and Newton 1999).

Air temperature has been used to predict water temperature. The correlation between air temperature and water temperature tends to decrease with increasing spatial distance between air and stream temperature measurements, and accurate estimation depends on the time lag between air and stream temperature (Stefan and Preud'homme 1993). Additionally, length of the time lag was found to be dependent on stream size, with smaller streams having smaller time lags, and prediction of stream temperature from air temperature was more accurate with smaller streams in Mississippi (Stefan and Preud'homme 1993). Danehy et al. (2005) found that inclusion of maximum air temperature in their model for streams in Idaho and Eastern Oregon improved its predictive capability for maximum stream temperature. Increases in stream temperature were also positively associated with maximum air temperatures for streams in British Columbia (Moore et al. 2005a).

A variable that has not always been quantified in past research of stream temperature is stream discharge and the role it plays in stream temperature dynamics. It is well known that smaller streams are more likely to be influenced by changes in riparian vegetation and thus solar input (e.g. Beschta et al. 1987). Less energy is required to heat a smaller volume of water than a larger volume of water, and thus streams with smaller discharges are likely to be more sensitive to changes in heat input (Moore and Miner 1997). Brown (1970) postulated a formula that has been used to determine stream temperature changes following a clearcut:

$$\Delta T = \frac{A*N}{Q} *0.000267 \qquad [2]$$

where ΔT is change in temperature (°F), A is surface area in square feet, N is solar load per unit area, and Q is discharge in cubic feet per second. Any change in stream temperature, according to this relationship, is dependent on stream surface area, amount of solar radiation reaching the stream, and discharge. Notably, a smaller discharge will result in a greater potential increase in temperature. Hetrick et al. (1998) found that stream temperature changed more in response to changes in streamflow than to percentage of shade in two small Alaskan streams. Because of the many cloudy days observed in the study area, solar radiation was not predominantly factored in stream temperature change. Although discharge was most important, the authors do not discount the value of shade, and note that canopy cover helped to lower the magnitude of changes in stream temperature. Moore et al. (2005a) found that higher discharges in streams in British Columbia also correlated with lower temperatures.

In the review by Tabbachi et al. (1998), they note that formation of pools caused by the presence of large wood and other obstructions such as boulders can also impact temperature by providing localized areas of deeper and cooler water. Temperature in pools can also be stratified, with differences of up to 2˚C found in some pools in streams in British Columbia (Moore et al. 2005a).

Basin elevation was found to be the most important predictor of stream temperature in second- to fourth-order streams of Idaho and Wyoming, but width and watershed aspect had very little influence on stream temperature (Isaak and Hubert 2001). The authors concluded that a wider stream has a greater ability to dissipate heat because of the larger volume of water, and therefore greater width results in slower changes to stream temperature. Increases in stream temperature have also occurred with a decrease in hydraulic gradient as found in five streams in New Brunswick; however, the reduction in gradient corresponded with an increase in solar radiation input (Bourque and Pomeroy 2001).

Models have been developed to predict stream temperature in response to several factors. The Stream Network Temperature Model (SNTEMP) was developed to predict stream temperature changes as water flows downstream (Bartholow 2000). Although both this model and Brown's equation [eqn 2] have proven to be relatively effective in predicting mean daily stream temperature, the importance of variables within the models differs. Brown's equation [eqn 2] focuses on the importance of solar radiation and discharge (Brown 1970), whereas the SNTEMP assumes water temperature is most sensitive to air temperature (Bartholow 2000).

There have been suggestions that each stream has its own particular temperature pattern or "signature" which reflects its individual environment and flow pattern (e.g. Zwieniecki and Newton 1999). This signature is likely to be influenced by several factors, including tributary inflows, pool location, substrate, and stream channel morphology (Zwieniecki and Newton 1999). Although generalizations have been made about increases in stream temperature as the stream flows downstream (e.g. Zwieniecki and Newton 1999, Sullivan and Adams 1989, Vannote et al. 1980), it is likely that stream temperature dynamics are more complex, with increases and decreases in temperature within a reach likely to occur. Smith (2004) found that streams in the Oregon Coast Range warmed, cooled, or had components of both warming and cooling as they traveled in a downstream direction. Furthermore, although she found that canopy cover was the most consistent predictor for stream temperature (R^2 = 0.49), 51% of stream temperature variability was left unexplained. Moore et al. (2005a) found that streams in their study in British Columbia also had warming, cooling, and intermediate temperature patterns.

Although many factors contribute to temperature, rarely does one factor independently influence stream temperature, and the relative importance of each factor can change both spatially and temporally (Danehy et al. 2005).

1.2.2. Stream Temperature and Aquatic Organisms

Forested headwater streams usually represent the majority of a drainage network, and provide a significant habitat for many organisms (Peterson et al. 2001). The natural flow regime (*sensu* Poff et al. 1997) maintains that organisms are specifically adapted to survive in a particular stream environment, and changes in this environment can either positively or negatively influence their survival. Most species have an optimum temperature range, and changes in stream temperature regimes can change dominance of species as well as stream community composition (Beschta et al. 1987).

Warmer water holds less oxygen than cooler water, which can result in increased stress and disease incidence among aquatic organisms. Metabolic rates of fish and other aquatic organisms are controlled by stream temperature (Beschta et al. 1987), and higher temperatures can lead to increased metabolism, thus influencing the productivity of the system. Changes in productivity can change the trophic status of the ecosystem, among other things, and modify the distribution of resources (Melody and Richardson 2004). Increased stream temperature can lead to changes in fish embryo development and timing of life history events, such as migration and spawning cues. Additionally, increased temperature can impede migration and facilitate the invasion of warm water species which can displace native species (Beschta et al. 1987).

Removal of vegetation has been documented to change the shading and rate of litter inputs into small streams, which can impact the benthos and limit secondary production and thus food availability (Melody and Richardson 2004). However, increased macroinvertebrate density has also been recorded as a result of algal blooms from increased light inputs; however, this generally corresponds with a reduction in biodiversity (Baillie et al. 2005).

Holtby (1988) studied the effects of logging on Coho salmon (*Oncorhynchus kisutch*) in British Columbia, and found that increases in stream temperature led to earlier emergence of salmon fry, as well as a longer summer growing season. This resulted in larger fingerlings, as well as improvement in winter survival, which increased yearling populations. However, yearling smolt migration also occurred earlier, which may have led to a reduced population of two-year-old smolts (Holtby 1988).

1.2.3. Riparian Management Areas and Stream Temperature

Riparian management areas are designed to protect water quality from non-point source pollutants, which come from a variety of dispersed sources. They have been used to maintain stream temperature, reduce sediment input, reduce nutrient input, and retain a riparian environment. They are also designed to provide large wood and organic matter to mountain streams (Osborne and Kovacic 1993). Width requirements for RMAs vary across the country, but mean RMA width for lakes, rivers, and streams in Canada and the United States ranges from 15 to 30 m. For small perennial streams, the average RMA width is 22 m (Lee et al. 2004).

Riparian management areas are used in forestry to separate a waterbody from an upland harvest in order to reduce disturbance to the waterbody and to maintain a riparian habitat (USEPA 2006). Recently, increased RMA retention has been attributed to objectives to maintain riparian corridors and protect riparian ecosystems (Lee et al. 2004). Guidelines for RMAs are increasingly site-specific and complex when compared to historical RMA directives, requiring an increased understanding of riparian dynamics (Lee et al. 2004). Guidelines for RMAs depend on a particular state’s rules as well as a landowner’s management objectives; however, the United States Environmental Protection Agency’s (USEPA) guidelines stipulate that an RMA width of 11 to 15 m is generally recommended for an RMA to be effective (http://www.epa.gov/owow/nps/forestrymgmt/).

Stability of RMAs can be impacted by blowdown, insects, disease, and logging activities, and some researchers have recommended site-specific designs for RMAs (Steinblums et al. 1984). Based on regressions developed to predict stability, RMA design should take into account anticipated RMA width, pre-harvest RMA basal area, and the dominant slope of both the riparian and harvest areas (Steinblums et al. 1984).

Recommended width of an RMA on state or private lands in Oregon depends on several factors, but is determined primarily based on location within Oregon. Width also depends on whether the stream is fish-bearing (Type F), non-fish-bearing (Type N), or is considered a domestic water source for use within homes and businesses (Type D). Finally, riparian buffer width depends on size of the stream: whether it is small (<0.06 cms), medium (0.06 – 0.28 cms), or large (>0.28 cms) (Table 1.1). (Logan 2002).

Table 1.1. Stream classification and size of required riparian management areas (RMAs) for private land in the Oregon Coast Range (adapted from Logan 2002).

Size	Type[2]	RMA width (m)
Small (<0.06 cms)[1]	F	15
	N	0
	D	6
Medium (0.06-0.28 cms)	F	21
	N	15
	D	15
Large (>0.28 cms)	F	30.5
	N	21
	D	21

[1]cms: discharge units of m^3sec^{-1}. [2] F: fish-bearing; N: non-fish-bearing; D: domestic water source

There are also specific basal area retention requirements within the RMA (known as standard targets in the Oregon Forest Practice Rules) depending on the type of harvest, as well as stream classification. Minimum levels of basal area must be retained, the majority of which is required to be conifer. Limited harvesting may take place within the RMA, particularly if there is more basal area in the RMA than the standard target or if the stream or riparian area is in need of restoration. If a landowner successfully restores these areas, he or she may harvest within the RMA to a level known as the active management target, a basal area retention below the standard target (Logan 2002).

State forests have different requirements for widths of RMAs. State RMAs are required to have four zones: aquatic, stream bank, inner RMA, and outer RMA. Regardless of the type and size of the stream, the entire RMA should be at least 52 m in width. However, requirements for basal area retention depend on the type of harvest as well as size and type of stream (see Northwest Oregon State Forests Management Plan, Appendix J, 2001).

Effectiveness of RMAs has been studied previously in other regions. In Alaskan headwater streams, sensitive fish species preferred pools with some cover (preferably large-wood cover), and streams that were exposed directly to clearcut harvesting had fewer pools and less large organic debris, and therefore less favorable habitat. However, streams that had intact RMAs maintained pool area, and blowdown from the RMA frequently added to the volume of organic debris (Heifetz et al.1986).

Nitschke's (2005) meta-analysis that compared wildfire effects on stream temperature to effects from clearcut harvesting suggested that clearcuts can have similar effects on stream temperature as wildfire. The difference in temperature between the wildfire and clearcut sites was not statistically significant, indicating that changes in temperature following intense wildfires were similar to changes in temperature following harvesting. However, mean temperature within streams with RMAs was significantly lower than wildfire sites, indicating that RMAs and intact riparian areas can help to moderate stream temperature following a disturbance.

1.2.4 Influence of Solar Radiation and Shade

Although not all studies have identified insolation as a primary driver of stream temperature, solar radiation has been documented to account for over 95% of heat input into a stream in the summer at midday in the Oregon Coast Range (Brown 1970). In their recent review of stream temperature literature, Moore et al. (2005b) conclude that shade is the key factor in controlling stream temperature, particularly in forested regions.

There is some disagreement on how effective shade is in moderating stream temperature (e.g. Larson and Larson 1996, Beschta 1997). However, most studies that examine shade agree that it plays a dominant role. An increase of 6ºC was found when riparian canopy was removed from Pacific Northwest headwater streams, and greater canopy retention helped to maintain stream temperatures (MacDonald et al. 2003). The authors also found that temperature increased in the first three years following harvest, and only decreased in the fourth year when understory vegetation began to shade the channel. Holtby (1988) reported that increases of over 3˚C occurred when 41% of a watershed in British Columbia was clearcut. Increases of 6-8ºC also occurred when canopy was removed in the Western Cascades of Oregon, and maximum temperatures corresponded with maximum inputs of solar radiation (Johnson and Jones 2000). Levno and Rothacher (1967) found that clearcutting harvests in the Oregon Cascades increased maximum stream temperature by 4˚F, but when the streambed was scoured by a winter storm that removed remaining riparian vegetation, maximum temperatures increased up to 12˚F. Additionally, following slash burning along the same channel, stream temperatures increased by an additional 8˚F (Levno and Rothacher 1969). In streams in British Columbia studied by Danehy et al. (2005) the maximum stream temperature increased with increasing insolation, and models which included solar radiation were better at predicting maximum stream temperature. Moore et al. (2005a) reported that maximum daily water temperatures increased up to 5˚C following harvest in Idaho and Eastern Oregon in the summer, and that although treatment effects were variable, this reflected the variation in solar radiation availability.

Greene (1950) concluded that shading was the controlling factor of stream temperature when an open-canopy stream in North Carolina was found to be, on average, 11.5˚F warmer than a nearby forested stream.

Variation in temperature along a stream reach has been correlated to the presence of intact RMAs, and blockage of direct insolation was determined to be of primary importance in influencing temperature in Southern Ontario streams (Barton et al. 1985). Smith (2004) found that canopy cover was the most influential factor controlling summertime stream temperatures in the Oregon Coast Range, suggesting that energy input from solar radiation was the dominant form of heat contribution to these streams. Slash covering a stream channel and therefore blocking solar radiation was thought to contribute to the lack of temperature change in Washington Coast Range streams following harvest (Jackson et al. 2001).

A commercial clearcut and a harvest that received herbicide in Pennsylvania both resulted in increases in temperature when compared to a forested control (Lynch et al. 1984). Although both treatments resulted in increases, the harvest receiving herbicide (which removed residual low lying cover) showed increases of up to 9˚C. Minimum temperatures were also significantly increased during the daytime, but decreased during the night, which was attributed to increased radiational cooling (Lynch et al. 1984). Temperature increases following logging were shown to occur as early as February at a site in Pennsylvania, and continue into November (Rishel et al. 1982).

A study using both SNTEMP and measured stream temperatures indicated that a wooded canopy provided the most shade for streams, as compared to RMAs dominated by grass and shrub cover in Minnesota. Also, it was found that shade significantly moderated both modeled and measured maximum stream temperatures for streams in Minnesota (Blann and Nerbonne 2002).

Conflicting evidence exists regarding the downstream recovery time of stream temperature after it is heated by exposure to solar radiation through the removal of canopy (e.g. Johnson 2004, Beschta et al. 1987). Some studies suggest that water returns to pre-disturbance trajectories downstream of a disturbance (e.g. Zwieniecki and Newton 1999), and other studies have stated that although shade can prevent stream heating, it does not cause decreases in stream temperature (Brown 1970). Bourque and Pomeroy (2001) found that temperatures in streams in New Brunswick increased when forest cover was removed and a greater amount of solar radiation was able to reach the stream. Temperatures also did not decrease downstream, illustrating that effects of temperature increase are not necessarily mediated when canopy is restored downstream. Greene (1950) stated that when an open-canopy stream cooled after traveling through a shaded reach in North Carolina that canopy cover was responsible for the cooling, but Beschta et al. (1987) maintain that streams do not cool unless there is a source of colder water. Meehan (1970) suggests that shade is a necessity for cooling streams and for maintenance of cool streamwater. Story et al. (2003) state that inflow of groundwater is a prerequisite for downstream cooling of streams flowing through clearcuts, and Holtby (1988) suggests that temperatures are not likely to return to pre-harvest levels below clearcuts unless riparian vegetation is restored. Riparian canopy closure influences the amount of solar radiation that reaches the stream, and therefore the quantity of shade that covers the stream is a driving factor for moderating stream temperature. The distinction should be made that shade does not, in itself, produce cooling but rather mediates delivery of solar radiation into a stream (Larson and Larson 1996).

Long-term effects of shade removal on stream temperature have also been documented. Ten to 15 years after a harvest on the Olympic Peninsula of Washington, significant increases in temperature were still found in water flowing through a harvested unit compared to an undisturbed stream nearby (Murray et al. 2000). Also, Johnson and Jones (2000) found that it took 15 years for stream temperatures to return to pre-disturbance levels in the Oregon Cascades, and coincided with return of the canopy. Holtby (1988) suggests that because riparian revegetation in British Columbia can take as long as 15 to 30 years, effects of logging on stream temperature could persist for at least that length of time.

1.3. Rationale

This research is part of a larger, ongoing study supported by the Oregon Department of Forestry (ODF). Goals of the ODF study are multiple, and include understanding factors that influence stream temperature and determining if RMAs as outlined by the Forest Practices Act and the Northwest State Forests Management Plan are effective in maintaining stream temperature patterns in Oregon Coast Range streams (Riparian Function and Stream Temperature Study Approach 2003). Knowing more about effectiveness of current RMA guidelines in maintaining stream temperature patterns will provide information for the ODF to either modify or maintain existing guidelines. Stream temperature, as an important component of a stream ecosystem, is influenced by many factors; however, solar radiation appears to be the most influential factor. Harvesting has potential to remove important shade which absorbs and deflects solar radiation, and stream temperature has been shown to increase substantially when this shade is removed. Riparian management areas are commonly used in conjunction with forest harvests to help moderate riparian vegetation removal, but their effectiveness and stability is still uncertain. Information about stream temperature and RMA effectiveness is scarce, and in order to protect these stream systems adequately, managers and policy makers should be informed as to effectiveness of the current rules.

1.4. Objective and Hypothesis

The objective of this study is to determine effectiveness of RMAs in maintaining warm-season maximum stream temperature patterns following harvest. Prior to harvest, these streams were found to have individual warming and cooling patterns (Smith 2004), and the degree to which these patterns are maintained after forest harvesting will be used to determine effectiveness of RMAs. I hypothesize that effective RMAs will be characterized by maintenance of pre-harvest warm-season maximum stream temperature patterns following forest harvesting.

Chapter II

Methods

2.1 Site Descriptions

Twenty two streams in the Oregon Coast Range, ranging from Astoria to Coos Bay (Figure 2.1), were selected for this study, and were chosen based on criteria developed by the ODF for a larger, ongoing study of riparian vegetation function and stream temperature. The streams were located on either private- or state-owned forestlands. Streams included in this study were selected for uniformity in channel morphology and riparian characteristics, and were classified as either small- or medium fish-bearing streams (Table 1.1). Additionally, streams with recent beaver activity, debris torrents, or dams were excluded from the study.

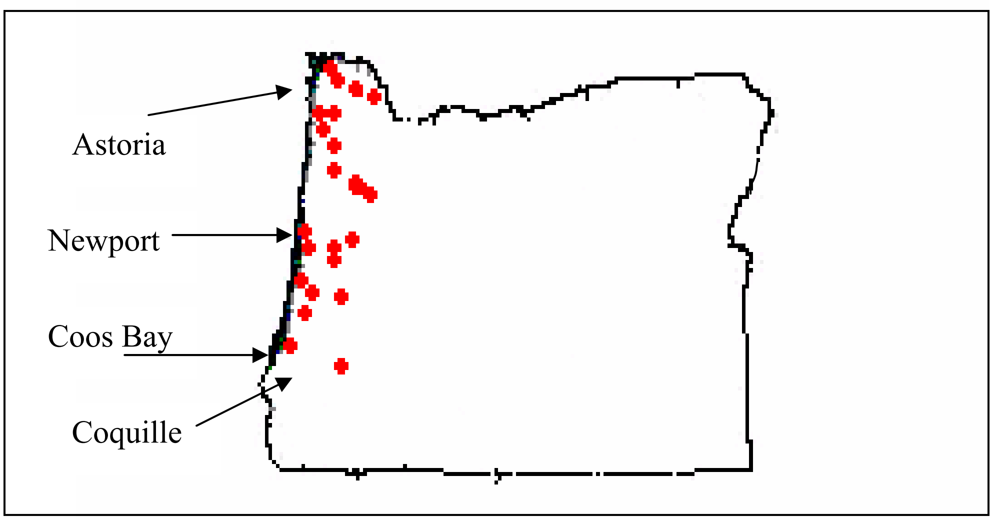


Figure 2.1. Location of 22 Oregon Coast Range headwater streams for temperature monitoring.

Composition of the channel substrate of the streams included silts, cobbles, boulders, and bedrock. The watersheds are dominated by red alder (*Alnus rubra*) and Douglas-fir (*Pseudotsuga menziesii*), with salmonberry (*Rubus spectabilis*) and devil's club (*Echinopanax horridum*) present in the majority of the riparian zones. Mean annual precipitation along the Coast Range is dominated by rainfall and is approximately 2,000 mm (http://www.ocs.orst.edu/allzone/allzone5.html).

2.2. Study Design

A Before-After-Control-Impact/Intervention (BACI) design was used in this study, with each stream assigned both an upstream control reach (not to be harvested for the study's duration) ≥213 m, and a downstream treatment reach (to be harvested at least two years after initiation of the study) ≥300 m (Figure 2.2). All but one of the 22 streams has at least two years of pre-treatment temperature data and one year of post-treatment temperature data, and channel characteristics were collected once prior to and once following harvest. Landowners harvested according to Oregon's Forest Practice Rules, which allows limited harvesting within the RMA, and riparian buffers ranged in width from 6 to 60 m on each side of the stream. Clearcut harvests occurred on one or both sides of the stream, and some harvests were one- or two-sided partial cuts.

2.3. Data Collection in the Field

Channel characterization data were collected every 60 m within the control and treatment reaches, and included canopy cover, gradient, wetted width, maximum depth, bankfull width, floodprone width, and channel substrate. Large wood pieces and wood jams were also tallied between each 60 m station (Table 2.1). Two additional variables (aspect and geology) were identified from Smith (2004). Geology at each site was classified as either igneous or sedimentary, and aspect ranged from North, Northeast, East, Southeast, South, Southwest, West, to Northwest.

Temperature data loggers (Onset © Stowaways or Hobos, accuracy ± 0.2˚C) were placed at 1) the top of the upstream control (referred to as 'upstream control'), 2) the interface between the control and the treatment reaches (referred to as 'downstream control'), and 3) the bottom of the treatment reach (referred to as 'treatment') (Figure 2.2), and were anchored to a heavy rock with surgical tubing to avoid loss during high flows. Temperature probes were in place from June through September, for up to three seasons (2002, 2003, and 2004) prior to harvest and for at least one June-through-September season (2004 and/or 2005) following harvest (Table 2.2). Probes recorded hourly maximum and minimum temperatures in ˚C.

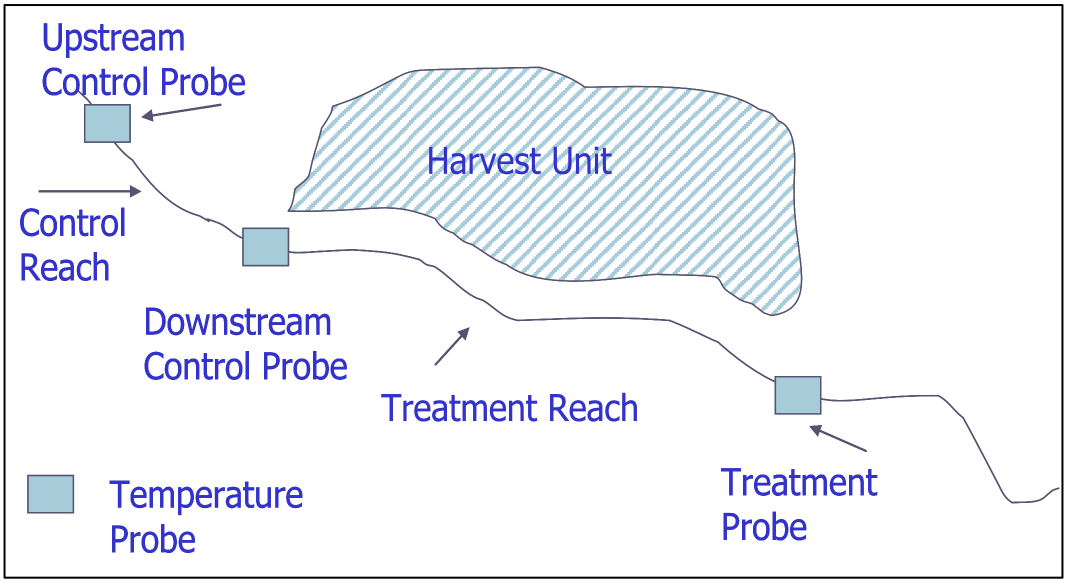


Figure 2.2. Location of control reach, treatment reach, and temperature probes used to determine effectiveness of riparian management areas in the Oregon Coast Range.

Table 2.1. Channel characterization variables collected every 60 m within the control and treatment reaches of 22 Oregon Coast Range headwater streams. (Adapted from Smith 2004).

Variable	**Description**
Shade	A hemispherical photograph was taken at each 60-m station at 0.9 m above the water surface. The camera was positioned facing north, and produces a 180 and 360 degree view of the canopy. Percent shade is calculated from the digitized photograph.
Gradient	Gradient was measured from one pool to the next pool upstream from each 60-m station using a clinometer.
Wetted width	The width of the wetted surface of the channel was measured. Mid-channel bars that were above the water surface were subtracted from the total width of the channel.
Maximum depth	The depth of the stream at the deepest point in the channel cross section.
Bankfull depth	The height of the wetted channel at the average annual peak flow was estimated, and the width of the channel at this point was measured.
Floodprone width	Twice the bankfull height was obtained at the deepest part of the channel. The tape measure was then extended to either side of the channel at this height until an incline was reached that would impede water flow. If greater than 20 m, the width was estimated.
Substrate	Substrate estimates of the relative percentages of bedrock, boulder, cobble, gravel, fines. Bedrock: solid rock Boulder: detached rock sized between a car and a basketball Cobble: sized between a basketball and a golf ball Gravel: sized between a golf ball and a ladybug Fines: substrate smaller than a ladybug
Large Wood	Large wood both within bankfull and between bankfull and 1.8 m above bankfull was tallied between each 60-m station. Large wood was considered anything with a small end diameter of at least 15 cm, and a length of at least 1.8 m. Number, height, width, and length of wood jams (a collection of wood pieces too great to count) was also tallied between each 60-m station.

Table 2.2. Number of Oregon Coast Range headwater streams evaluated for this study and their pre- and post-harvest years.

Number of streams	2002	2003	2004	2005
8	Pre-harvest	Pre-harvest	Post-harvest	Post-harvest
7	Pre-harvest	Pre-harvest	Pre-harvest	Post-harvest
6		Pre-harvest	Pre-harvest	Post-harvest
1			Pre-harvest	Post-harvest

2.4 Data Analysis

All statistical analyses were completed using SAS version 9.1 (SAS Institute Inc. 1989). Statistical significance was based on $\alpha = 0.05$.

2.4.1. Channel Characteristics

Differences between pre-harvest and post-harvest channel characteristics in the control and treatment reaches were determined by subtracting the pre-harvest values from the post-harvest values measured at each 60-m station. The number of wood pieces and volumes of wood jams were standardized to numbers per 300 m of channel length. Means and standard deviations of these differences for the control and treatment reaches of each stream were calculated. A two-sided t-test was used to determine if the changes between pre- and post-harvest channel characteristics in the control reach were significantly different from the changes in the treatment reach.

2.4.2. Climate Characteristics

Daily temperatures and total monthly precipitation for the years 2002-2005 in May-August for Oregon Climate Service Stations 350328 (Astoria), 356032 (Newport), and 351836 (Coquille) were obtained from the Oregon Climate Service (http://www.ocs.orst.edu/allzone/allzone5.html). These stations represent northern, central, and southern portions, respectively, of the distribution of study streams (Figure 2.1). Daily temperatures were averaged to produce monthly means and standard deviations. Both temperature and precipitation data were graphed.

2.4.3. Stream Temperature

Maximum daily stream temperatures for the period of July 15th to August 31st were calculated. These dates were chosen because peak streamwater temperatures occur in the Oregon Coast Range during this period, and for this study this period will be defined as the 'warm season' (Smith 2004). Using each day's maximum temperature, the 7-day moving mean of the daily maximum (7DMMDMax) was computed for July 15th to August 31st. It is calculated for each day by taking the maximum daily temperatures for the three preceding days, the maximum daily temperature for that day, and the maximum daily temperatures for the three following days, and averaging these values. Differences in 7DMMDMax between probes (i.e. Downstream Control – Upstream Control (referred to as 'control'), and Treatment – Downstream Control (referred to as 'treatment')) were then calculated to reduce spatial correlation and filter out the confounding effect of climate differences among years.

These differences were then averaged for each reach, and were standardized to be the mean difference per 300 m. This value is referred to as the ‘temperature gradient’.

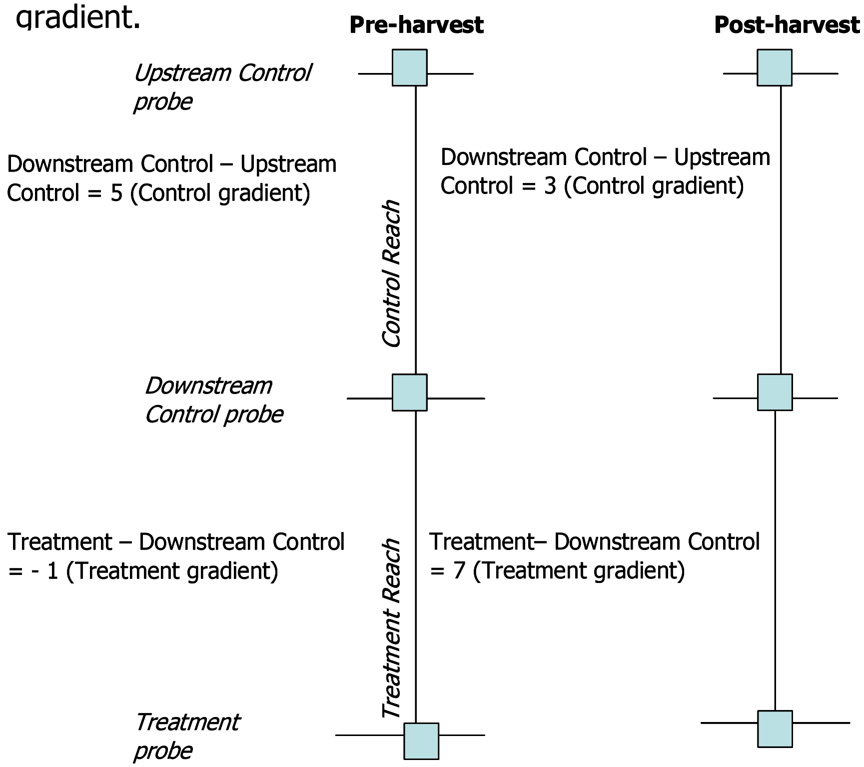
2.4.3.1. Warm-Season Maximum Stream Temperature Characteristics

The mean temperature gradient for the control and treatment reaches for each pre-harvest year (2002, 2003, and/or 2004) and each post-harvest year (2004 or 2005) and the standard deviation of the means were calculated.

2.4.3.2. Change in Warm-Season Maximum Stream Temperature Characteristics

In order to determine if there were statistically significant differences in the mean warm-season temperature gradient between years and between reaches within streams, a repeated measures analysis of variance (RMANOVA) was completed. The RMANOVA was conducted using one year pre-harvest data (2003 or 2004) and one year post-harvest data (2004 or 2005), as well as two years pre-harvest data (2002/2003 or 2003/2004) and one year post-harvest data (2004 or 2005) to determine if the RMAs maintained pre-harvest warm-season temperature patterns. A RMANOVA was also conducted between two pre-harvest years (2002 vs. 2003, or 2003 vs. 2004) to see if there were significant differences between years and reaches prior to any treatment. Estimates of the mean temperature gradients in the control reach and treatment reach pre- and post-harvest were obtained, as well as the differences in each reach pre- and post-harvest. Additionally, the pre-harvest difference in the mean temperature gradient between the control and treatment reaches was compared to the post-harvest difference between the control and treatment reaches (Figure 2.3).

Figure 2.3. Schematic and example of how estimates of changes in temperature gradients were obtained. ‘Control’ and ‘Treatment’ refer to temperature gradient/300m in the respective reach. Negative value indicates decrease in reach temperature gradient characterized by cooling or less warming; positive value indicates an increase in temperature gradient.



A: Difference between Control Reach gradients:

Post(Control) – Pre(Control)

=3 - 5

= - 2

B: Difference between Treatment Reach gradients:

Post(Treat) – Pre(Treat)

=7 – (-1)

=8

C: Difference between Control and Treatment Reach Gradients Pre- and Post-harvest:

(Post(Treatment gradient) – Pre(Treatment gradient)) – (Post(Control gradient) – Pre(Control gradient))

= 8 – (-2)

=10

2.4.3.3. Relationships between Warm-Season Maximum Stream Temperature Gradient and Channel Characteristics

Simple linear regression was used to determine the presence of significant relationships between temperature gradient and channel characteristics. Explanatory variables were the mean of each of the channel characteristics measured at 60-m intervals within a particular reach, and the response variable was the temperature gradient for each corresponding reach. Explanatory variables with the highest significance ($p < 0.05$) and the higher R^2 values were considered the best predictors for temperature gradient. Relationships that were considered for each reach among the 22 controls and each reach among the 22 treatments had only one explanatory variable, because the sample size ($n = 22$ for control reaches, $n = 22$ for treatment reaches) was not large enough to accommodate two-variable selections.

Exploration of two-variable models was accomplished by treating each reach (control and treatment) in each stream as a separate statistical unit, which increased the sample size to 44.

2.4.3.4. Warm-Season Stream Temperature Patterns of Individual Streams

The 7DMMDMax occurring each day between July 15th and August 31st for the downstream control and treatment probes was obtained. The relationship between the downstream control and treatment probes for these values on each stream was visually assessed for all pre-harvest and post-harvest years. Additionally, 95% confidence intervals for predicted pre-harvest temperatures were determined.

The metric used by the ODF and Oregon Department of Environmental Quality (ODEQ) to determine if a water body has exceeded the temperature standard is the maximum 7DMMDMax, or the maximum mean temperature for the warmest week of the season (Max7Day). This value for each probe was obtained for each stream in each year, as well as the date on which it occurred.

Chapter III

Results

3.1 Stream Channel Characteristics

3.1.1 Shade Characteristics

Prior to treatment, shade in control reaches ranged from 72 to 96%, with a mean of 85% (±8). In the year following harvest, shade in control reaches ranged from 83 to 99%, with a mean of 89% (±5) (Figure 3.1A). Shade in treatment reaches prior to harvest ranged from 70 to 95%, with a mean of 86% (± 7). Following harvest, shade in treatment reaches ranged from 51 to 99%, with a mean of 79% (±13) (Figure 3.1B).

In control reaches, percent shade increased by a mean of 3% (± 8) in the year following harvest, whereas in the treatment reaches, percent shade decreased by a mean of 6% (±10). The change in percent shade in control reaches was significantly different than the change in treatment reaches (p-value=0.0021) when pre-harvest and post-harvest means were compared (Figure 3.1C).

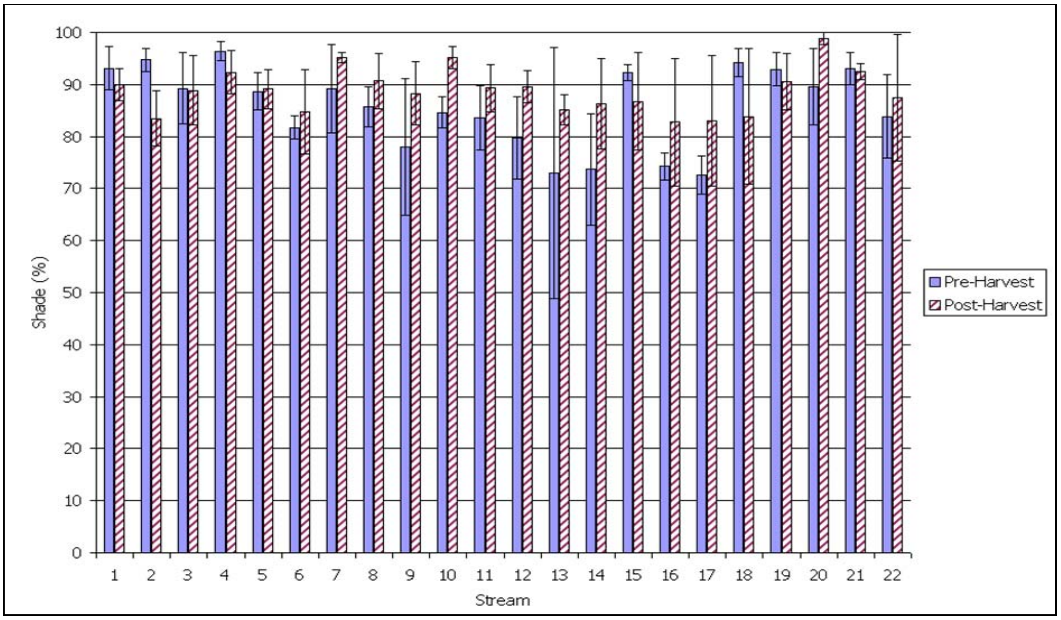


Figure 3.1A. Percent shade in control reaches pre- and post-harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

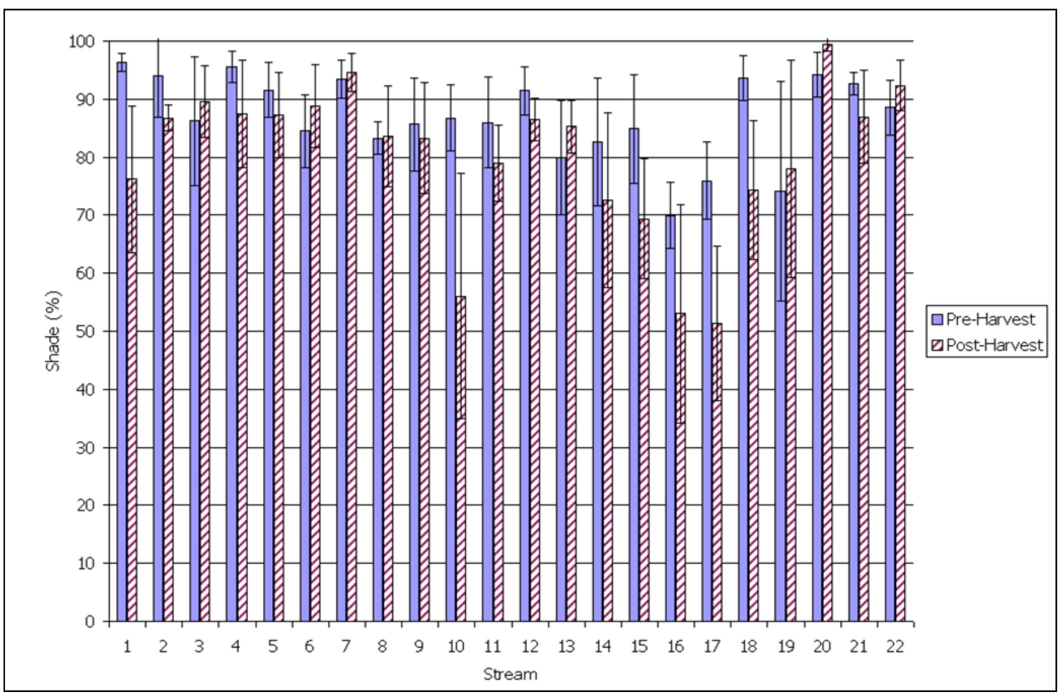


Figure 3.1B. Percent shade in treatment reaches pre- and post-harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

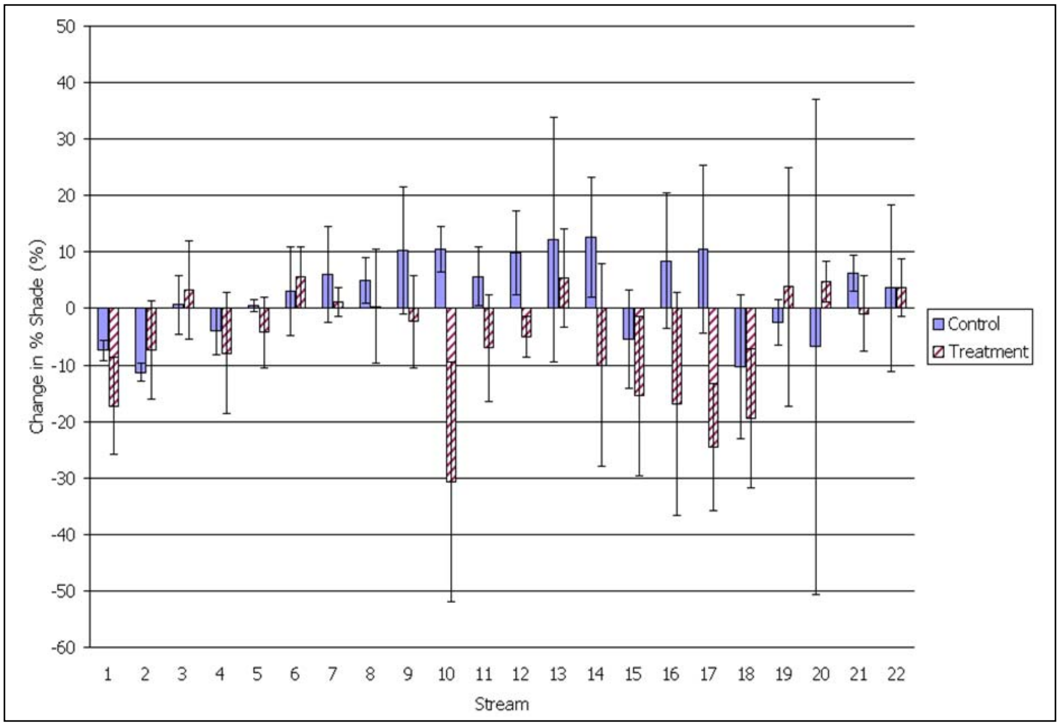


Figure 3.1C. Change in percent shade in control and treatment reaches following harvest in 22 Oregon Coast Range headwater streams. Error bars represent on standard deviation of the mean.

3.1.2. Stream Channel Morphology

Following harvest, stream gradient in the control and treatment reaches was 0.5% (± 1) and 1.3% (±1) lower, respectively, than gradients observed prior to harvest (Figure 3.2A).Wetted width in control and treatment reaches increased following harvest by 0.6 m (± 0.7) and 0.5 m (± 0.9), respectively (Figure 3.2B). Maximum streamwater depth in the control and treatment reaches increased 0.03 m (± 0.07) and 0.05 m (±0.07) following harvest, respectively (Figure 3.2C). Bankfull width in control reaches increased by 0.1 m (± 0.7) following harvest, and in treatment reaches decreased by 0.1 m (±1) (Figure 3.2D). Floodprone width in control reaches increased following harvest by 1.6 m (±5) and in the treatment reach by 2.0 m (±4) (Figure 3.2E). These changes in stream gradient, wetted width, maximum depth, bankfull width, and floodprone width in the control reach following harvest were not significantly different than changes in the treatment reach (p-values= 0.44, 0.33, 0.42, 0.81, respectively).

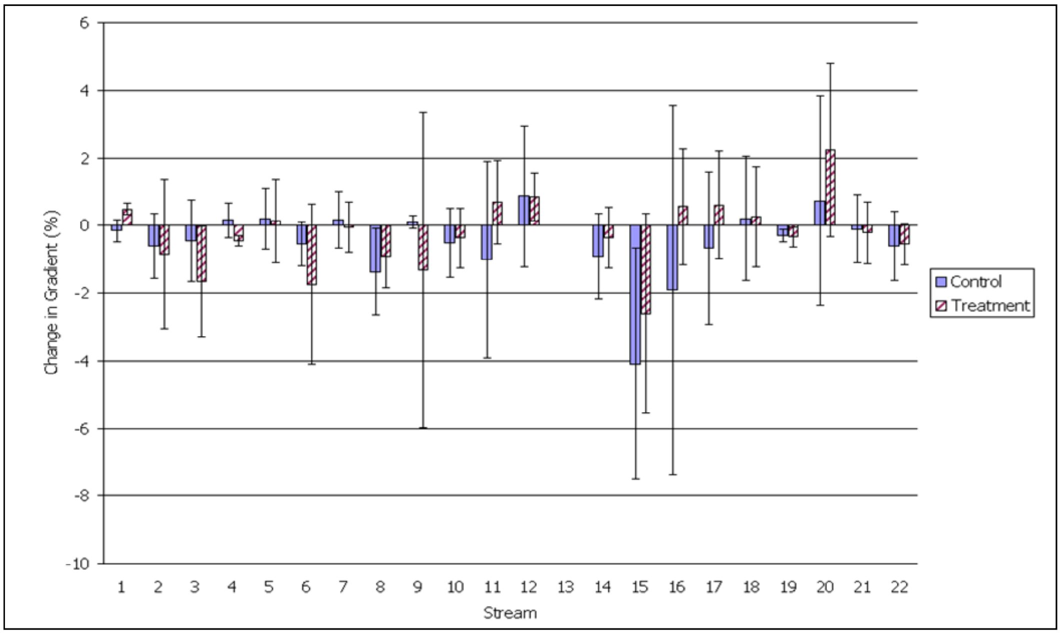


Figure 3.2A. Mean change in gradient in control and treatment reaches following harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

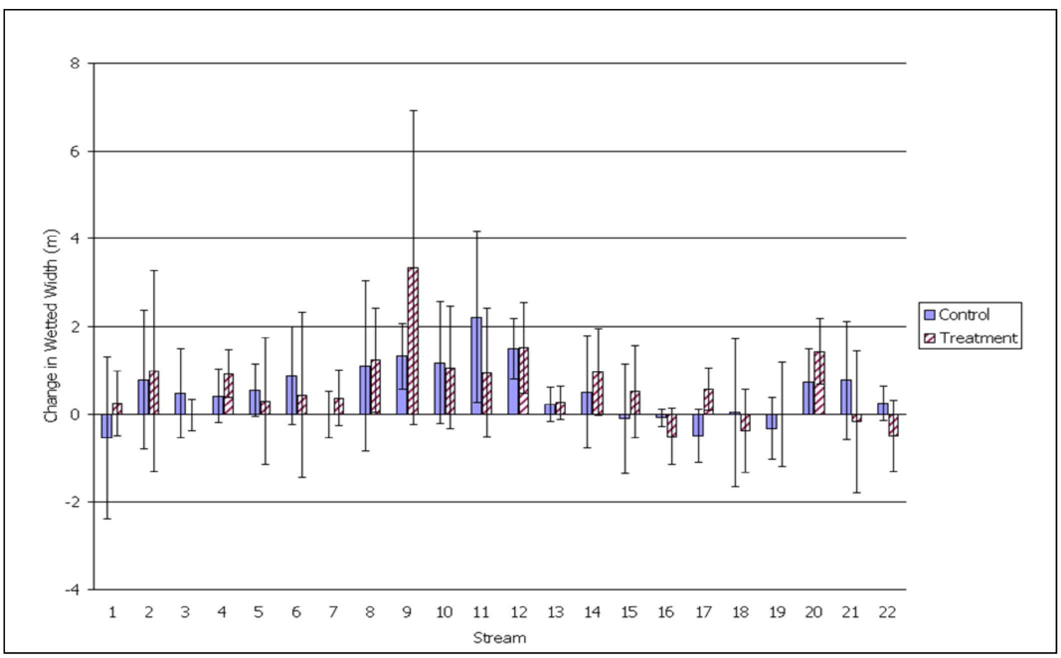


Figure 3.2B. Mean change in wetted width in control and treatment reaches following harvest in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

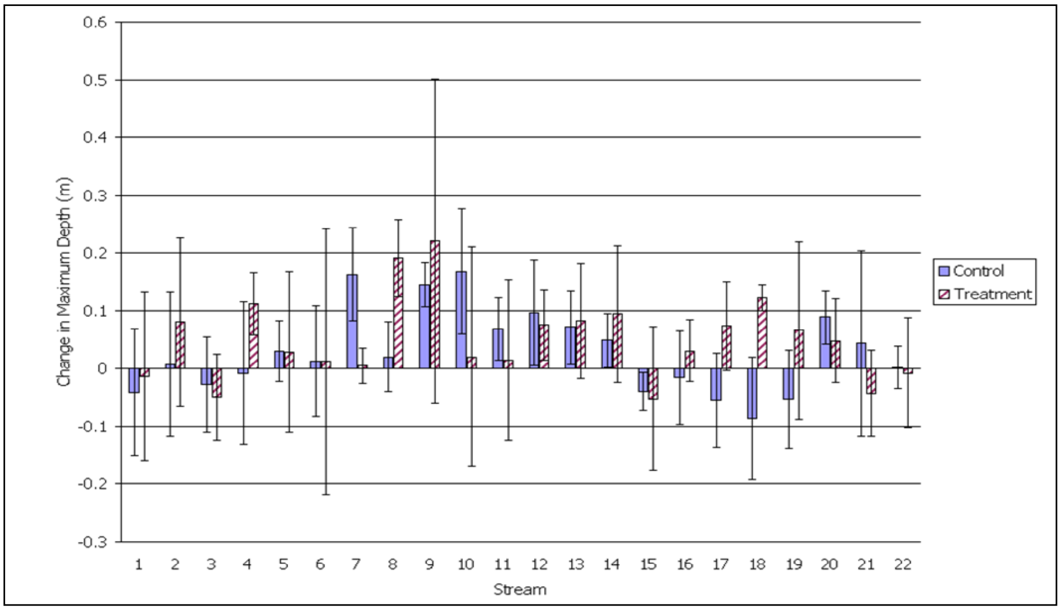


Figure 3.2C. Mean change in maximum depth in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

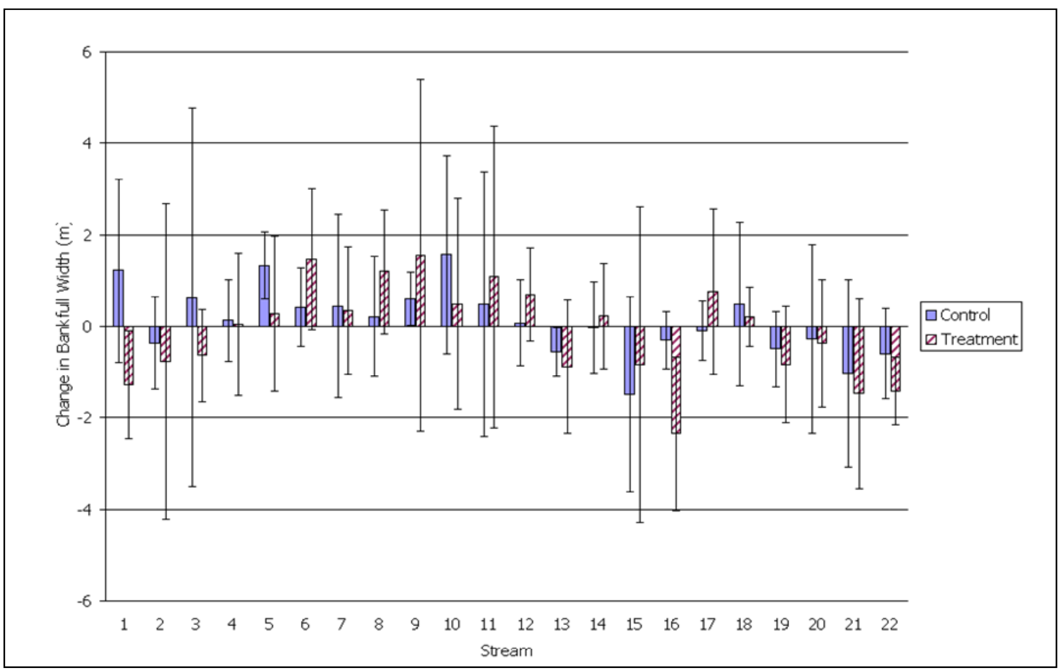


Figure 3.2D. Mean change in bankfull width in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

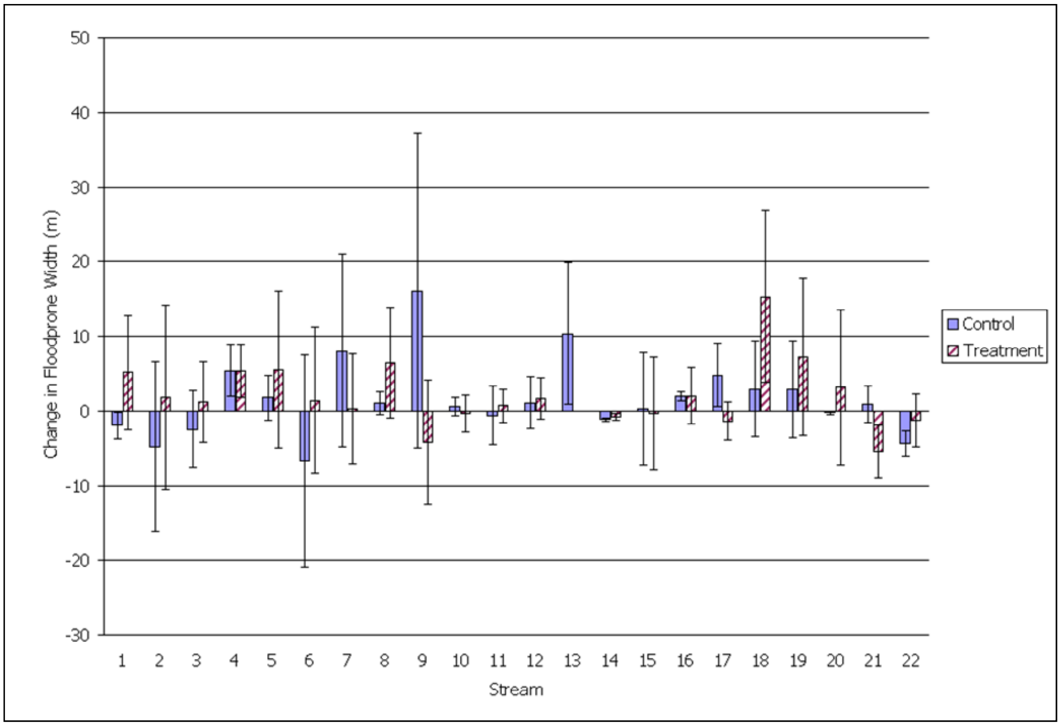


Figure 3.2E. Mean change in floodprone width for control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

3.1.3. Channel Substrate Characteristics

Percent bedrock in control and treatment reaches increased following harvest by 3% (±8) and 2% (±5), respectively (Figure 3.3A). Percent boulder increased in control and treatment reaches following harvest by 9% (±10) and 8% (±9), respectively (Figure 3.3B). Percent cobble increased in control and treatment reaches following harvest by 16% (±15) and 15% (±16), respectively (Figure 3.3C). Percent gravel decreased in control and treatment reaches following harvest by 11 (±16) and 5% (±19), respectively (Figure 3.3D). Percent fines decreased in control and treatment reaches following harvest by 18% (±18) and 14% (±22), respectively (Figure 3.3E). Change in bedrock, boulder, cobble, gravel, and fines in treatment reaches following harvest was not significantly different than change in control reaches (p-values=0.45, 0.81, 0.92, 0.25, 0.57, respectively).

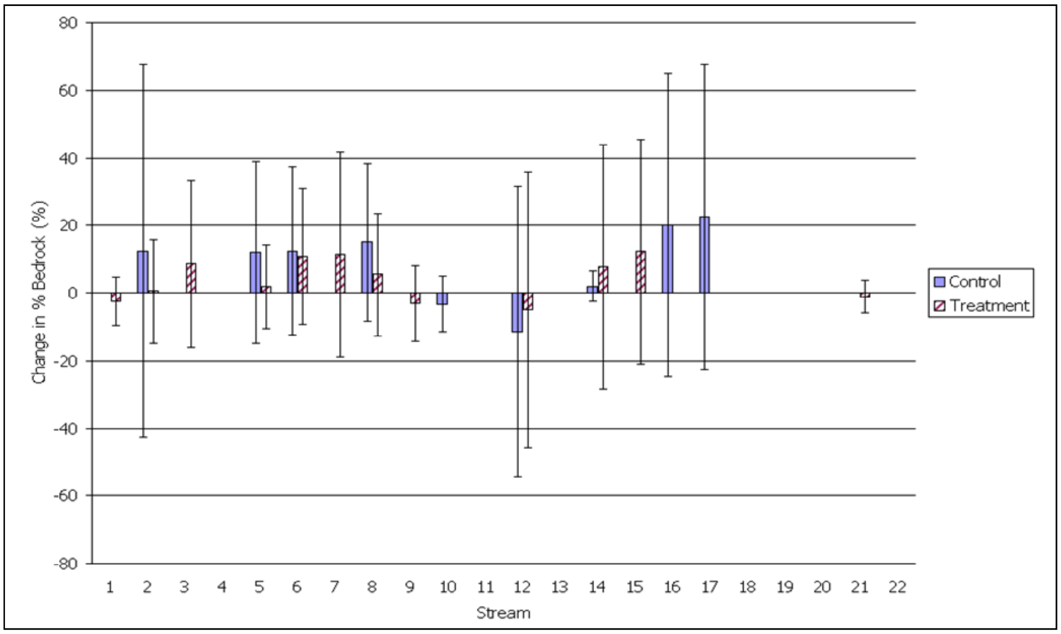


Figure 3.3A. Mean change in percent bedrock in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

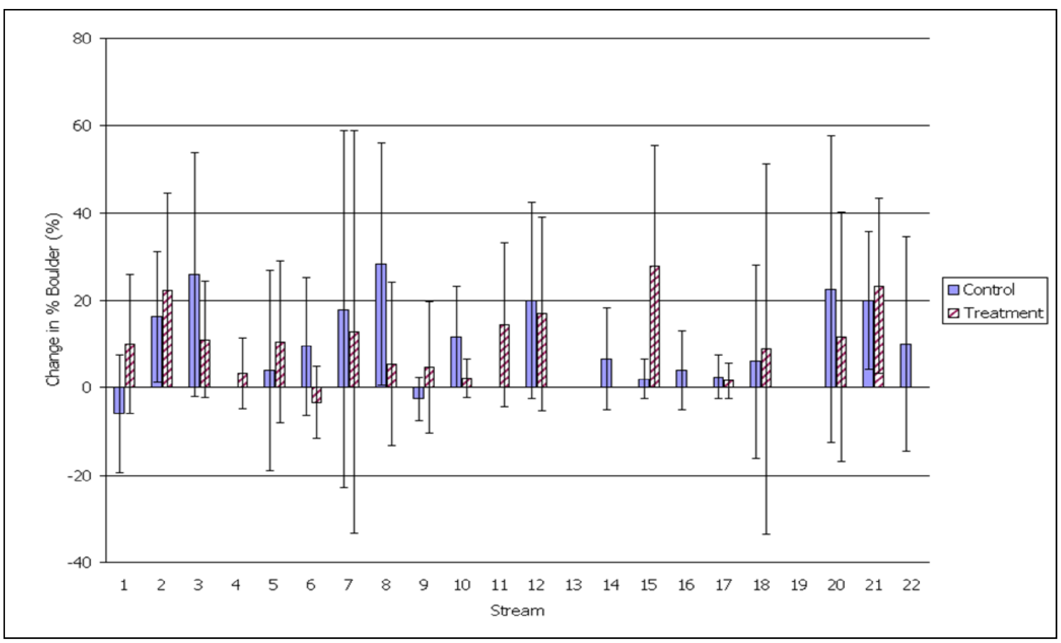


Figure 3.3B. Mean change in percent boulder in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

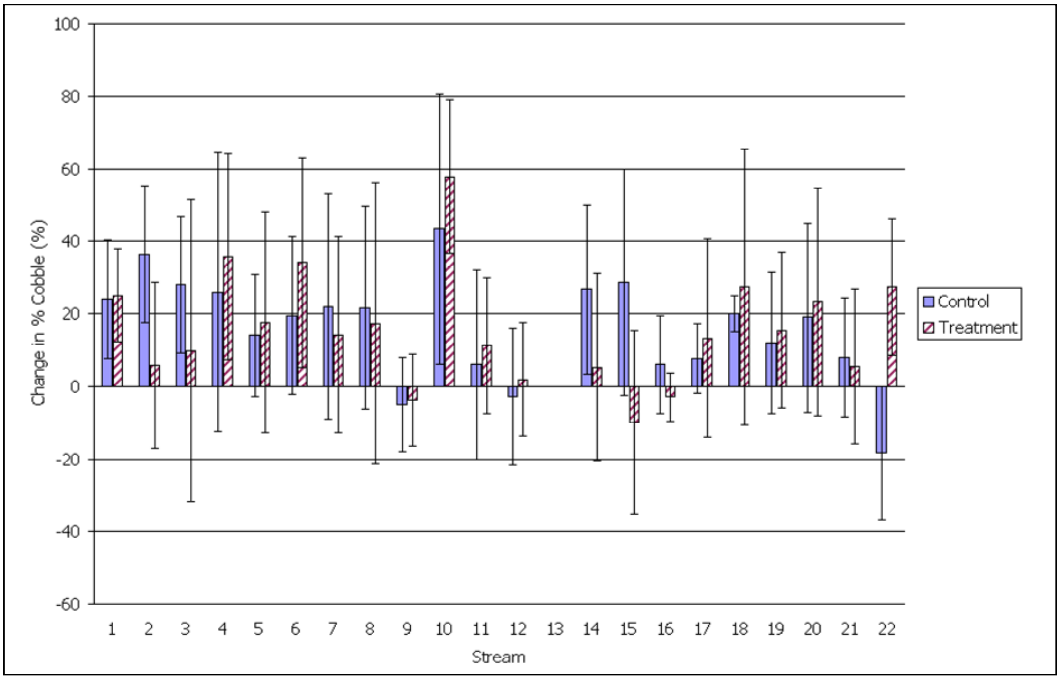


Figure 3.3C. Mean change in percent cobble in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

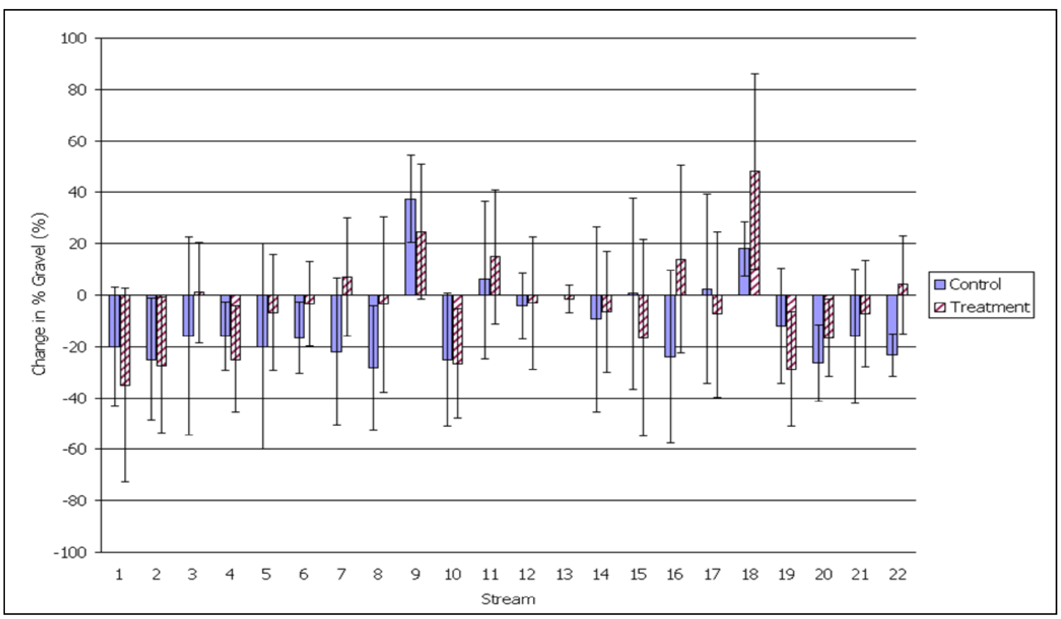


Figure 3.3D. Mean change in percent gravel in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

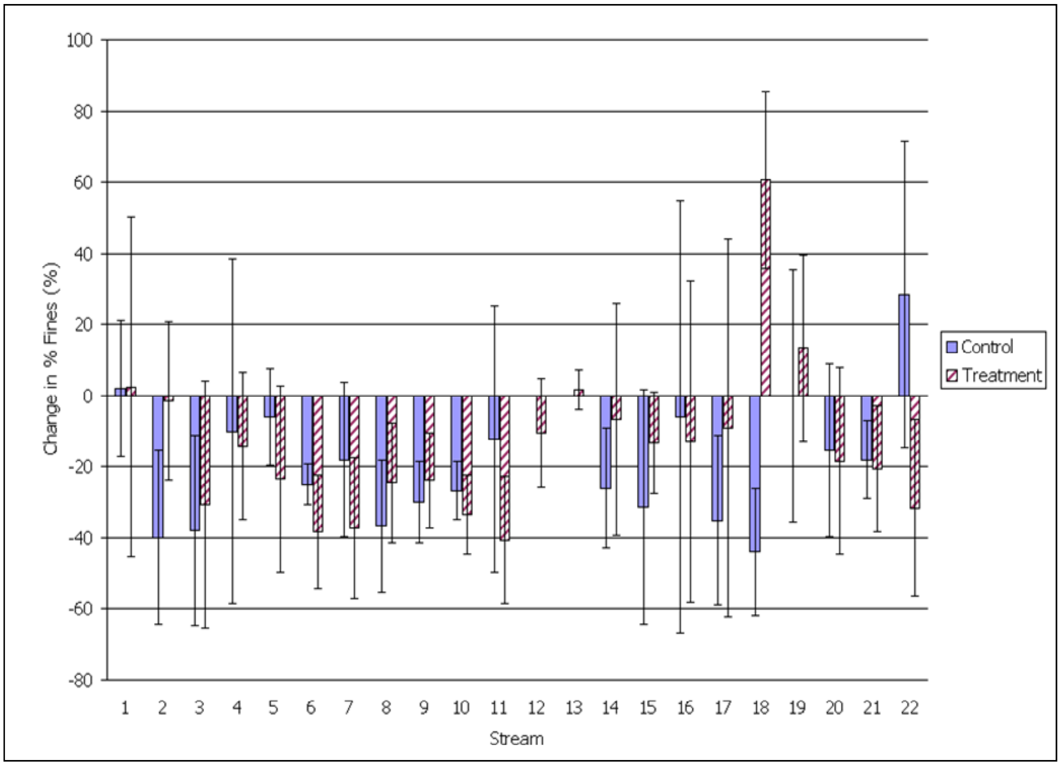


Figure 3.3E. Mean change in percent fines in control and treatment reaches following harvest for 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

3.1.4. Large Wood Characteristics

Number of wood pieces per 300 m within the bankfull depth in control reaches decreased by a mean of 2 (± 5) following the harvest year, and increased in treatment reaches by a mean of 0.5 (± 5) (Figure 3.4A). Number of wood pieces per 300 m between the bankfull depth and 1.8 m above bankfull depth in control reaches increased by 1 (± 5), and increased in treatment reaches by 3 pieces (± 4) (Figure 3.4B). Volume of wood jams per 300 m in control reaches decreased by a mean of 18 m^3 (±98) following harvest, and in treatment reaches decreased by a mean of 14 m^3 (±34) (Figure 3.4C). Changes in wood pieces both within and above bankfull depth, and changes in wood jam volume in treatment reaches following harvest were not significantly different than changes in control reaches (p-values=0.18, 0.24, 0.87, respectively).

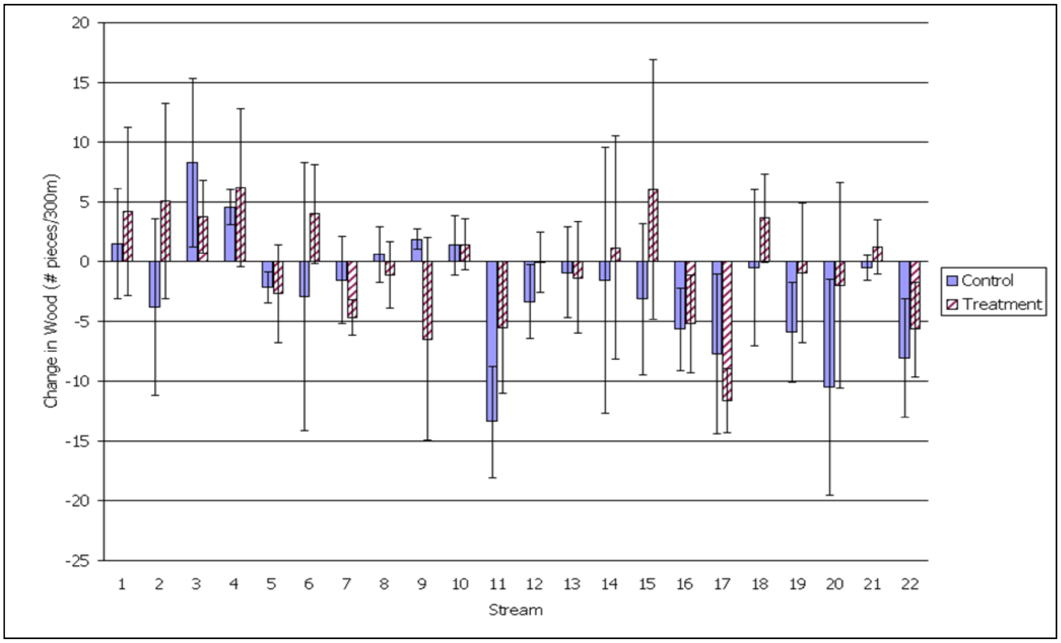


Figure 3.4A. Mean change in number of wood pieces per 300 m within the bankfull width following harvest in control and treatment reaches in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

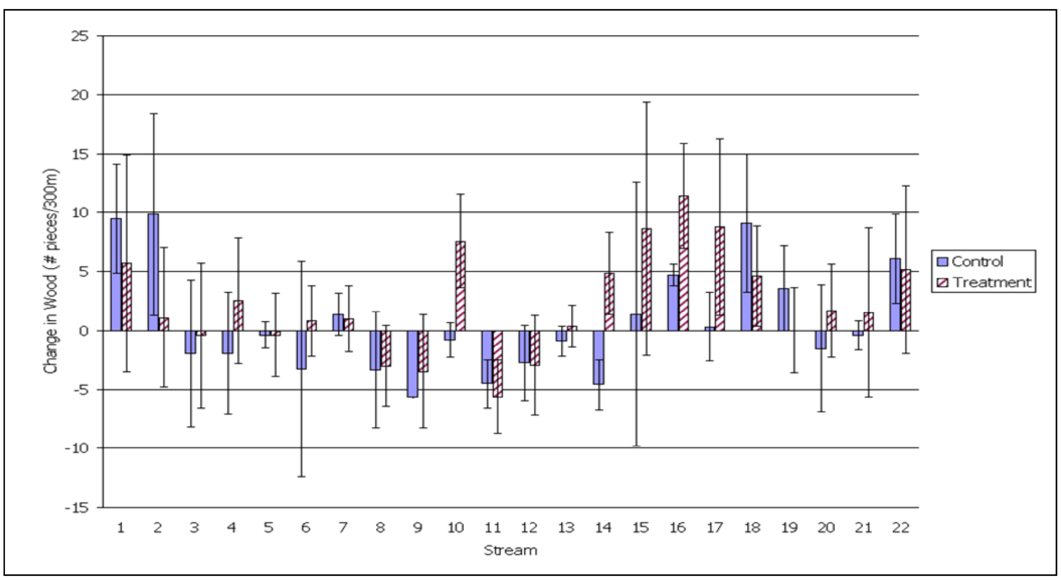


Figure 3.4B. Mean change in number of wood pieces per 300 m within the bankfull width and 1.8 m above bankfull width following harvest in control and treatment reaches of 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

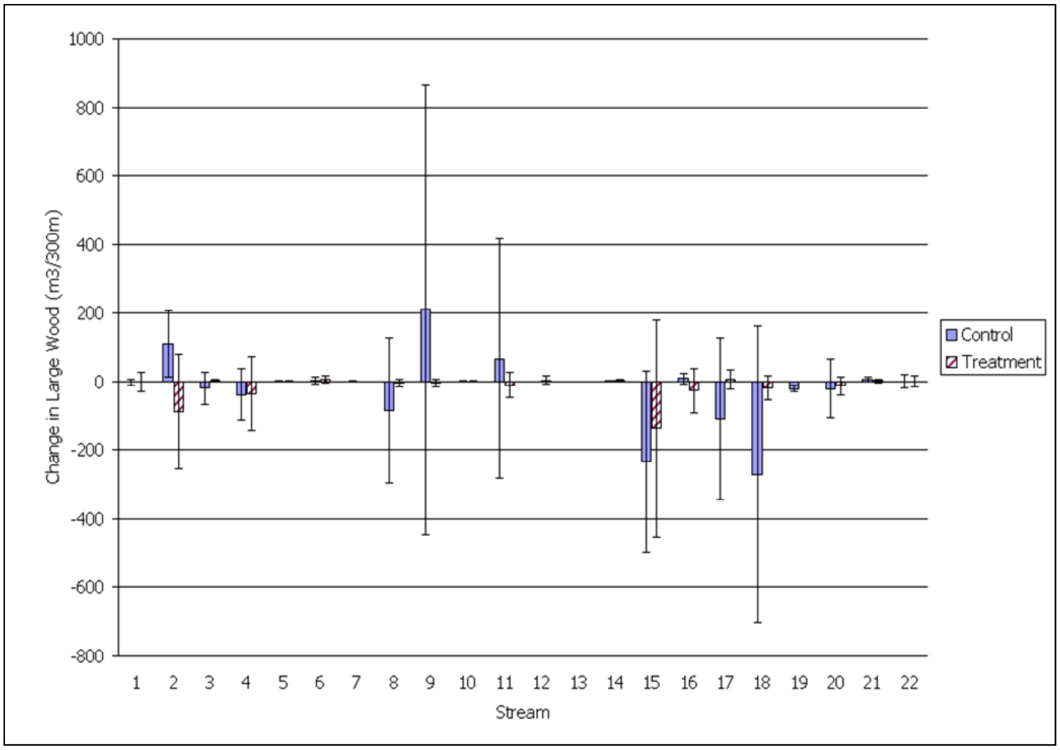


Figure 3.4C. Mean change in wood jam volume (m^3) per 300 m following harvest in control and treatment reaches in 22 Oregon Coast Range headwater streams. Error bars represent one standard deviation of the mean.

3.2. Climate Characteristics

3.2.1. Mean Monthly Air Temperature for 2002-2005

Mean monthly air temperature range among the four years between May and August of this study in Astoria was 12.2 to 16.3˚C (±0.9) in 2002, 12.9 to 16.6˚C (±0.4) in 2003, 15.3 to 17.7 (±0.4) in 2004, and 13.4 to 16.8˚C (±0.8) in 2005 (Figure 3.5A). Mean monthly air temperature range among the four years in Newport was 13.5 to 14.8˚C (±0.7) in 2002, 13.7 to 15.6˚C (±0.5) in 2003, 12.9 to 16.1˚C (±0.4) in 2004, and 13.9 to 15.6˚C (±0.9) in 2005 (Figure 3.5B). Mean monthly air temperature range among the four years in Coquille was 12.2 to 16.7˚C (±1.0) in 2002, 14.1 to 16.7˚C (±0.3) in 2003, 14.3 to 18.5˚C (±0.45) in 2004, and 14.1 to 17.3˚C (±1.1) in 2005 (Figure 3.5C).

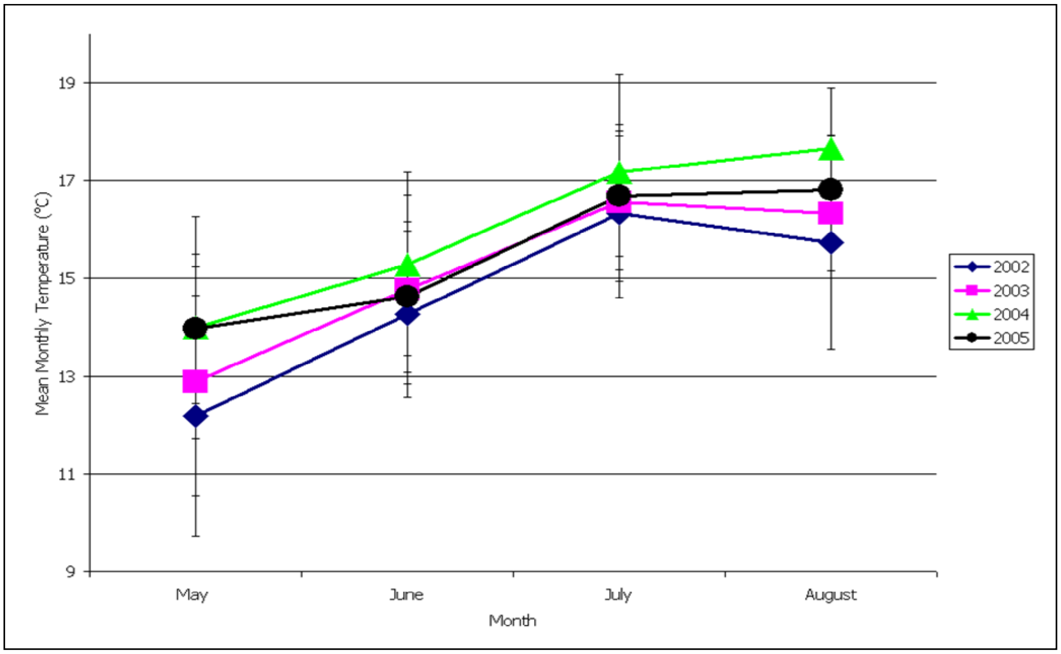


Figure 3.5A. Mean monthly air temperature for Oregon Climate Service Station #350328 (Astoria) for 2002 to 2005. Error bars represent one standard deviation of the mean.

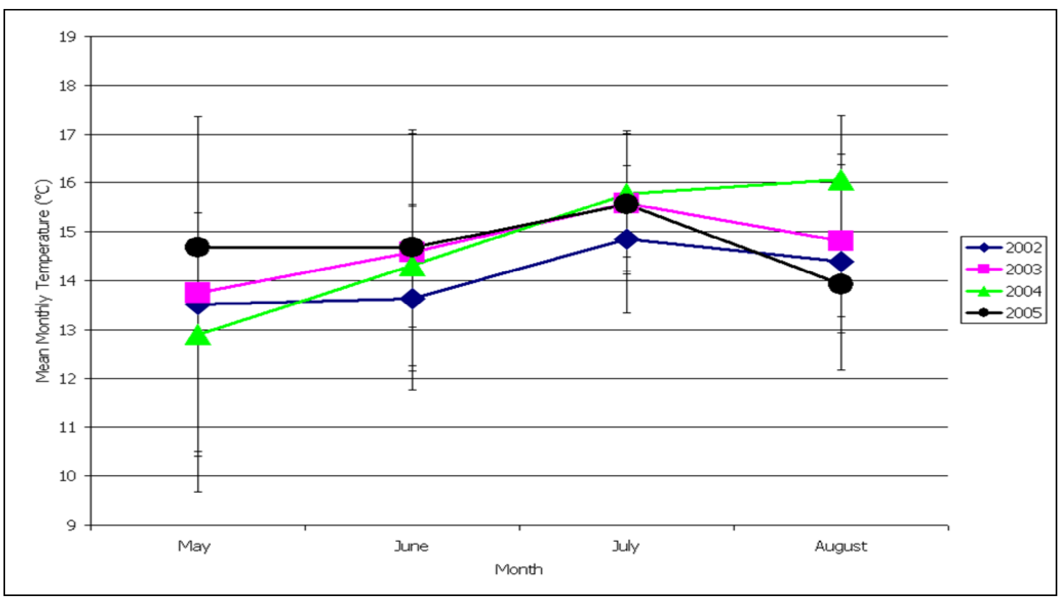


Figure 3.5B. Mean monthly air temperature for Oregon Climate Service Station #356032 (Newport) for 2002 to 2005. Error bars represent one standard deviation of the mean.

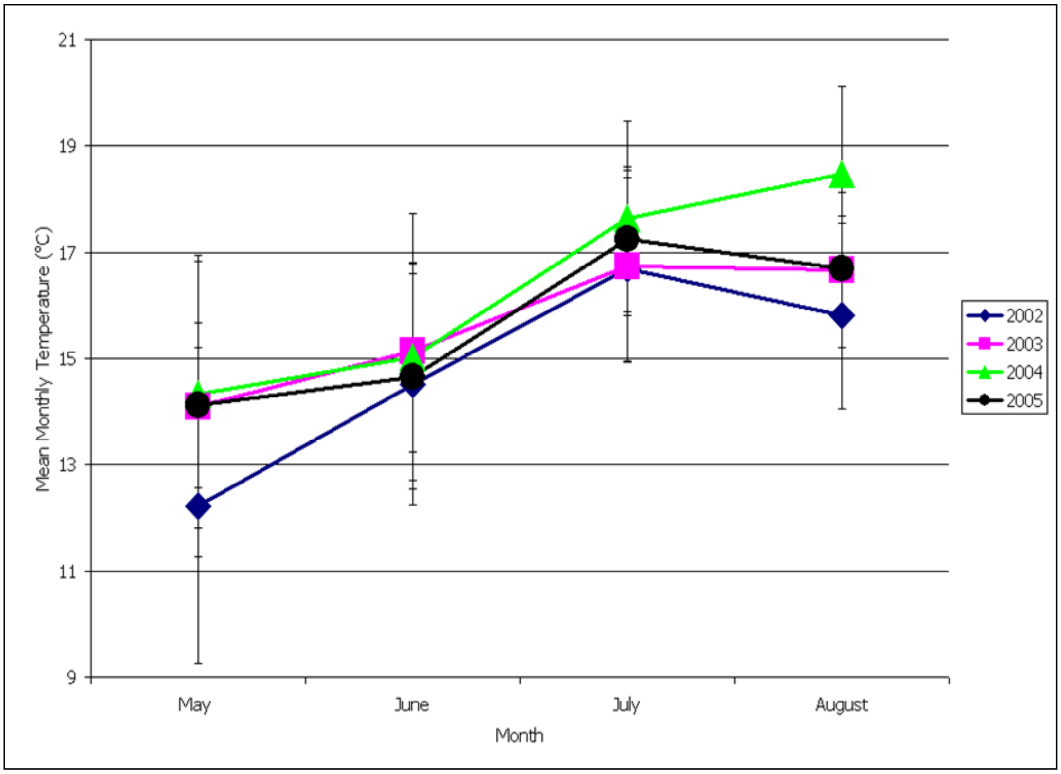


Figure 3.5C. Mean monthly air temperature for Oregon Climate Service Station #351836 (Coquille) for 2002 to 2005. Error bars represent one standard deviation of the mean.

3.2.2. Total Monthly Precipitation

Total monthly precipitation between May and August for Astoria in 2002, 2003, 2004, and 2005 ranged from 0.8 mm in August to 58.9 mm in June, 2.5 mm in August to 55.3 mm in May, 3.8 mm in July to 100.8 mm in August, and 6.4 mm in August to 138.7 mm in May, respectively (Figure 3.6A). Total monthly precipitation for Newport in 2002, 2003, 2004, and 2005 ranged from 2.5 mm in August to 60 mm in June, 2 mm in August to 33.8 mm in May, 0.5 mm in July to 81.8 mm in August, and 1.5 mm in August to 130.6 mm in June, respectively (Figure 3.6B). Total monthly precipitation for Coquille in 2002, 2003, 2004, and 2005 ranged from 0.8 mm in July to 24.9 mm in June, 0 mm in July to 42.9 mm in May, 0.25 mm in July to 51.3 mm in May, and 0 mm in August to 159 mm in May, respectively (Figure 3.6C).

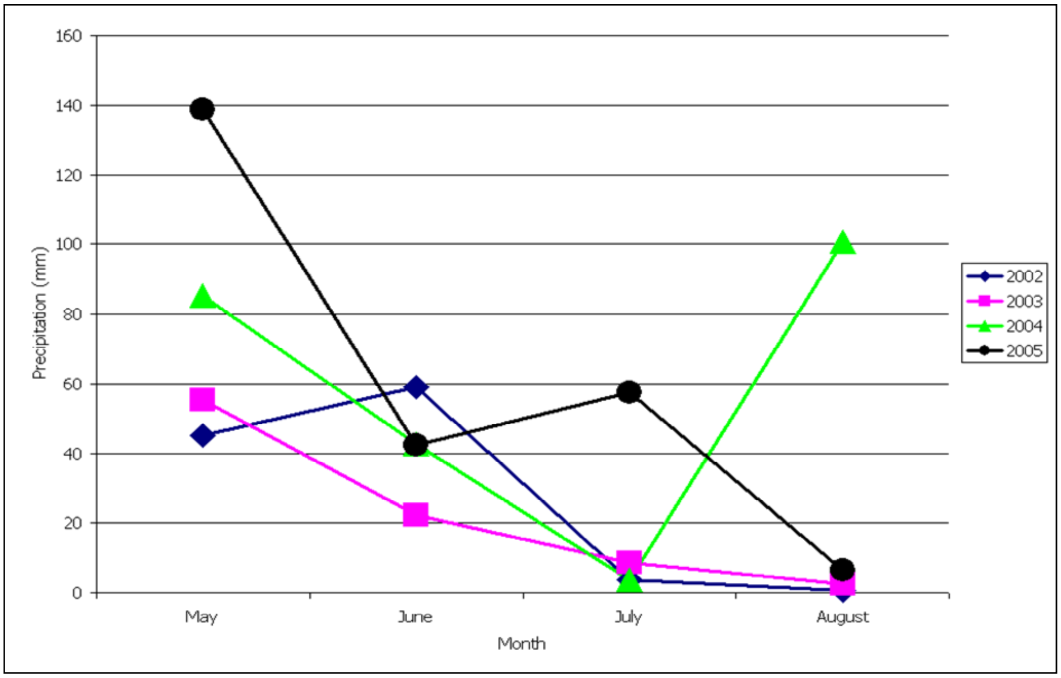


Figure 3.6A. Total monthly precipitation for Oregon Climate Service Station #350328 (Astoria) for 2002 to 2005.

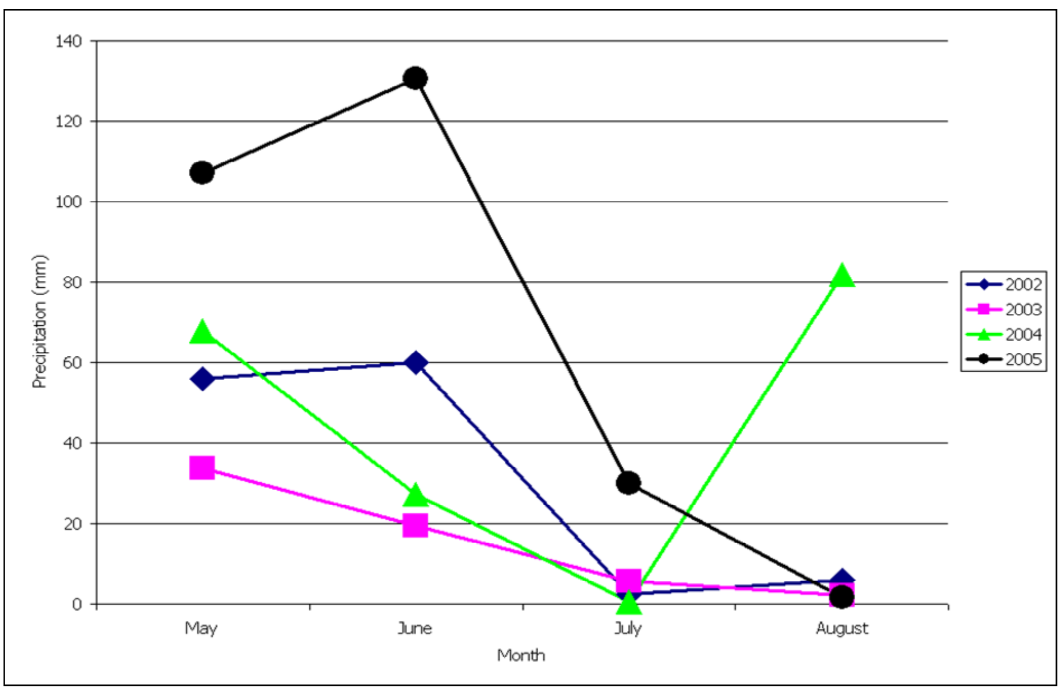


Figure 3.6B. Total monthly precipitation for Oregon Climate Service Station #356032 (Newport) for 2002 to 2005.

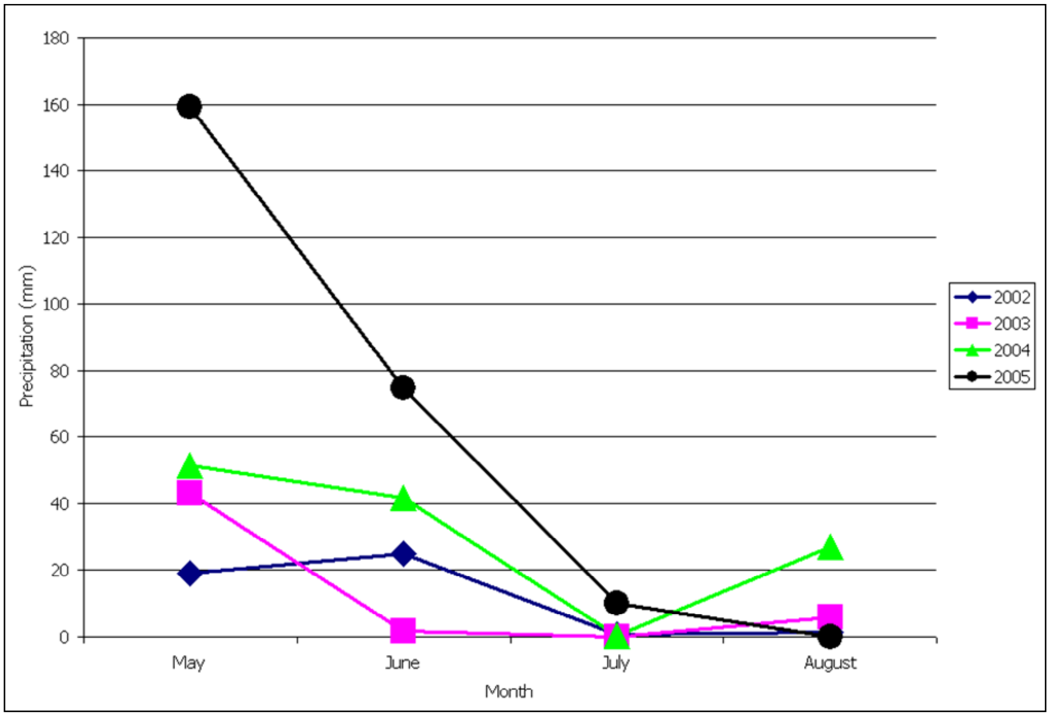


Figure 3.6C. Total monthly precipitation for Oregon Climate Service Station #351836 (Coquille) for 2002 to 2005.

3.3. Warm-Season Stream Temperature Characteristics

3.3.1. Warm-Season Stream Temperature Gradients

Warm-season temperature gradient in the control reaches in pre-harvest year 2002 averaged 0.4°C (±0.7), and in the treatment reaches averaged 0.1°C (± 0.4) (Figure 3.7A). Warm-season temperature gradient in the control reaches in pre-harvest year 2003 averaged 0.6°C (±1), and in the treatment reaches averaged -0.1°C (± 1) (Figure 3.7B). Warm-season temperature gradient in the control reaches in 2004 (for those streams that remained unharvested) averaged 0.3°C (±0.6), and in the treatment reaches averaged 0.0°C (±0.4) (Figure 3.7C).

Following harvest, streams treated in 2004 had a mean warm-season temperature gradient of 0.4°C (± 0.7) in control reaches, and 0.3°C (± 0.6) in treatment reaches (Figure 3.7D). Streams treated in 2005 had a mean warm-season temperature gradient of 0.3°C (±0.6) in the control reach, and 0.4°C (±0.9) in the treatment reach (Figure 3.7E).

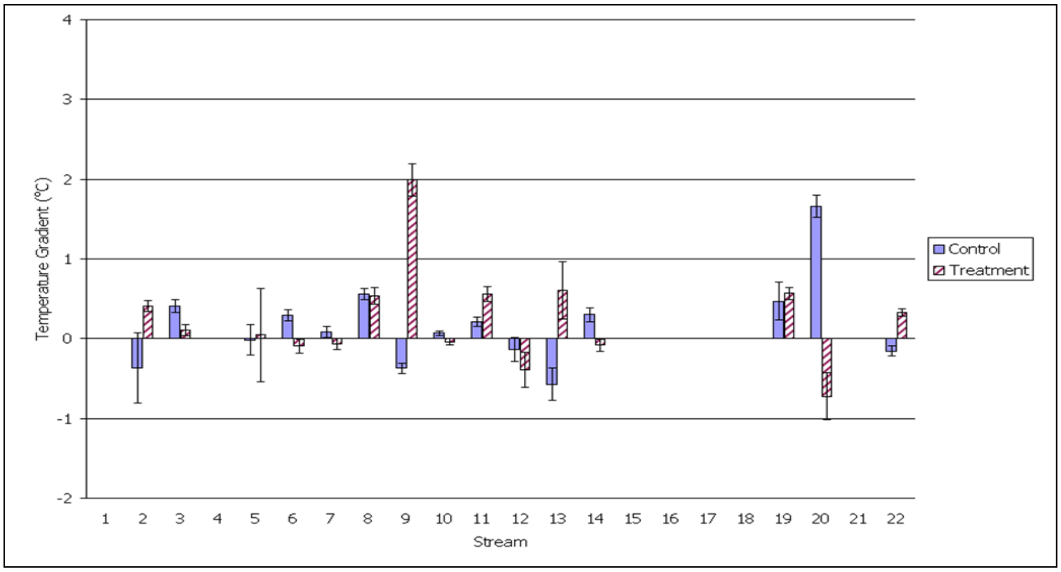


Figure 3.7A. Mean warm-season temperature gradient in the control and treatment reaches of Oregon Coast Range headwater streams in pre-harvest year 2002. Missing values indicate streams that were not yet installed with temperature probes. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

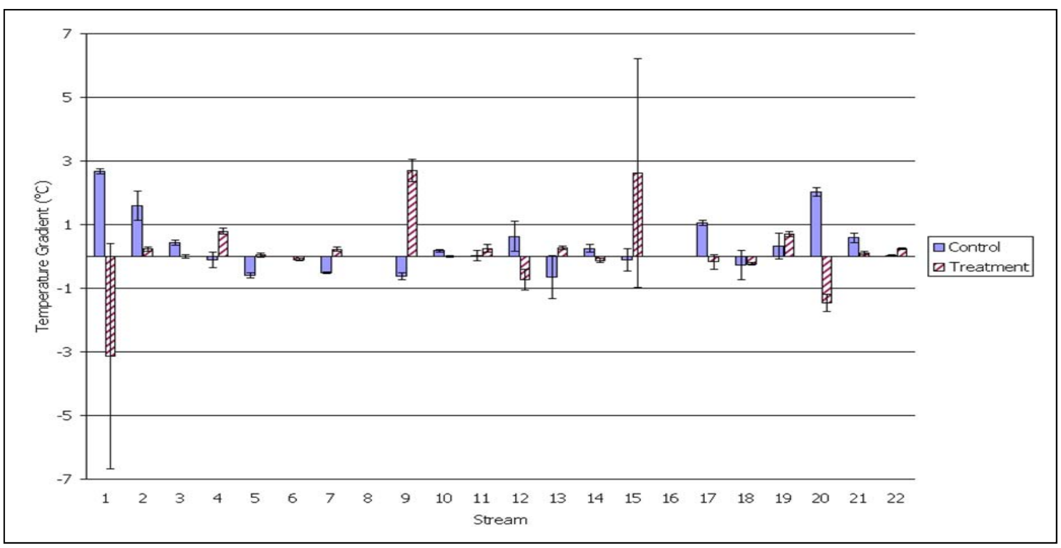


Figure 3.7B. Mean warm-season temperature gradient in the control and treatment reaches for Oregon Coast Range headwater streams in pre-harvest year 2003. Stream #8 and #16 missing data because of missing temperature probes. Error bars represent one standard deviation from the mean (n=48 days, July 15th to August 31st). Note change in scale from Figure 3.7A.

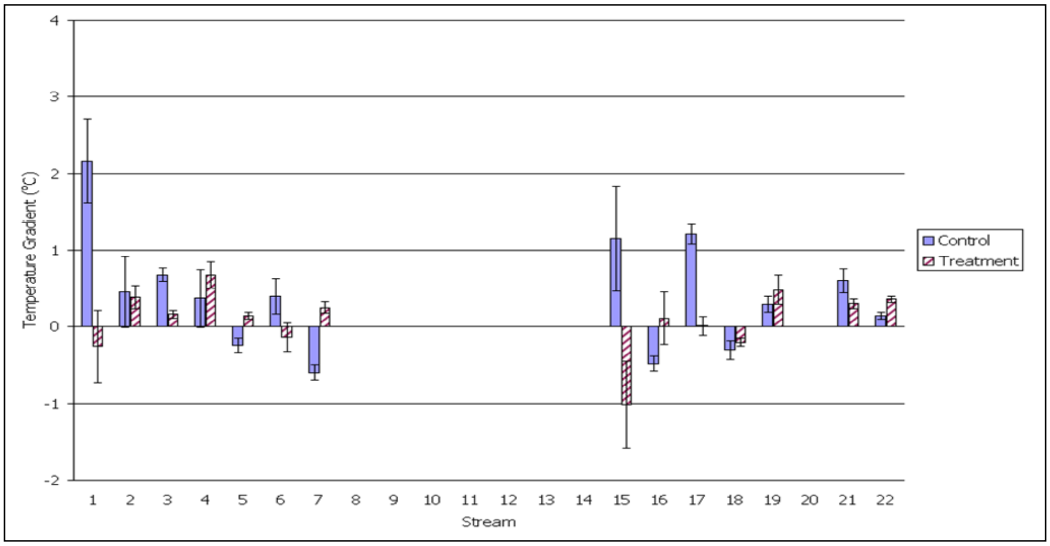


Figure 3.7C. Mean warm-season temperature gradient in the control and treatment reaches for Oregon Coast Range headwater streams in pre-harvest year 2004. Missing data indicate streams that were harvested in 2004. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

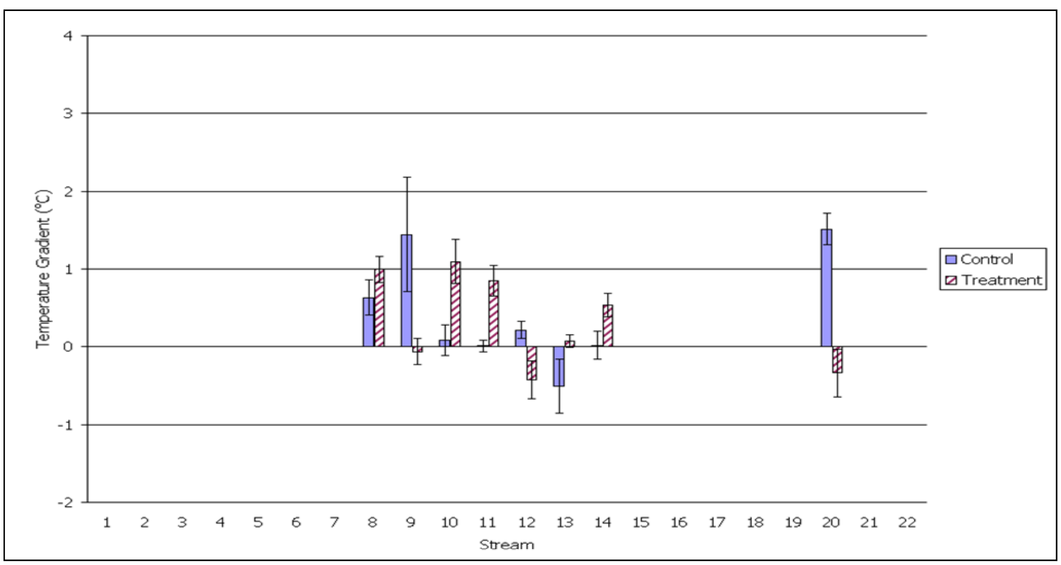


Figure 3.7D. Mean warm-season temperature gradient in 2004 following harvest for the control and treatment reaches for Oregon Coast Range headwater streams. Missing data indicate streams harvested in 2005. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

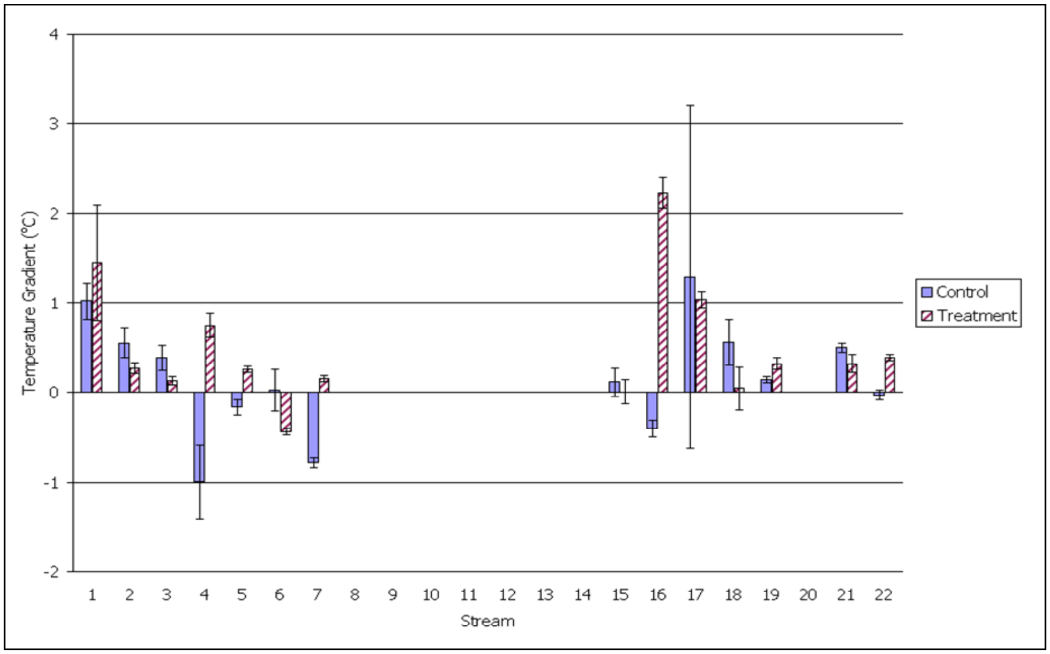


Figure 3.7E. Mean warm-season temperature gradient in 2005 following harvest for the control and treatment reaches for Oregon Coast Range headwater streams. Missing data indicate streams harvested in 2004. Error bars represent one standard deviation of the mean (n=48 days, July 15th to August 31st).

Warm-season temperature gradients in the two pre-harvest years were variable. In control reaches during July 15th to August 31st of the first pre-harvest year, the mean temperature gradient was 0.4°C, a change significantly greater than zero (p-value=0.02, S.E.=0.18) (Figure 3.8). Mean temperature gradient was 0.1°C (p-value=0.71, S.E.=0.17) in the treatment reaches during July 15th to August 31st in the first pre-harvest year. During the same sampling period in the second pre-harvest year, mean temperature gradient in the control reaches was 0.4°C (p-value=0.01, S.E.=0.17) and mean temperature gradient in treatment reaches was 0.0°C (p-value=0.85, S.E.=0.17) (Figure 3.8).

Mean warm-season temperature gradient in control reaches in the first pre-harvest year was the same (0.0°C) as that observed in the second pre-harvest year (p-value=0.95, S.E.=0.21) (Table 3.1). Mean temperature gradient in treatment reaches in the first pre-harvest year was 0.1°C lower than that observed in the second pre-harvest year (Table 3.1). This difference was not statistically significant (p-value=0.55, S.E.=0.21). Difference in temperature gradients between the control and treatment reaches in the first-pre harvest year was 0.1°C less than that observed in the second pre-harvest year, but was not significantly different (p-value=0.65, S.E.=0.30) (Table 3.1).

Post-harvest mean warm-season temperature gradient in control reaches, combining all streams using two pre-harvest years (either 2002 & 2003, or 2003 & 2004), was 0.3°C (p-value=0.13, S.E.=0.17), and in treatment reaches using one-year-post-harvest data (either 2004 or 2005) was 0.4°C (p-value=0.01, S.E.=0.17) (Figure 3.8).

Mean warm-season temperature gradient in the control reaches following harvest was cooler by 0.2°C than that observed pre-harvest, but this change was not significant (p-value=0.30, S.E.=0.17). However, mean temperature gradient in treatment reaches was 0.4°C warmer than observed prior to harvesting. This increase was significant (p-value=0.02, S.E.=0.17) (Table 3.2). The resulting mean difference in warm-season temperature gradient between treatment and control reaches following harvest was 0.6°C greater than that observed prior to harvest, which is also a significant increase (p-value 0.01, S.E. 0.24), indicating that, on average, a statistically significant increase in warming occurred in the treatment reaches following harvest (Table 3.2).

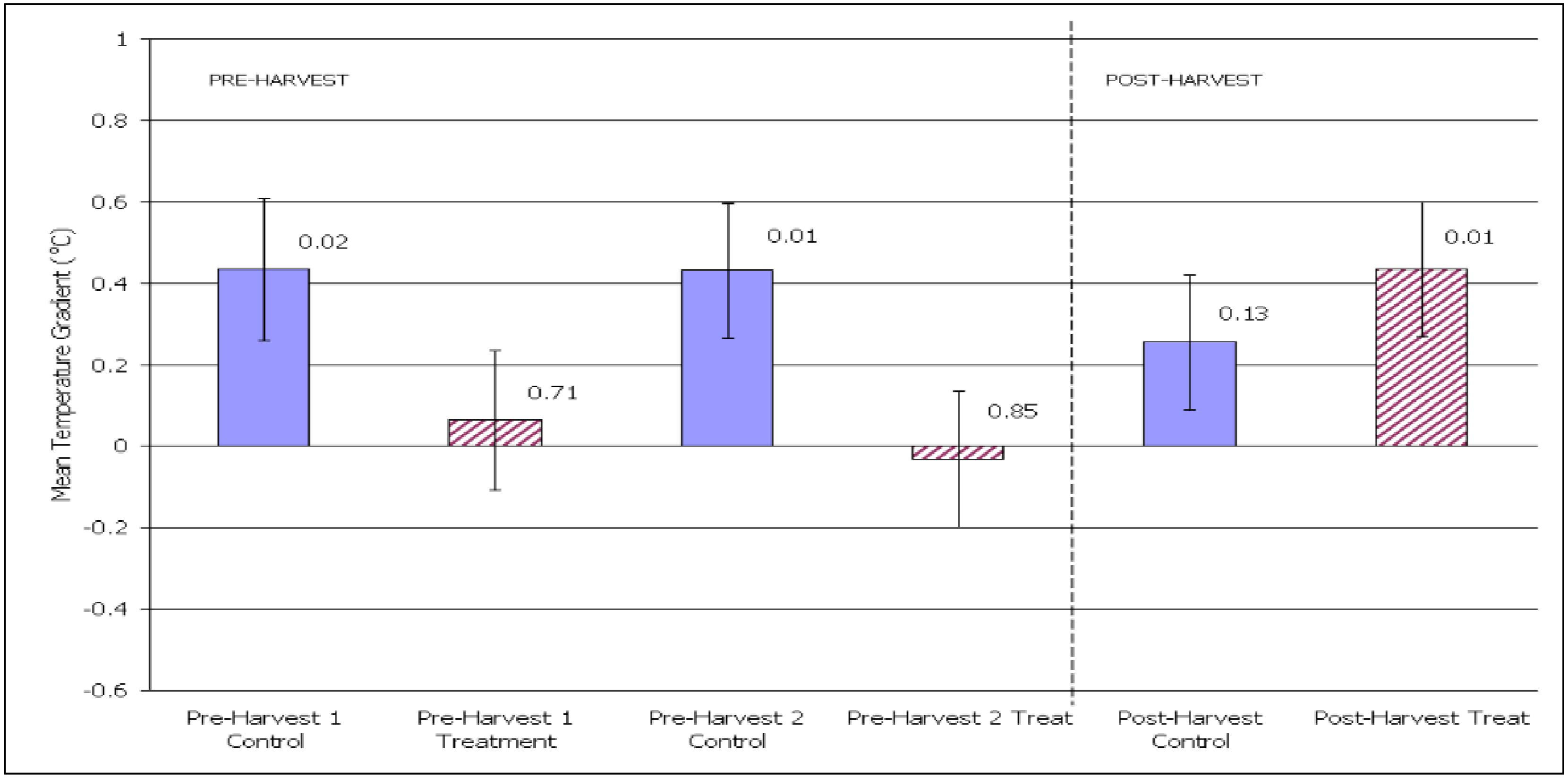


Figure 3.8. Mean warm-season temperature gradient/300 m for 22 streams in the Oregon Coast Range using two years pre- harvest and one year post-harvest data for the mean 7-day moving mean of the daily maximum (7DMMDMax) between July 15th and August 31st (2002-2005). Error bars represent one standard error of the mean and p-values are indicated. Significance level is 0.05, testing if temperature gradient is significantly different

Table 3.1. Changes in warm-season mean temperature gradient among 22 streams in the Oregon Coast Range between two pre-harvest years.

	Estimate (°C)	Standard Error	P-value
A[1]	0.0	0.21	0.95
B	0.1	0.21	0.55
C	-0.1	0.30	0.65

[1]Value A: Post(Control) – Pre(Control). Value B: Post (Treatment) – Pre(Treatment). Value C: (Post (Treatment) – Pre(Treatment)) – (Post(Control) – Pre(Control)).

Table 3.2. Changes in warm-season mean temperature gradient among 22 streams in the Oregon Coast Range comparing two years pre-harvest with one year post-harvest.

	Estimate (°C)	Standard Error	P-value
A[1]	-0.2	0.17	0.30
B	0.4	0.17	0.02
C	0.6	0.24	0.01

[1]Value A: Post(Control) – Pre(Control). Value B: Post (Treatment) – Pre(Treatment). Value C: (Post (Treatment) – Pre(Treatment)) – (Post(Control) – Pre(Control)).

3.3.2. Relationships Between Channel Characteristics and Warm-Season Stream Temperature Gradient

Percentage of channel substrate comprised of gravel was the strongest predictor of mean warm-season temperature gradient in control reaches (p-value = 0.01, Pearson correlation coefficient = 0.54, R^2 = 0.30) followed by geologic substrate and percentage of the channel substrate comprised of boulder (Table 3.3). However, shade was the strongest predictor of mean warm-season temperature gradient in treatment reaches (p-value = 0.00, Pearson correlation coefficient = -0.69, R^2 = 0.46) followed by number of large wood pieces between bankfull width and 1.8 m above bankfull width (Table 3.4). Relationships between shade and mean changes in temperature gradient for control and treatment reaches following harvest show a strong linear correlation within treatment reaches and no relationship within control reaches (Figure 3.9).

Table 3.3. Relationships between selected stream channel characteristics and mean temperature gradient in control reaches of 22 Oregon Coast Range headwater streams. Variables in bold are significant at alpha = 0.05.

Variable	Pearson Correlation Coefficient	p-value	R^2
Gravel	**0.54**	**0.01**	**0.29**
Geology	**-0.39**	**0.03**	**0.21**
Boulder	**0.45**	**0.04**	**0.20**
Gradient	0.40	0.10	0.13
Fines	-0.27	0.22	0.07
Wood Jam Volume	0.22	0.32	0.05
Maximum Depth	0.22	0.33	0.05
Shade	0.16	0.49	0.02
Wetted Width	0.14	0.53	0.02
Bankfull Width	0.13	0.57	0.02
Cobble	-0.08	0.71	0.01
High Wood	0.08	0.73	0.01
Bedrock	0.07	0.78	0.00
Low Wood	0.07	0.77	0.00
Aspect	0.05	0.82	0.00
Floodprone Width	0.01	0.95	0.00

Table 3.4. Relationships between selected channel characteristics and mean temperature gradient in treatment reaches of 22 Oregon Coast Range headwater streams. Variables in bold are significant at alpha = 0.05.

Variable	Pearson Correlation Coefficient	p-value	R^2
Shade	**-0.69**	**≤0.01**	**0.46**
High Wood	**0.44**	**0.04**	**0.20**
Boulder	-0.42	0.05	0.17
Fine	0.40	0.07	0.16
Bankfull Width	-0.33	0.14	0.11
Wetted Width	-0.32	0.15	0.10
Maximum Depth	-0.25	0.27	0.06
Floodprone Width	-0.23	0.31	0.05
Cobble	-0.20	0.38	0.04
Aspect	0.18	0.42	0.03
Bedrock	-0.15	0.49	0.02
Gravel	-0.08	0.71	0.01
Wood Jam Volume	-0.08	0.71	0.01
Gradient	-0.06	0.79	0.00
Low Wood	-0.06	0.81	0.00
Geology	0.03	0.89	0.00

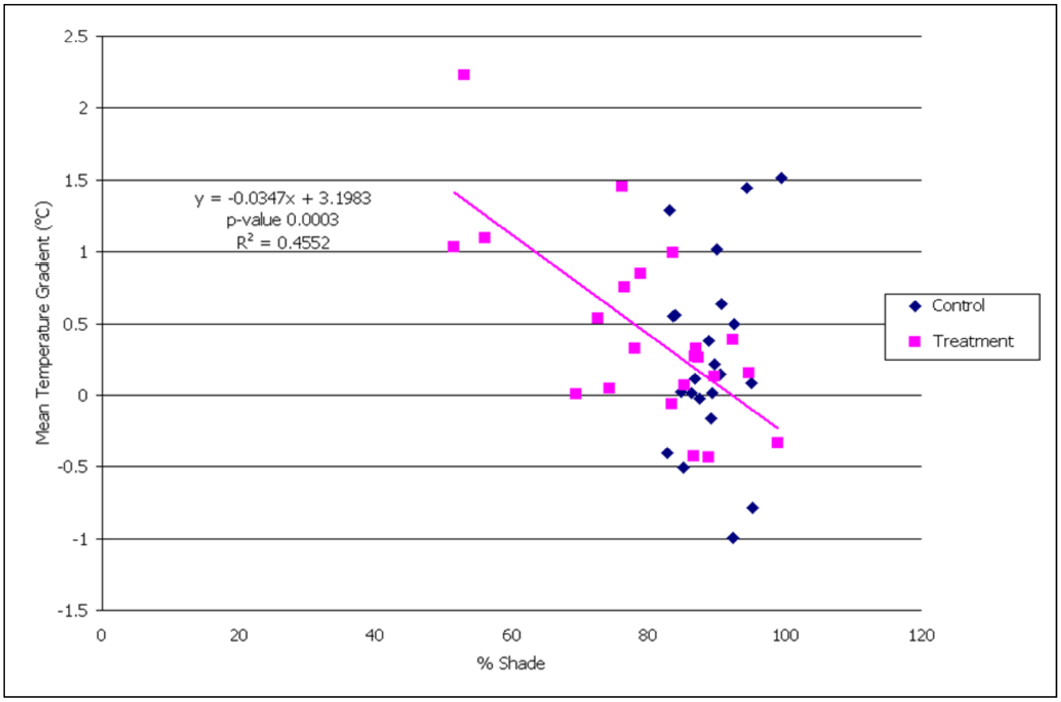


Figure 3.9. Relationship between percent shade and temperature gradient in control and treatment reaches in the summer following harvest of 22 Oregon Coast Range headwater streams. Trend line and equation are provided for relationships between shade and temperature gradient in treatment reaches.

If each reach (control and treatment) in each stream is treated as a separate statistical unit (n = 44), then the two-variable model using shade and channel gravel content is the strongest predictor (p-value = 0.04, adjusted R^2 = 0.27) for mean temperature gradient (Table 3.5). Shade alone is the second best predictor (p-value = ≤0.01, Pearson Correlation Coefficient=-0.43, R^2 = 0.19) for stream temperature gradient using a sample size of 44 reaches (control and treatment reaches in each stream) (Table 3.6).

Table 3.5. Relationships between selected pairs of channel characteristics and mean temperature gradient in both treatment and control reaches following harvest for 22 Oregon Coast Range streams (n=44). Variables in bold are significant at alpha = 0.05.

Variables	P-value	Adjusted R^2
Shade+gravel	**0.04**	**0.27**
Shade+gradient	0.17	0.23
Shade+boulder	0.28	0.21
Shade+geology	0.11	0.20
Shade+floodprone width	0.49	0.20
Shade+cobble	0.56	0.20
Shade+maximum depth	0.64	0.19
Shade+fine	0.73	0.19
Shade+bankfull width	0.80	0.19
Shade+aspect	0.85	0.19
Shade+wetted width	0.87	0.19
Shade+bedrock	0.87	0.19
Shade+jam volume	0.45	0.16
Shade+high wood	0.59	0.16
Shade+low wood	0.65	0.16

Table 3.6. Relationships between selected channel characteristics and mean temperature gradient in control and treatment reaches following harvest for 22 Oregon Coast Range streams (n=44). Variables in bold are significant at alpha = 0.05.

Variable	Pearson Correlation Coefficient	P value	R^2
Shade	**-0.44**	**≤0.01**	**0.19**
High Wood	0.26	0.09	0.07
Gravel	0.22	0.15	0.05
Geology	-0.20	0.89	0.04
Gradient	0.15	0.34	0.02
Cobble	-0.11	0.46	0.01
Aspect	0.11	0.46	0.01
Bankfull Width	-0.10	0.52	0.01
Floodprone Width	-0.09	0.56	0.01
Wood Jam Volume	0.09	0.58	0.01
Wetted Width	-0.07	0.67	0.00
Fines	0.05	0.73	0.00
Bedrock	-0.04	0.78	0.00
Maximum Depth	0.03	0.84	0.00
Low Wood	0.00	0.96	0.00
Boulder	0.00	0.97	0.00

3.4. Warm-Season Temperature Patterns of Individual Streams

3.4.1. Cooling Pattern Following Harvest

Following harvest, one stream had 7DMMDMax temperatures between July 15th and August 31st lower than predicted with a 95% confidence interval based on pre-harvest relationships (Figure 3.10).

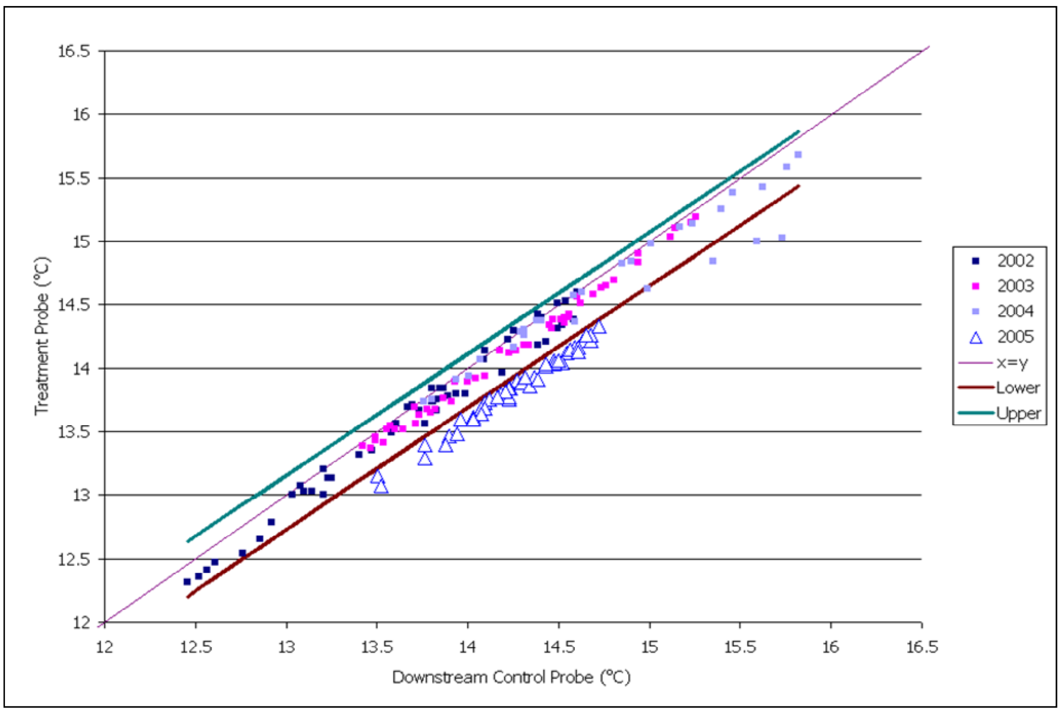


Figure 3.10. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #6 in pre-harvest (2002, 2003, 2004) and post-harvest year (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

3.4.2. No Change in Warm-Season Temperature Pattern Following Harvest

Following harvest, nine streams had observed 7DMMDMax temperatures between July 15th and August 31st within the 95% confidence interval predicted by pre-harvest temperature relationships between control and treatment reaches (Figures 3.11A to 3.11I).

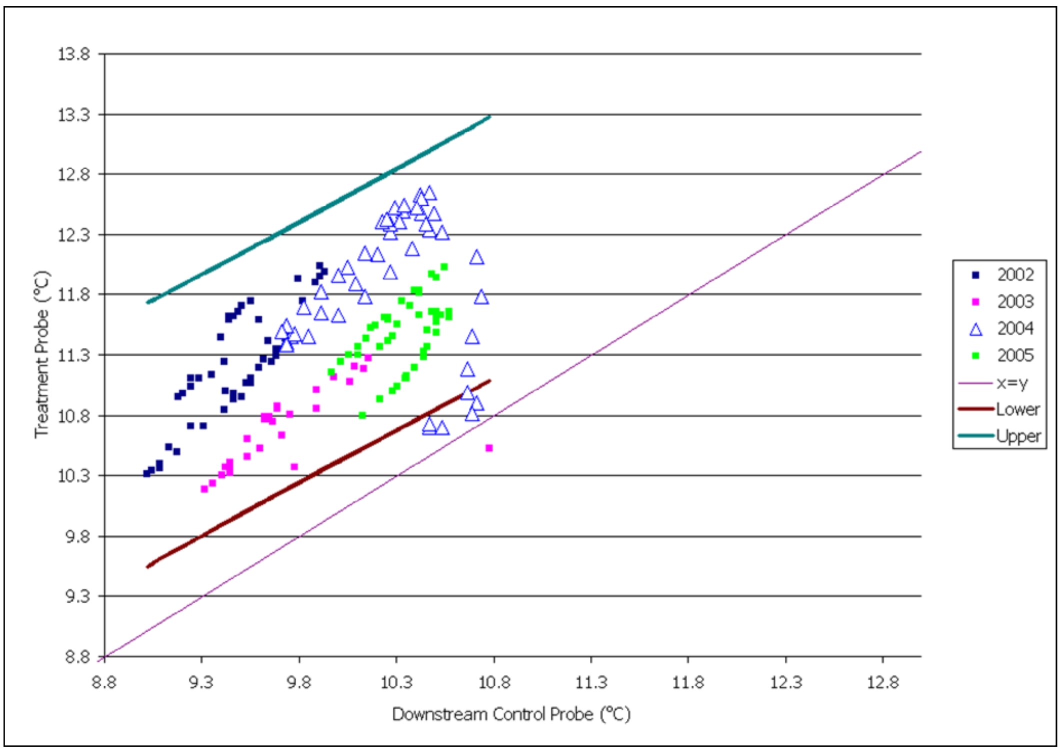


Figure 3.11A. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #2 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

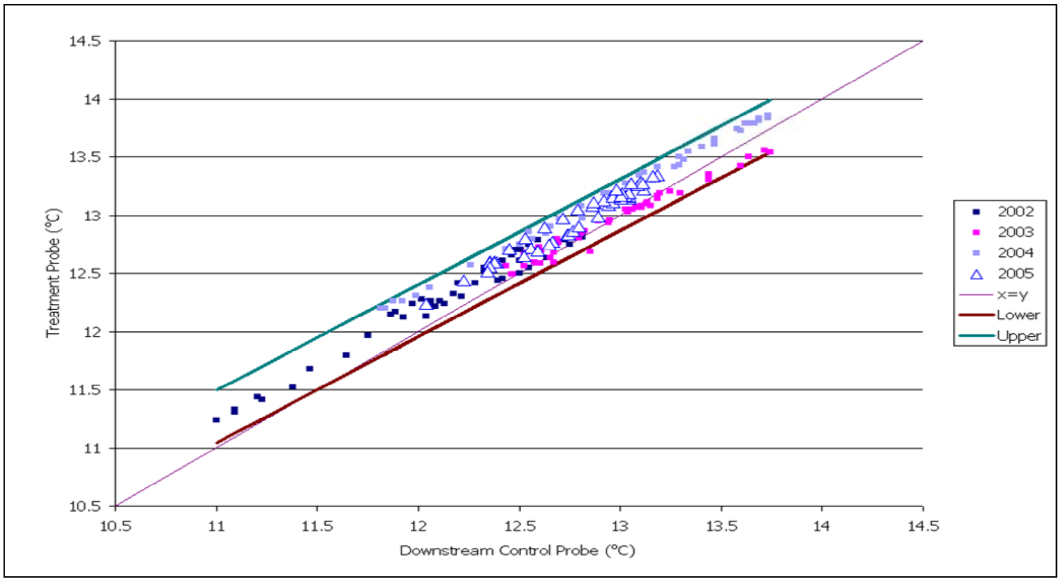


Figure 3.11B. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #3 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

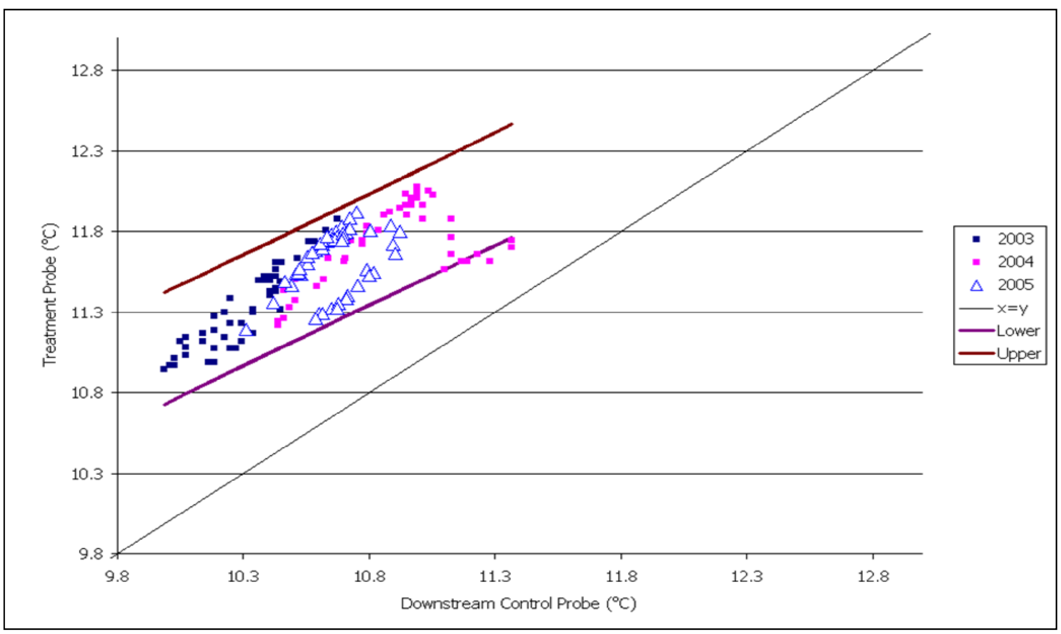


Figure 3.11C. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #4 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

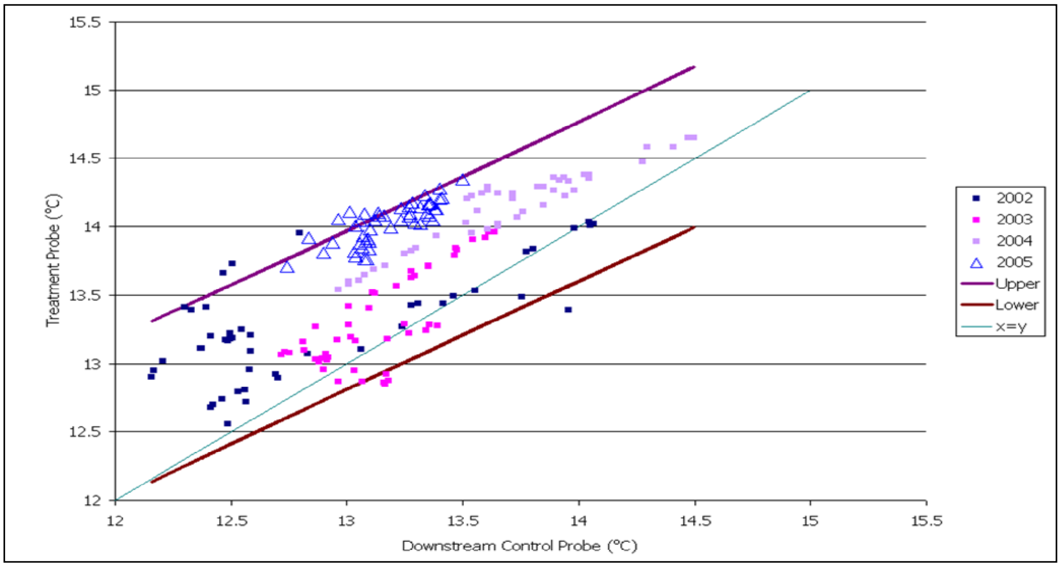


Figure 3.11D. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #5 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

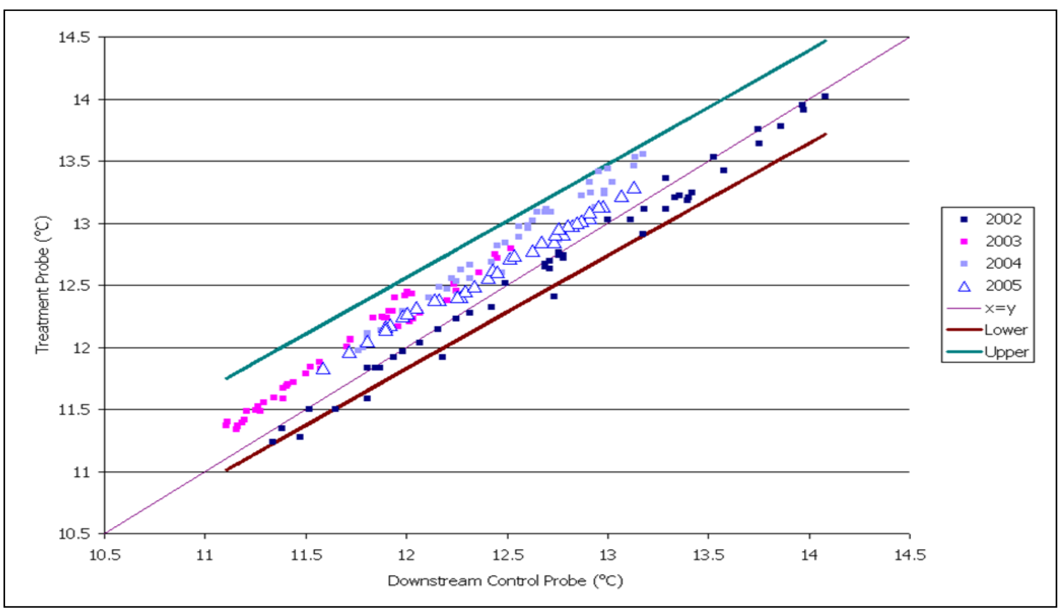


Figure 3.11E. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #7 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

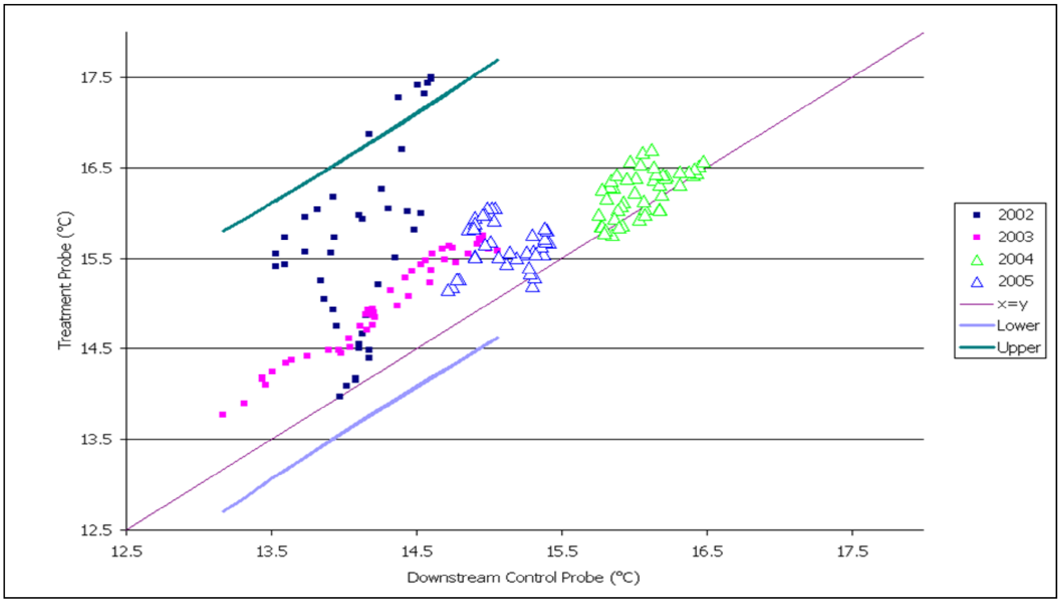


Figure 3.11F. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #13 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

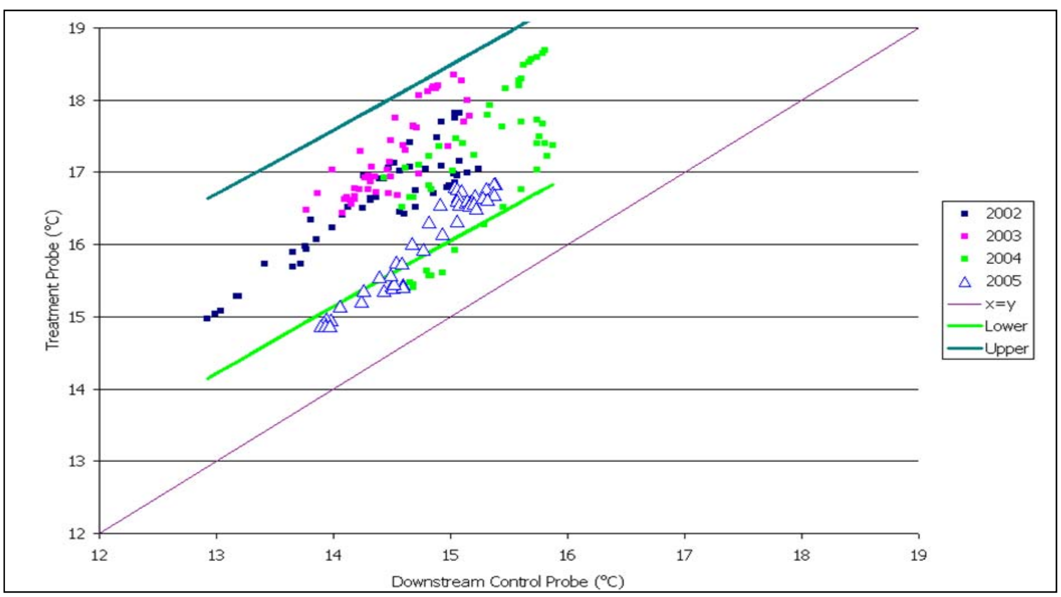


Figure 3.11G. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #19 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

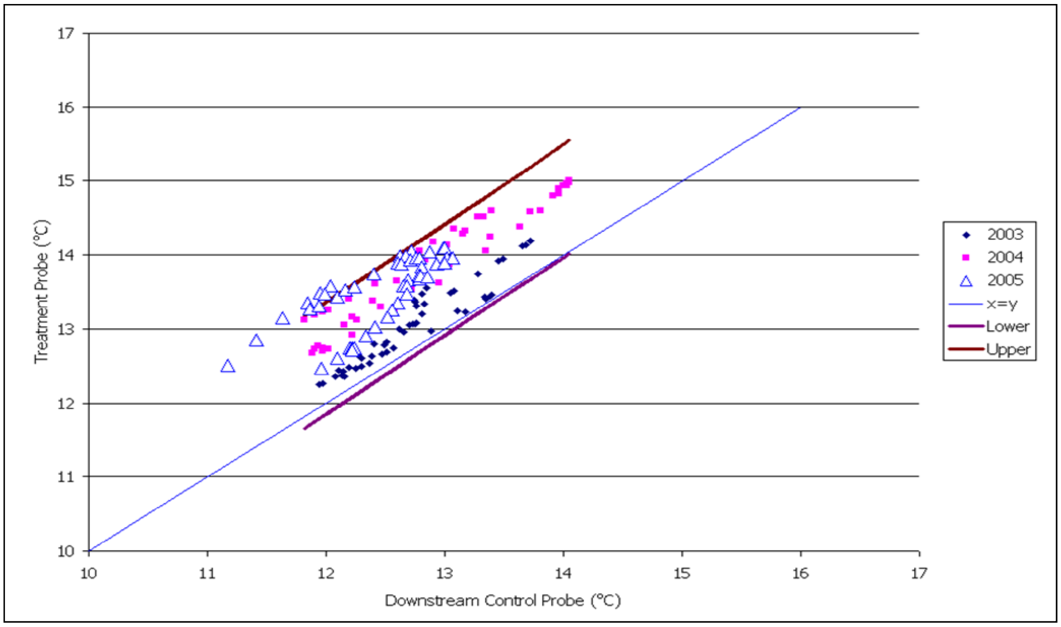


Figure 3.11H. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #21 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

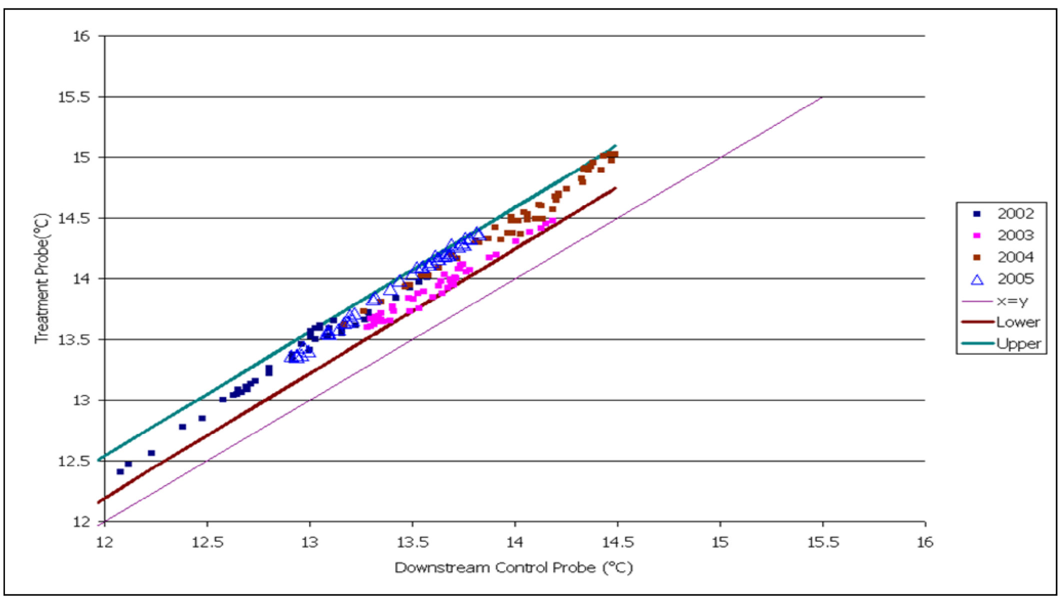


Figure 3.11I. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #22 in pre-harvest (2002, 2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

3.4.3. Warm-Season Warming Pattern Following Harvest

Following harvest, 12 streams had warmer 7DMMDMax temperatures between July 15th and August 31st in the treatment reach than predicted from pre-harvest temperature relationships between control and treatment reaches (Figures 3.12A to 3.12L).

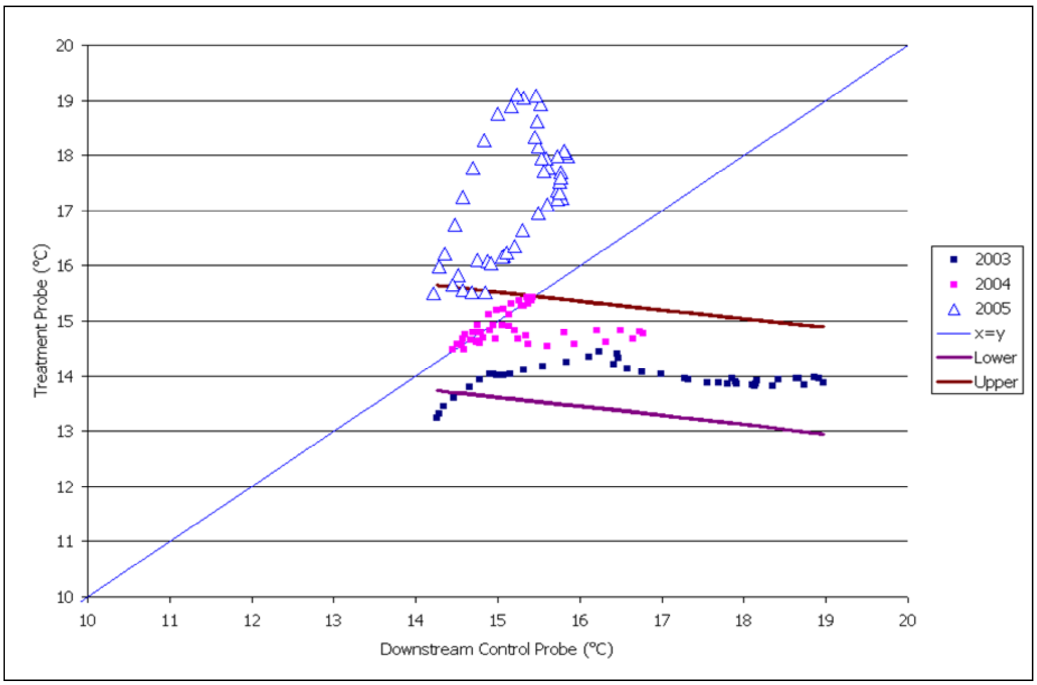


Figure 3.12A. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #1 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

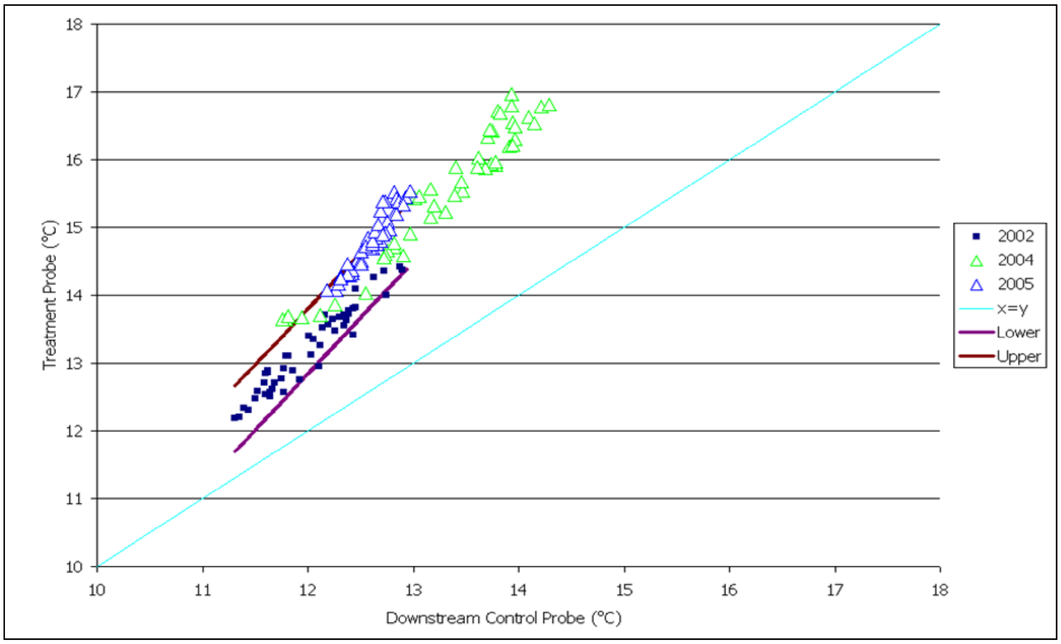


Figure 3.12B. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #8 in pre-harvest (2002) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

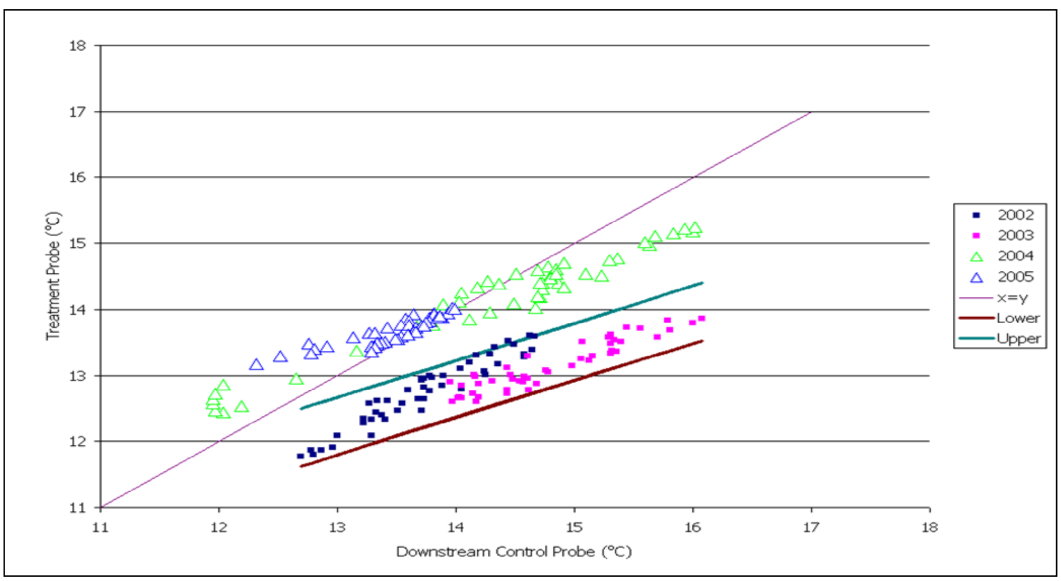


Figure 3.12C. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #9 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

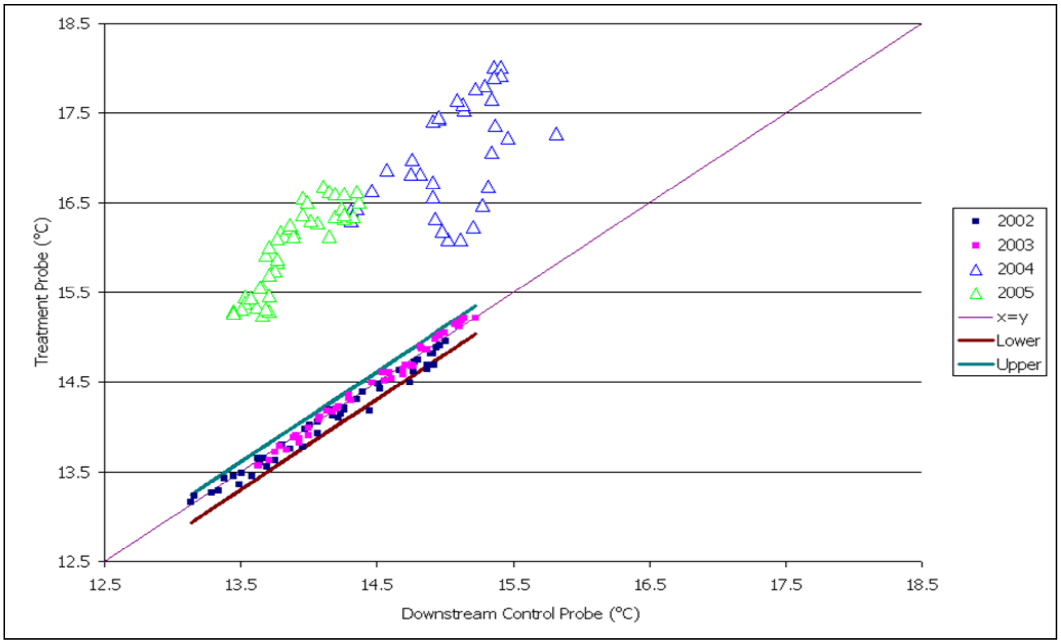


Figure 3.12D. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #10 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

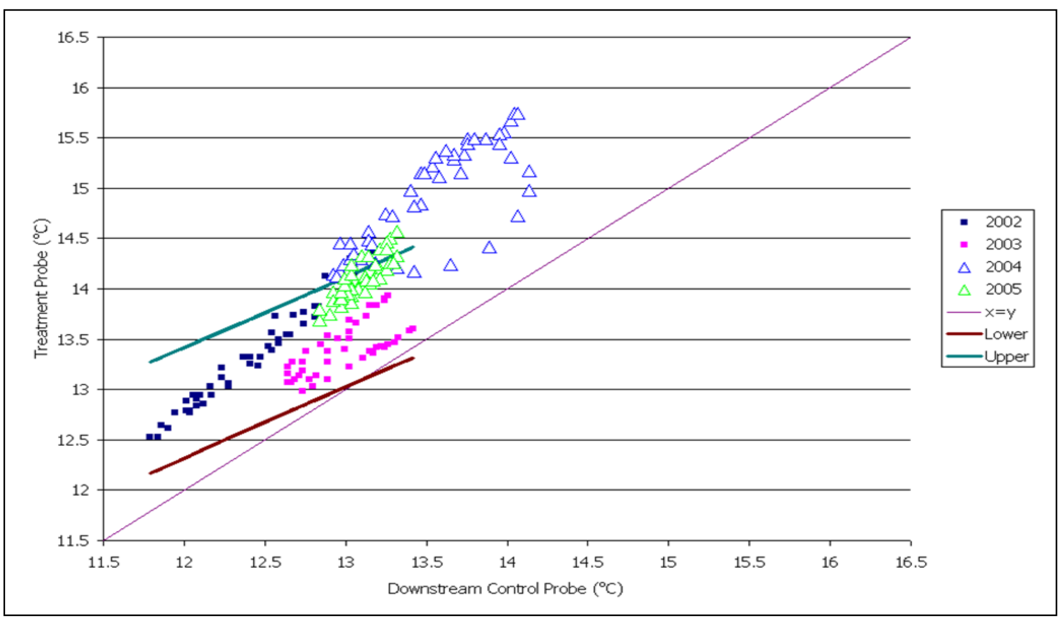


Figure 3.12E. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #11 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

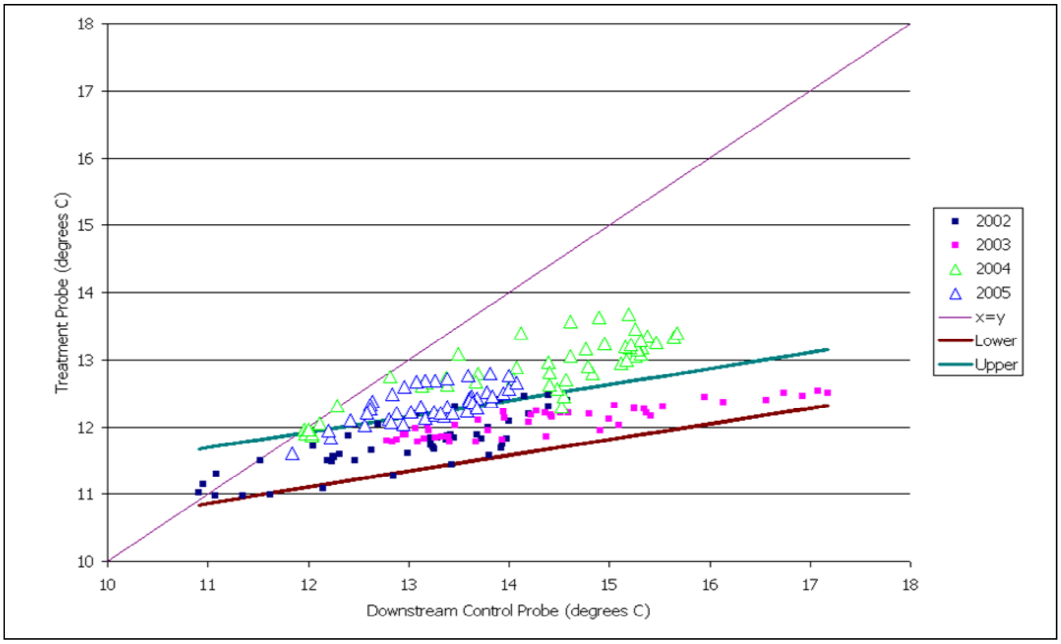


Figure 3.12F. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #12 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence intervals based on pre-harvest temperatures.

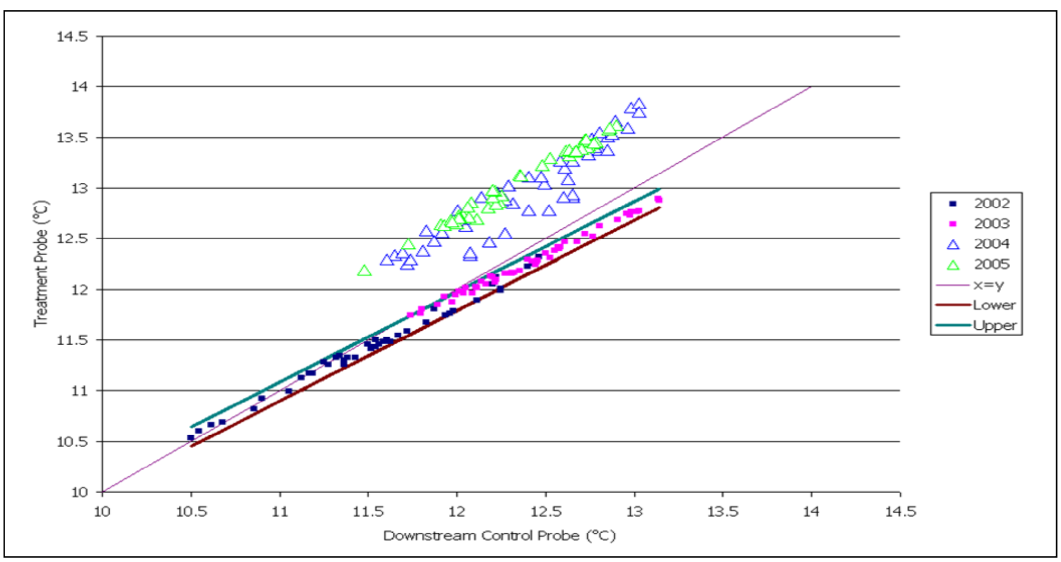


Figure 3.12G. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #14 in pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

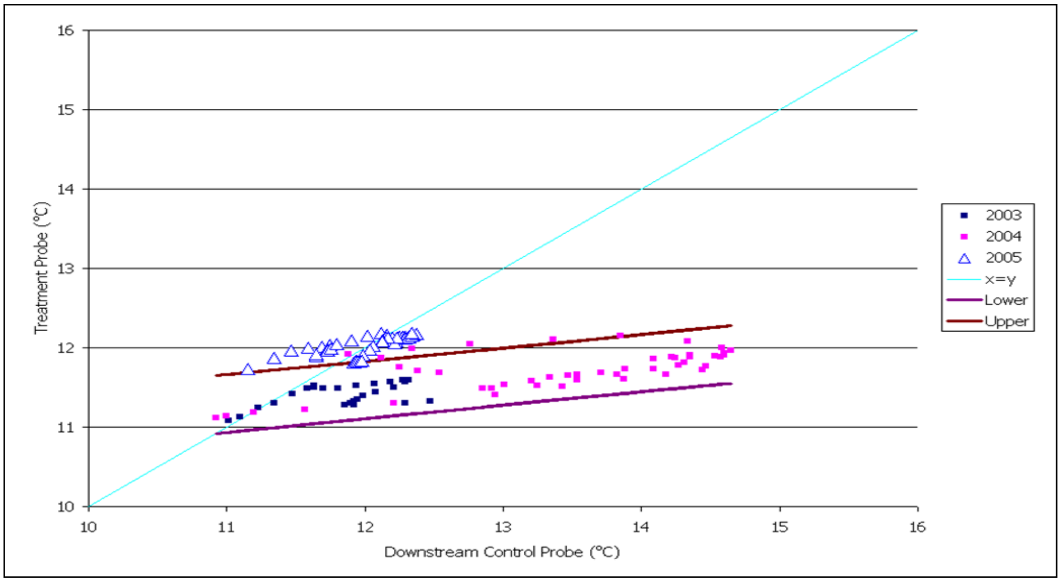


Figure 3.12H. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #15 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

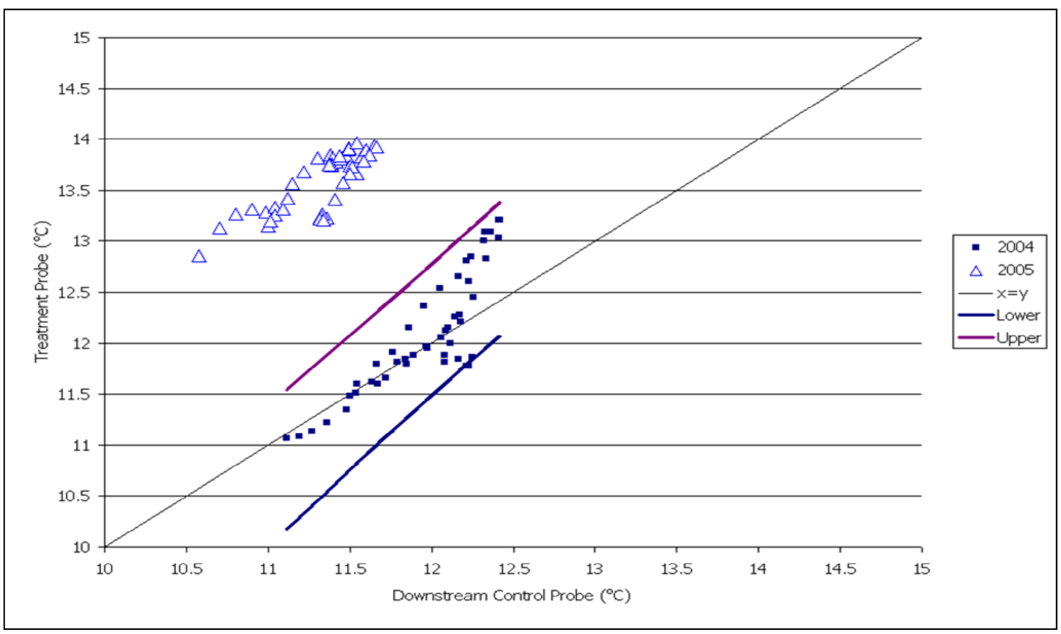


Figure 3.12I Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #16 in pre-harvest (2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

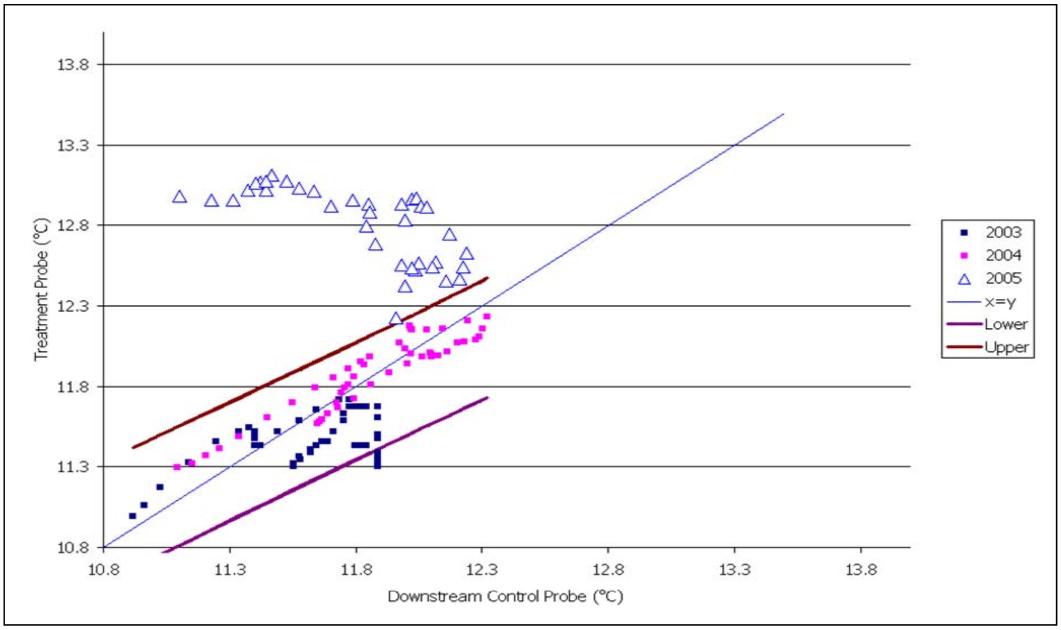


Figure 3.12J. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #17 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

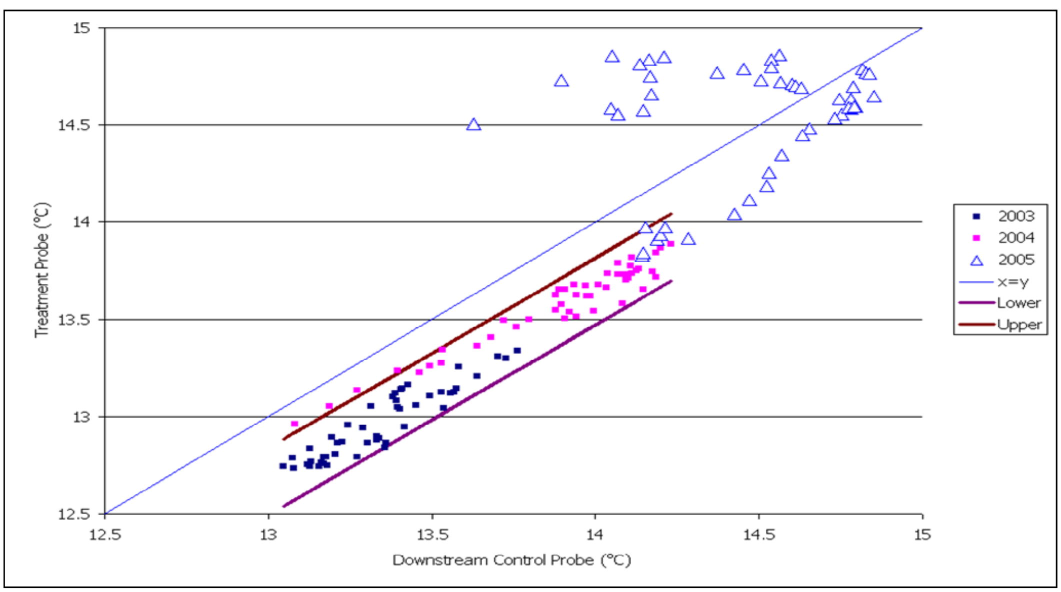


Figure 3.13K. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #18 in pre-harvest (2003, 2004) and post-harvest years (2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

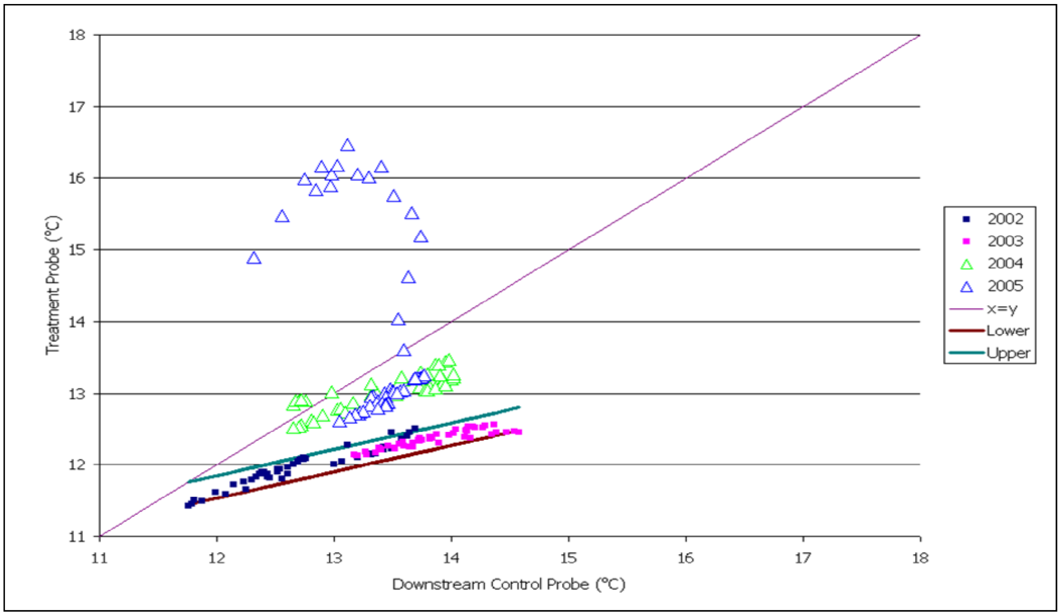


Figure 3.13L. Relationship between 7DMMDMax temperatures in the control and treatment reaches for Stream #20 pre-harvest (2002, 2003) and post-harvest years (2004, 2005). Lower and Upper represent 95% confidence interval based on pre-harvest temperatures.

3.4.4. Maximum Temperatures of Individual Streams

The maximum 7-day moving mean of the daily maximum (Max7Day) is the metric used by the ODEQ to determine if a waterbody has exceeded water quality temperature standards. Prior to harvest, the Max7Day at the upstream control, downstream control, and treatment probes ranged from 10.4 to 15.8°C, 9.9 to 19.0°C, and 11.3 to 18.3°C, respectively. After harvest, the upstream control, downstream control, and treatment probes ranged from 10.2 to 17.0°C, 10.6 to 16.5°C, and 11.9 to 19.1°C, respectively (Table. 3.7). The Max7Day occurred on a variety of dates between July 15th and August 31st, depending on individual streams and year of measurement (Table 3.8).

Table 3.7. Max7Day values (˚C) for 22 Oregon Coast Range headwater streams between July 15th and August 31st. Values in bold indicate first year after harvest. * indicates missing temperature probes; blanks indicate streams not yet installed with probes.

	2002			2003			2004			2005		
Stream	Probe 1[1]	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3
1				15.3	19.0	14.4	15.8	16.8	15.4	**14.9**	**15.9**	**19.1**
2	10.4	9.9	12.0	10.8	10.8	11.3	11.0	10.7	12.6	**10.2**	**10.6**	**12.0**
3	12.5	12.8	12.9	13.3	13.7	13.6	13.0	13.7	13.9	**12.7**	**13.2**	**13.3**
4				11.2	10.7	11.9	11.5	11.4	12.1	**12.5**	**10.9**	**11.9**
5	14.4	14.1	14.0	14.3	13.6	14.0	14.9	14.5	14.7	**13.8**	**13.5**	**14.3**
6	14.4	14.6	14.6	*	15.3	15.2	15.5	15.8	15.7	**14.8**	**14.7**	**14.3**
7	14.0	14.1	14.0	13.1	12.5	12.8	13.8	13.2	13.6	**14.0**	**13.1**	**13.3**
8	12.2	12.9	14.4	12.9	*	14.9	**13.3**	**14.3**	**17.0**	12.5	13.0	15.5
9	13.2	14.7	13.6	13.6	16.1	13.9	**14.3**	**16.0**	**15.2**	13.2	14.0	14.0
10	14.9	15.0	15.0	15.1	15.2	15.2	**15.3**	**15.8**	**18.6**	14.1	14.4	16.7
11	13.0	13.2	14.4	13.3	13.4	13.9	**14.2**	**14.1**	**15.7**	13.4	13.3	14.6
12	14.6	14.6	12.5	15.5	17.2	12.5	**15.3**	**15.7**	**13.7**	14.5	14.1	12.8
13	15.0	14.6	17.5	15.6	15.1	15.7	**17.0**	**16.5**	**16.7**	16.8	16.3	16.1
14	12.3	12.5	12.3	13.0	13.1	12.9	**13.0**	**13.0**	**13.8**	12.9	12.9	13.6
15				12.8	12.5	11.6	13.4	14.6	12.2	**12.4**	**12.4**	**12.2**
16							12.9	12.4	13.2	**12.2**	**11.7**	**14.0**
17				11.2	11.9	11.7	11.4	12.3	12.2	**11.0**	**12.2**	**13.1**
18				14.2	13.8	13.3	14.6	14.2	13.9	**14.5**	**14.9**	**14.9**
19	14.6	15.2	17.8	15.9	15.2	18.3	15.5	15.9	18.7	**15.2**	**15.4**	**16.8**
20	12.0	13.7	12.5	12.4	14.6	12.6	**12.4**	**14.0**	**13.5**	15.6	13.8	16.5
21				12.9	13.7	14.2	13.3	14.0	15.0	**12.5**	**13.1**	**14.1**
22	13.8	13.6	14.0	14.2	14.2	14.5	14.3	14.5	15.0	**13.8**	**13.8**	**14.4**

[1]Probe 1: Upstream Control, Probe 2: Downstream Control, Probe 3: Treatment Probe.

Table 3.8. Date on which the Max7Day occurred for 22 Oregon Coast Range streams. Values in bold indicate first year after harvest. * indicates missing temperature probe; blanks indicate streams not yet installed with probes.

	2002			2003			2004			2005		
Stream	Probe 1[1]	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3	Probe 1	Probe 2	Probe 3
1				24-Jul	16-Aug	31-Jul	27-Jul	19-Aug	26-Jul	**7-Aug**	**5-Aug**	**19-Aug**
2	30-Aug	14-Aug	15-Aug	31-Aug	11-Aug	30-Jul	25-Aug	23-Aug	25-Jul	**26-Jul**	**28-Jul**	**16-Aug**
3	14-Aug	14-Aug	15-Aug	30-Jul	30-Jul	31-Jul	17-Aug	17-Aug	18-Aug	**17-Aug**	**16-Aug**	**16-Aug**
4				30-Jul	29-Jul	30-Jul	25-Aug	27-Aug	25-Jul	**6-Aug**	**17-Aug**	**28-Jul**
5	14-Aug	14-Aug	13-Aug	10-Aug	10-Aug	10-Aug	24-Jul	24-Jul	24-Jul	**29-Jul**	**29-Jul**	**29-Jul**
6	23-Jul	23-Jul	23-Jul	*	24-Jul	24-Jul	25-Jul	25-Jul	25-Jul	**21-Jul**	**16-Aug**	**16-Aug**
7	23-Jul	23-Jul	23-Jul	24-Jul	24-Jul	24-Jul	24-Jul	24-Jul	24-Jul	**24-Jul**	**24-Jul**	**24-Jul**
8	14-Aug	15-Aug	14-Aug	30-Jul	*	30-Jul	**25-Jul**	**25-Jul**	**18-Aug**	2-Aug	28-Aug	28-Aug
9	23-Jul	23-Jul	24-Jul	24-Jul	24-Jul	25-Jul	**25-Jul**	**25-Jul**	**25-Jul**	14-Aug	14-Aug	13-Aug
10	22-Jul	22-Jul	22-Jul	15-Jul	15-Jul	15-Jul	**19-Jul**	**28-Jul**	**20-Jul**	20-Jul	20-Jul	24-Aug
11	15-Aug	15-Aug	15-Aug	11-Aug	24-Jul	11-Aug	**24-Jul**	**21-Aug**	**25-Jul**	28-Aug	2-Aug	28-Aug
12	23-Jul	23-Jul	25-Jul	24-Jul	24-Jul	25-Jul	**26-Jul**	**26-Jul**	**19-Aug**	28-Jul	16-Aug	18-Aug
13	29-Aug	13-Aug	13-Aug	15-Jul	15-Jul	19-Jul	**23-Jul**	**23-Jul**	**19-Aug**	16-Jul	16-Jul	22-Aug
14	14-Aug	14-Aug	14-Aug	27-Aug	25-Jul	24-Jul	**17-Aug**	**18-Aug**	**18-Aug**	16-Aug	6-Aug	6-Aug
15				30-Jul	12-Aug	31-Jul	24-Jul	19-Aug	22-Aug	**16-Aug**	**16-Aug**	**29-Jul**
16							18-Aug	18-Aug	18-Aug	**16-Aug**	**17-Aug**	**13-Aug**
17				31-Aug	31-Aug	31-Jul	22-Aug	22-Aug	22-Aug	**16-Aug**	**19-Aug**	**13-Aug**
18				30-Jul	25-Jul	25-Jul	26-Jul	26-Jul	26-Jul	**5-Aug**	**11-Aug**	**28-Jul**
19	14-Aug	23-Jul	14-Aug	27-Jul	31-Jul	28-Jul	27-Jul	17-Aug	27-Jul	**6-Aug**	**6-Aug**	**6-Aug**
20	14-Aug	15-Aug	15-Aug	24-Jul	28-Aug	24-Jul	**19-Aug**	**19-Aug**	**25-Jul**	28-Jul	6-Aug	20-Jul
21				25-Jul	25-Jul	25-Jul	17-Aug	17-Aug	17-Aug	**17-Aug**	**17-Aug**	**6-Aug**
22	15-Aug	15-Aug	14-Aug	25-Jul	25-Jul	25-Jul	20-Aug	19-Aug	19-Aug	**7-Aug**	**16-Aug**	**17-Aug**

[1]Probe: Upstream Control, Probe 2: Downstream Control, Probe 3: Treatment Probe.

Chapter IV

Discussion

4.1. Channel Characteristics

Following harvest, there were non-significant increases and decreases in the various measured channel characteristics. Shade was the only riparian characteristic to decrease significantly by 6% in treatment reaches compared to control reaches from pre- to post-harvest periods. Decreases in riparian canopy cover following harvest around streams with riparian buffers have been documented in a number of studies (e.g. Zwieniecki and Newton 1999, Dignan and Bren 2003). The significant reduction in percent shade in my study is unlikely to be entirely a result of either sampling error or even natural variability because of the accuracy of hemispherical photography in measuring percent canopy cover (Ringold et al. 2003, Kelley and Krueger 2005).

Both wetted width and maximum depth showed a tendency to increase following harvest, however differences between the control and treatment reaches were not significant. Boothroyd et al. (2004) found significant increases in channel width following harvest, which they attributed to reduced evapotranspiration and interception, thus leading to increases in streamflow. However, because two different field crews measured channel characteristics in the pre- and post-harvest years in my study, the slight, non-significant increases in wetted width and maximum depth are more likely caused by differences in sampling technique. The mean increase in floodprone width in both the control and treatment reaches is likely a reflection of the increase found in maximum depth and thus bankfull depth, because floodprone width is based on these measurements. The decrease in channel gradient in both the control and treatment reaches following harvest was not significantly different, and is again most likely a result of differences in sampling technique.

Small increases in percent bedrock, boulders, and cobbles comprising streambed substrate following harvest were not significantly different between the control and treatment reaches. Johnson and Jones (2000) and Levno and Rothacher (1967) noted that debris-flow scour contributed to increased bedrock exposure in the Oregon Cascades. It is possible that debris flows could have occurred in the winter prior to harvest and contributed to the increased bedrock exposure, as well as the increases in percent boulder observed in my study. However, it is more likely that these differences are a result of the subjectivity of measurements by different sampling crews.

Percentages of both gravels and fines in streambeds decreased following harvest, but neither of these changes were statistically significant between the control and treatment reaches. Some studies have found increases in fine sediments following harvest (e.g. Ward et al. 2001, Grant and Wolff 1991, Beschta 1978) from increased erosion and runoff. The small decreases in gravels and fines in the streams in my study are, again, probably more likely a result of differences in field crews.

4.2. Warm-Season Stream Temperature Patterns

4.2.1. Pre-Harvest Warm-Season Stream Temperature Patterns

The majority of studies of stream temperature in forested headwater catchments have focused on either paired watersheds, or in-depth analyses of one or a few streams (e.g. Hewlett and Fortson 1982, Feller 1981, Hetrick et al. 1998). Few studies have examined more than ten streams (Sullivan and Adams 1989, Zwieniecki and Newton 1999, Jackson et al. 2001, Smith 2004). Previous studies have also focused on various measures of stream temperature, including (1) instantaneous values of maximum temperature before and after harvest (Feller 1981), (2) average changes in maximum and minimum temperatures (Hewlett and Fortson 1982), and (3) change between maximum pre- and post-treatment temperatures (Swift and Messer 1971). My study used the differences in 7DMMDMax between upstream and downstream temperature probes between July 15th and August 31st to filter out climatic fluctuations, as well as ensuring that the warmest period of the year for Oregon Coast Range headwater streams was used. My study is unique because of its larger sample size which allowed for BACI analysis and use of statistical analyses based on a large sample of headwater streams.

Among the twenty two streams in my study, the magnitude of cooling and warming differed among pre-harvest years, as well as within streams. Mean warm-season temperature gradient in control reaches was 0.4°C in each of the first and second pre-harvest years. In treatment reaches for the first pre-harvest year, the warm-season temperature gradient averaged 0.1°C, and in the second pre-harvest year the warm-season temperature gradient averaged 0.0°C. In the first pre-harvest year, nine streams warmed and six streams cooled in the control reach, with one stream indicating no warming or cooling pattern. In the treatment reach, nine streams warmed and seven streams cooled prior to harvest (Figure 3.7A). In the second pre-harvest year, 11 streams warmed and seven streams cooled in the control reach, with two exhibiting neither cooling nor warming. In the treatment reach, 10 streams warmed and seven cooled, with one exhibiting no cooling or warming (Figure 3.7B). Prior to treatment, 14 streams maintained patterns of consistent warming or cooling across all years within reaches, and, of those 14, only four streams indicated patterns of warming in a downstream direction across all years through both control and treatment reaches. Eight streams had inconsistent warming or cooling between reaches, as well as across years.

The River Continuum Concept (RCC) predicts that stream temperature increases as streams flow toward valley bottoms (Vannote et al. 1980). Zwieniecki and Newton (1999) found that in streams they studied in the Oregon Coast Range, temperatures tended to increase from the ridgeline to the confluence, although there was some variability. Johnson (2004) found increases of 4-5˚C over a 200 m bedrock reach in the Oregon Cascades. However, the warming trend predicted by the RCC was not always observed in my study. Prior to any disturbance, some streams heated with distance from the divide, some streams cooled, and some cooled in the control reach and warmed in the treatment, and some warmed in the control reach and cooled in the treatment reach. Moore et al. (2005a) also found that streams they studied in British Columbia had differential areas of cooling and warming, and that they followed no specific trend in downstream warming. Danehy et al. (2005) found general increases in temperature downstream in Idaho and Eastern Oregon, but also found small decreases caused by local stream factors, such as groundwater inflows.

4.2.2. Post-Harvest Warm-Season Stream Temperature Patterns

Following harvest, warm-season stream temperature gradients in control reaches were similar to what they had been prior to harvest.

However, warm-season stream temperature gradients in treatment reaches increased, indicating that an increased level of warming was taking place that had not occurred prior to harvest. As noted in Table 3.2, temperature gradients in the treatment reach increased by a mean of 0.4˚C following harvest when compared with two years of pre-harvest data. Control reaches, conversely, decreased by 0.2˚C when compared to data from two years prior to harvest. In control reaches following harvest, 16 streams exhibited warming trends and six streams indicated cooling trends. In treatment reaches, 18 streams warmed and four cooled following harvest.

Increases in stream temperature following harvest are common (e.g., Levno and Rothacher 1967, MacDonald et al. 2003, Beschta and Taylor 1988). Harr and Fredriksen (1988) reported increases of 2-3˚C in streamwater temperature following harvest in Western Oregon. Moore et al. (2005a) found increases of up to 5˚C in streams following clearcut harvesting in British Columbia, and Holtby (1988) found increases of greater than 3˚C following harvest of 41% of a watershed in another study in British Columbia. Swift and Messer (1971) reported increases of up to 12˚C following complete clearcuts adjacent to streams in the Appalachian Mountains. Baillie et al. (2005) observed increases of up to 5.6˚C following harvest near streams in New Zealand. Maximum mean monthly stream temperatures increased up to 7˚C in the summer in a clearcut watershed in Wales (Stott and Marks 2000). However, no studies have examined the change in temperature from upstream to downstream in a control and treatment reach both before and after harvest in numbers of streams approaching that used in my study.

4.2.3. Effectiveness of Riparian Management Areas

I hypothesized that RMAs implemented through current Oregon RMA guidelines on private and state lands would be effective if pre-harvest, warm-season maximum-temperature patterns were maintained following harvest treatments. Comparisons of temperature patterns between control and treatment reaches both pre- and post-harvest indicate that my hypothesis should be rejected because warm-season maximum- temperature patterns were not maintained when mean values across all study streams were considered. Difference in warm-season temperature gradients between control and treatment reaches averaged 0.6˚C, based on two years of pre-harvest and one year of post-harvest data. This indicates that more warming or less cooling occurred in treatment reaches than occurred in control reaches during July to August when pre-harvest and post-harvest periods were compared.

Zwieniecki and Newton (1999) reported that when canopy cover was reduced to 78% in the Oregon Coast Range, mean stream temperature increased by 1.09˚C. Johnson and Jones (2000) found that removal of riparian cover in the Oregon Cascade Range corresponded to increases in both maximum and minimum stream temperatures, and that maximum temperatures occurred at the time of maximum solar input. Furthermore, they found that stream temperature returned to pre-disturbance levels 15 years following harvest, which coincided with return of canopy coverage. Johnson (2004) found that artificially shading a section of stream in Oregon's Cascade Range reduced the amount of solar radiation reaching the stream surface, and highlighted the importance of shade in influencing daily maximum stream temperatures.

Following partial harvesting in the Olympic Peninsula of Washington, stream temperatures were found to increase by up to 3˚C compared to unharvested controls, and this was linked to a corresponding reduction in shade cover (Murray et al. 2000). MacDonald et al. (2003) found that when limited riparian vegetation was retained in riparian areas in British Columbia, stream temperatures increased by nearly 6˚C compared to pre-harvest levels. Moreover, temperatures in streams that had high retention of riparian vegetation had statistically insignificant increases of less than 1˚C following harvest (MacDonald et al. 2003).

Studies in other parts of the country have found that removal of canopy corresponded with increases in stream temperature. Burton and Likens (1973) found heating of 4-5˚C following strip cutting in the Hubbard Brook Experimental Forest in New Hampshire, which they concluded occurred as a result of reduced shade and increased exposure of the stream to solar radiation. In Pennsylvania, stream temperatures of up to 32˚C were recorded in a clearcut receiving herbicide treatment, which also had mean temperatures 9˚C higher than in a corresponding control stream. The herbicide effectively removed any lower vegetation from shading the stream, and increases in temperature were attributed to a 450-m-long opening in the canopy which allowed increased exposure to solar radiation. Additionally, a buffered stream in the same study had post-harvest temperatures only slightly higher than in the corresponding control, and temperatures lower than in the clearcut which received herbicide treatment (Rishel et al. 1982, Lynch et al. 1984).

In a study that clearfelled 100% of a catchment in New Zealand, including riparian vegetation, Baillie et al. (2005) found that monthly maximum temperatures three years following harvest had increased up to 5˚C compared to an unharvested reference stream. They found that harvesting the riparian zone increased instream light levels by up to 90%, the remainder of the shade being provided by steep banks and regenerating vegetation. Dignan and Bren (2003) found that following harvest in Australia, there were detectable increases in light penetration to the stream, which illustrated the potential for increased exposure to solar radiation.

One study in particular, however, found limited increases in stream temperature, as well as decreases, following clearcut harvesting in seven streams in Washington's Coast Range (Jackson et al. 2001). The authors attributed this to the large-scale deposition of slash and woody debris into and near the stream, which effectively shaded the water and prevented penetration of solar radiation (Jackson et al. 2001).

Considered by many to be the most important factor influencing temperature in small headwater streams (e.g. Beschta 1997, Brown 1969), solar radiation and the role that riparian vegetation plays in moderating its influence is a key consideration for maintenance of pre-harvest stream temperature patterns. Significant reductions in percent shade and significant increases in temperature gradients following harvest found in my study support the importance of shade in moderating changes in stream temperature.

Recommendations for an effective riparian buffer strip vary. Some stipulate that site-specific designs should be completed prior to harvest (e.g. Steinblums et al. 1984), and others suggest that riparian buffer widths of 30 m are sufficient to supply shade levels similar to that of old-growth forests (Beschta et al. 1987). However, riparian buffers have been considered effective for maintaining stream temperature if similar levels of shade are retained regardless of width. Boothroyd et al. (2004) found that temperature in harvested streams with no riparian buffers in New Zealand were up to 2˚C higher than both pre-harvest sites and harvested streams that retained buffers. The vegetative structure of post-harvest buffers was predominantly the same as pre-harvest, and cover values were generally similar. Additionally, they found that light levels in the streams with buffers were substantially lower than in harvested streams with no riparian buffer (Boothroyd et al. 2004). In their review of RMA literature, Broadmeadow and Nisbet (2004) note that although it is not possible to specify definitive widths, buffers of 5- to 30- m width have been found to be 50 to 75% effective in maintaining several aquatic functions, including shade production. Also, they recommend that the riparian buffer should mimic the state of the riparian area and aquatic zone prior to harvest. Brazier and Brown (1973) found that temperature was poorly correlated with both RMA timber volume and width in streams in western Oregon, but that designing buffers to maintain shade rather than volume could be more effective in maintaining stream temperature.

Barton et al. (1985) found no correlation between riparian buffer width and maximum stream temperature in Southern Ontario streams, which could suggest that as long as sufficient shade is maintained buffer width may be irrelevant. Bourque and Pomeroy (2001) also found that there was no clear relationship between riparian buffer width and stream warming in New Brunswick, and particularly noted that a stream with 60-m-wide buffers had consistently higher temperatures than a stream with a 30-m buffer.

Dignan and Bren (2003) found distinct changes in light penetration in the riparian zone following upslope harvest in Australia, but suggest that buffers of 70- to 100-m would be sufficient to maintain the pre-harvest light environment. The network model of Blann et al. (2002)

suggests that riparian buffers that provided at least 50% shade were adequate for mediating maximum stream temperatures.

4.2.4. Relationships Between Warm-Season Stream Temperature Gradients and Channel Characteristics

4.2.4.1 Control Reach

Percentage of gravel in the streambed was the most significant predictor for warm-season stream temperature gradients in the control reach following harvest, accounting for approximately 29% of the variation in temperature gradients. A higher percentage of gravel in the control reach corresponded to higher mean temperature gradients, which implies that warmer temperatures correspond to greater percentages of gravel. This suggests that hyporheic flow and transient storage could be playing a role in moderating stream temperature in the control reach of these streams. Edwards (1998) suggests that considerable alluvial porosity in the Pacific North Coastal region allows for high flow velocities within large interstitial spaces in the streambed, which can contribute to the formation of hyporheic environments. Valett et al. (1996) also found that greater hydraulic conductivities resulted in greater exchanges between surface and subsurface water. Morrice et al. (1997) reported that increased alluvial grain size corresponded with higher hydraulic conductivities, creating more of a potential for hyporheic exchange. However, they found that residence time in the hyporheic zone also decreased with increasing hydraulic conductivity, and therefore reduced contact time with cooler water. Stream reaches with increased gravel percentages found in my study could be associated with increased hydraulic conductivity, and therefore shorter residence times with less hyporheic interaction.

Streambed heat conduction may also be playing a relatively important role in the observed temperature gradients in control reaches where shade is at consistently high levels. Johnson and Jones (2004) suggest that conduction from the streambed into the water may be more important than is generally recognized, and that after solar radiation inputs, streambed conduction may be the most important contributor to stream temperature. Sinokrot and Stefan (1993) reported that streambeds can act as energy sinks during the day and sources at night, which contributes to stream heating at night. Also, they concluded that streambeds composed of rocks, as opposed to very fine sediments, are better conductors of heat.

Geologic parent material (i.e. sedimentary sandstone versus igneous basalt) was also a strong predictor of warm-season stream temperature in the control reach, explaining 21% of the variation in temperature gradients. Streams dominated by basalt parent geology tended to have higher temperature gradients, therefore warming more through the control reach, than streams dominated by sedimentary bedrock. Parent geology was noted to contribute to the size of channel substrate particles in the Pacific Northwest (Edwards 1998), which can influence both the magnitude of hyporheic exchange as well as streambed conduction. Wroblicky et al. (1998) found that streams with sedimentary sandstone parent geology in New Mexico had smaller hyporheic cross-sectional areas, which implies less volume was available for hyporheic exchange. Valett et al. (1996) also found less hydraulic exchange in sandstone-dominated catchments in New Mexico, which is opposite to the findings in my study. Although more warming appeared to have occurred in the basalt streams than the sedimentary streams in my study, it could be related to subsurface flow. However, a definitive conclusion cannot be drawn. Johnson (2004) reported that a section of a reach in the Oregon Cascades that had a higher percentage of bedrock also had higher maximum temperatures, and concluded this was caused by greater streambed conduction. In my study, streams with basalt geology tended to have higher percentages of bedrock, which could explain the higher temperature gradients observed in the igneous-dominated control reaches of these streams.

In a case with small inputs of solar radiation the importance of streambed conduction in small streams of Mississippi and Minnesota was highlighted (Sinokrot and Stefan 1993). The control reach in most of the streams in my study was heavily forested, with shade values averaging 89%. This high level of shading is similar to levels observed in old-growth Douglas-fir forests (Beschta et al. 1987) and the canopy likely reflects or absorbs the majority of incoming solar radiation. With inputs of solar radiation into the stream at such low levels, the relative influence of other moderators of stream temperature, such as streambed gravel or geology, may be easier to observe.

4.2.4.2. Treatment Reach

Shade was the most significant predictor for warm-season stream temperature gradient in treatment reaches following harvest, indicating that a shift in the relative importance of stream temperature factors occurred between the unharvested control and harvested treatment reaches. As shade decreased, warm-season stream temperature gradient increased. Shade accounted for almost 46% of the temperature variability in the treatment reaches of these streams, which corresponds to the value that Smith (2004) found when she examined these streams prior to harvest (49%).

Solar radiation has been documented by a number of studies (Brown 1970, Beschta et al. 1987, Moore et al. 2005a, Danehy et al. 2005) as being the strongest driver of stream temperature, and the change in temperature predictors from bedrock in the heavily shaded control to shade in the treatment reach in the same stream as found in this study reinforces this concept. If canopy cover is reduced following harvest, then it is likely that larger areas of the streams will be directly exposed to solar radiation, which may account for the observed increases in temperature. In the review by Poole and Berman (2001), they note shade as being one of the more important factors for insulating stream temperature from changes in the rate of heat input into and/or out of a stream. The regression model of Danehy et al. (2005) based on streams in Idaho and Northeast Oregon similarly found solar radiation to be the best predictor for stream temperature, and as inputs of solar radiation increased, so did stream temperature. Smith (2004) in studying the same streams used in my study prior to harvest found shade to be the best predictor for the 7DMMDMax in both the control and treatment reaches. This may have not been seen in my study because of the difference in temperature metrics by Smith (2004). Using the SNTEMP model, Bartholow (2000) found that small reductions in shade cover resulted in the largest increases in maximum daily stream temperature compared to other variables in the model.

Number of wood pieces between bankfull width and 1.8 m above bankfull width was also a significant predictor for warm-season stream temperature gradient in the treatment reach. Number of wood pieces was correlated positively with temperature gradient, indicating that the temperature gradient was higher with more pieces of wood above bankfull width. It is possible that following harvest, blowdown in the riparian buffer occurred, which could have reduced the quantity and quality of shade remaining in the RMA. Steinblums et al. (1984) note that in western Oregon, the majority of damage to riparian buffers is caused by windthrow, which allows greater penetration of solar radiation into the stream. Although windthrow was not specifically examined in my study, it is possible that streams with a greater proportion of the riparian buffer damaged by windthrow heated up more following treatment. The moderating influence provided by canopy cover over streams was reduced following a harvest in British Columbia when the majority of protective vegetation was lost because of windthrow (MacDonald et al. 2003).

4.2.5. Warm-Season Temperature Patterns of Individual Streams

Of the twelve streams in my study that exhibited increased values of 7DMMDMax between July 15th and August 31st following treatment, all but two had reductions in percent shade. In particular, some of the streams with the larger increases in temperature similarly had the largest reductions in percent shade. For example, prior to harvest, the 7DMMDMax temperatures in the control reach were similar to those in the treatment reach in Stream #10. However, during the same summer period in two post-harvest years, 7DMMDMax temperatures in the treatment reach were greater than those observed in the control reach. This corresponded to a decrease in shade of more than 30%. This was also observed in Stream #17, where following harvest, increases in the 7DMMDMax occurred along with a 25% decrease in shade within the treatment reach. Lynch et al. (1984) found that streams in Pennsylvania that had been clearcut and herbicided were up to 9˚C warmer than nearby control streams as well as nearby commercial harvests with riparian buffers. The herbicided clearcuts also exceeded water quality standards more often (Lynch et al. 1984). Bourque and Pomeroy (2001) concluded that the increase in temperature in their study in New Brunswick varied based on several factors, including the amount of forested area in the catchment, and that temperature increases were generally dependent on the amount of solar radiation reaching the stream. Hetrick et al. (1998) found that in sections of streams in southeastern Alaska with open canopy, significantly more solar radiation was able to reach the stream and thus influence temperature. Harr and Fredriksen (1988) found that annual maximum stream temperature increased by up to 3˚C following clearcut harvesting alongside a stream in western Oregon. In addition, they noted that stream temperatures appeared to be returning to pre-harvest levels within three years of harvest, which corresponded to regrowth of riparian vegetation that provided shade.

Nine of the streams in this study had either very little or no change in the 7DMMDMax following harvest. Of these nine, six retained shade at a level similar to pre-harvest, or actually increased in shade, possibly through increases in streamside vegetation. Streams with greater canopy cover are less likely to increase in temperature (Brown 1969, Beschta et al. 1987), and as the canopy was maintained in these streams at levels corresponding to pre-harvest, large changes in temperature would be unexpected. These results correspond to those found by Hetrick et al. (1998) that in closed canopy sections of streams in southeastern Alaska, less solar radiation was able to reach the stream surface and influence stream heating than in open sections of the stream. Also, decreases in monthly mean temperature maxima of up to 5˚C were observed in a forested stream in Scotland when compared to non-forested moorland, which was attributed to the blocking of solar radiation by the forested canopy (Webb and Crisp 2006). However, decreases in shade in my study occurred at two of the streams with no significant corresponding increase in temperature. The moderating influence of groundwater and hyporheic flow on stream temperature has been described in some studies (e.g. Poole and Berman 2001, Story et al. 2003). Story et al. (2003) found that cooling generally occurred only when the surface water interacted with groundwater sources in streams in British Columbia, and that high rates of cooling were also associated with greater transient storage. Influence of groundwater and hyporheic water could explain the lack of a significant increase in the 7DMMDMax in these two streams, despite the reduction in shade.

Of the twelve streams that heated following harvest, all of which had riparian buffers, nine had clearcut harvesting on both sides, two had clearcut harvesting on one side, and one had a partial cut on one side. The majority of the streams that had little-to-no change following harvest had either a clearcut harvest on one side, or were subjected to partial cuts. Additionally, streams that retained the smallest levels of shade were also the streams that were clearcut on both sides.

Prior to harvest, the 7DMMDMax for Stream #6 in the control reach was similar to that in the treatment reach. However, following harvest the 7DMMDMax for the treatment reach decreased significantly outside of the 95% confidence interval. The amount of shade in both the control and treatment reach appears to have increased following harvest, and there was also between 85 and 90% shade both before and after the harvest year. The observed cooling could be related to the increase in stream shading, as was observed by Johnson (2004) following artificial shading of a stream reach in the Cascades of Oregon, in which cooling of 2-4°C was observed. Cooling could also have occurred from decreased evapotranspiration and interception, and increased subsurface flow from the harvest upslope (Hewlett and Helvey 1970), which could result in increased discharge in the stream.

4.2.6. Maximum Temperatures of Individual Streams

The ODF currently uses the maximum mean temperature for the warmest week of the year (Max7Day) as a standard for evaluating water quality. The water quality standard for stream temperature in core cold water habitat in the Oregon Coast Range is a Max7Day of 16°C (http://www.deq.state.or.us/wq/wqrules/wqrules.htm). Four of the streams observed in this study exceeded this temperature standard prior to any treatments. Following harvest, these four streams as well as three additional streams exceeded the water quality temperature standard at least once between July 15th and August 31st following harvest. That the streams, prior to any harvest, were already exceeding the maximum water quality temperature standard indicates that meeting current standards in some streams may not be physically possible. It is interesting to note that following harvest, only three additional streams exceeded the state's water quality temperature standard, and that the highest observed Max7Day for all streams following harvest was 19.1°C, found at a Treatment probe. This occurred on a stream that had a Max7Day of 19°C the previous year which occurred at the Downstream Control probe. Again, this demonstrates the inherent variability within these small headwater streams. Ice (2004) suggests that streamwater temperature guidelines not be based only on biologically beneficial or physically attainable temperatures, but should also rely on identification of natural stream temperature patterns. Also, use of physical models in determining what is generally expected in the area being studied before implementation of standards could be helpful for setting more achievable standards.

Johnson and Jones (2000) found that increased daily temperature maxima occurred earlier in the season following harvest than had been observed prior to harvest. They also noted that timing of stream temperature maxima coincided with timing of maximum solar radiative inputs. In my study, only one stream had a Max7Day temperature occur earlier in the year at the Treatment probe than observed prior to harvest. Stream #11 had a Max7Day occur at the Treatment probe on August 15th in the first pre-harvest year, and on August 11th in the second pre-harvest year. Following harvest, the Max7Day occurred on 25th July. However, in the second post-harvest year, the Max7Day occurred on August 28th. Other studies have also found that the timing of stream temperature maxima occurs earlier in the year following harvest than that observed prior to harvest (e.g. Rishel et al. 1982). However, that does not appear to have occurred in my study. Although no definitive conclusions can be drawn, changes in the date of the Max7Day may be caused by the natural variability within the streams as well as likely variations in groundwater influences, and year-to-year climatic variation.

Chapter V

Conclusions and Management Implications

The inherent variability of warm-season maximum temperature in heavily shaded headwater streams of the Oregon Coast Range has been reported previously (Smith 2004). However, few studies have examined impacts of forest harvesting on temperature in the context of natural variability, instead focusing on maximum daily, monthly, or seasonal temperatures. My study helps provide further information on the natural variability of warm-season stream temperature, as well as harvest impacts on stream temperature patterns within the context of this natural variability. Effectiveness of RMAs as outlined by Oregon's current Forest Practice Rules was based on maintenance of warm-season maximum stream temperature patterns following harvest in the presence of RMAs. Pre-harvest warm-season maximum temperature patterns were not consistently maintained in the studied streams following harvest. This suggests that current RMAs for small- and medium fish-bearing streams of the Oregon Coast Range are not effective for maintenance of warm-season temperature patterns.

Many of the streams in my study subjected to significant reductions in shade also had significant increases in warm-season stream temperature. Streams that were characterized by greater retention of shade also had little or no change in warm-season temperature patterns following harvest. Thus, RMAs that maintained shade at levels similar to pre-harvest conditions appear to be more effective in maintaining pre-harvest warm-season temperature patterns. This suggests that RMA design might be improved if percentages of shade present prior to harvest were taken into account and attempts to maintain this shade following harvest were emphasized.

This study also reinforced the concept that solar radiation is one of the most important factors driving stream temperature, at least among the variables examined in this study, and shade covering stream channels functions to moderate its influence. In the heavily shaded control reaches observed in this study, shade was not an important component in predicting temperature prior to harvesting. However, in the treatment reaches following harvest shade was the most important predictor, indicating a shift in the relative importance of temperature drivers from channel substrate to shade. When more solar radiation was able to reach the treatment reaches of these streams, the role that shade played in absorbing or reflecting it became more apparent. This should continue to be an important consideration for RMA design.

Setting a water quality standard is a necessary step for identifying anti-degradation measures. However, some streams in my study exceeded the standard of 16°C for a maximum seven-day mean (Max7Day) prior to forest harvesting, and with no upstream disturbance, which indicates that inherent variability should be taken into consideration when water quality standards are set. If undisturbed, heavily forested headwater streams cannot meet the water quality standard, it is unlikely that in their disturbed state the water quality standard will be met.

One of the key strengths of this study was the presence of both pre- and post-treatment data, as well as the ability to compare upstream (control) and downstream (treatment) reaches of each stream. Few studies have had a comprehensive BACI design, and the uniqueness of this allowed for different analyses than have been undertaken in other studies. However, more intensive sampling of channel characteristics would have been useful in my study, particularly for shade measurements. Also, temperature in small streams has been shown to fluctuate over very small spatial and temporal scales. If this study is repeated, installation of more temperature probes along each reach may prove useful in increasing precision of temperature gradients and temperature changes within each reach. Discharge is also a factor that influences stream temperature, particularly warm-season stream temperatures. Measurement of discharge through either dilution gauging or some other means would likely help to explain more of the temperature variability found in these streams.

There are many challenges associated with site-specific RMA designs, as well as generalized recommendations for width of RMAs. Temperature variability in small headwater streams is well known, and not all the processes that contribute to stream temperature are well understood. However, my study helps to reinforce the role of solar radiation and shade as being important for stream temperature, and RMAs that retain sufficient shade are likely to be the most effective for maintaining warm-season stream temperature patterns in the Oregon Coast Range. Improved understanding of all factors that contribute to stream temperature would help to clarify inherent variability observed in this study, as well as leading to more effective design of RMAs.

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APPENDIX

Table 1. Means and standard deviations of selected channel characteristics for control reaches of 22 Oregon Coast Range streams.

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank-full Width (m)	Post-Harvest Bank-full Width (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
1	2.80 (2.39)[1]	1.20 (1.60)	1.52 (0.46)	0.88 (0.05)	0.09 (0.03)	0.05 (0.05)	3.29 (1.00)	4.23 (0.98)	8.13 (2.33)	1.29 (0.30)
2	17.50 (7.51)	15.50 (4.80)	1.69 (0.52)	2.48 (1.16)	0.47 (0.14)	0.48 (0.25)	4.23 (1.29)	3.86 (0.96)	13.11 (11.64)	1.18 (0.29)
3	14.67 (2.16)	12.60 (5.85)	1.77 (0.54)	2.20 (0.80)	0.19 (0.06)	0.17 (0.08)	3.61 (1.10)	4.53 (3.23)	6.26 (5.15)	1.38 (0.99)
4	2.50 (1.22)	2.40 (1.67)	1.42 (0.43)	1.82 (0.34)	0.13 (0.04)	0.12 (0.07)	3.37 (1.03)	3.70 (0.88)	6.51 (1.67)	1.13 (0.27)
5	13.33 (9.46)	14.80 (8.17)	1.52 (0.46)	2.06 (0.57)	0.09 (0.03)	0.12 (0.04)	2.14 (0.65)	3.33 (0.54)	6.54 (1.10)	1.02 (0.16)
6	5.40 (2.70)	4.00 (3.65)	3.84 (1.17)	5.19 (1.20)	0.15 (0.05)	0.18 (0.03)	5.82 (1.78)	6.78 (1.81)	17.78 (9.68)	2.07 (0.55)
7	4.00 (1.41)	4.60 (1.52)	1.66 (0.51)	1.65 (0.22)	0.15 (0.05)	0.14 (0.08)	2.94 (0.90)	3.70 (1.84)	8.64 (3.17)	1.13 (0.56)
8	15.17 (8.68)	10.67 (8.07)	2.18 (0.67)	3.29 (1.81)	0.22 (0.07)	0.24 (0.08)	4.32 (1.32)	4.53 (1.89)	8.03 (4.94)	1.38 (0.58)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 1 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank-full Width (m)	Post-Harvest Bank-full Width (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
9	1.75 (0.50)	2.00 (1.00)	3.13 (0.95)	4.45 (0.33)	0.11 (0.03)	0.25 (0.08)	5.18 (1.58)	5.79 (0.89)	10.67 (6.47)	1.76 (0.27)
10	7.00 (2.37)	5.33 (2.50)	1.89 (0.57)	3.06 (1.51)	0.14 (0.04)	0.31 (0.10)	2.92 (0.89)	3.96 (2.35)	5.32 (3.32)	1.21 (0.72)
11	14.33 (11.08)	11.00 (3.35)	1.74 (0.53)	3.96 (1.71)	0.07 (0.02)	0.14 (0.03)	3.97 (1.21)	4.46 (1.91)	9.65 (5.23)	1.36 (0.58)
12	6.33 (5.89)	11.00 (2.45)	1.45 (0.44)	2.95 (0.69)	0.11 (0.03)	0.21 (0.08)	4.27 (1.30)	4.34 (0.58)	7.32 (1.61)	1.32 (0.18)
13	1.00 (0.00)	1.00 (0.00)	0.97 (0.29)	1.17 (0.34)	0.11 (0.03)	0.17 (0.09)	3.15 (0.96)	2.41 (0.64)	53.35 (2.16)	0.73 (0.20)
14	12.00 (4.85)	9.00 (2.65)	1.48 (0.45)	1.99 (1.01)	0.09 (0.03)	0.13 (0.03)	3.04 (0.93)	3.02 (1.42)	5.08 (5.23)	0.92 (0.43)
15	28.67 (7.55)	16.00 (8.33)	1.17 (0.36)	1.03 (0.80)	0.10 (0.03)	0.04 (0.03)	4.22 (1.29)	2.98 (0.67)	9.53 (4.01)	0.91 (0.20)
16	18.20 (15.82)	16.00 (6.30)	0.58 (0.18)	0.43 (0.53)	0.07 (0.02)	0.05 (0.04)	1.62 (0.49)	1.37 (0.95)	6.81 (0.77)	0.42 (0.29)
17	14.40 (13.32)	14.75 (9.93)	1.16 (0.35)	0.66 (0.46)	0.18 (0.06)	0.14 (0.10)	1.65 (0.50)	1.26 (0.71)	3.76 (2.25)	0.38 (0.22)

Table 1 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Width (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
18	12.17 (5.91)	14.20 (5.00)	1.95 (0.59)	2.10 (1.20)	0.24 (0.07)	0.15 (0.09)	2.59 (0.79)	3.04 (1.35)	6.10 (1.52)	0.93 (0.41)
19	2.00 (0.63)	1.00 (0.00)	2.21 (0.67)	1.81 (0.78)	0.21 (0.06)	0.16 (0.09)	3.49 (1.06)	3.05 (0.76)	8.10 (2.30)	0.93 (0.23)
20	21.00 (10.20)	27.20 (9.28)	0.87 (0.27)	1.63 (0.27)	0.06 (0.02)	0.15 (0.05)	3.17 (0.97)	2.77 (0.53)	4.57 (0.91)	0.85 (0.16)
21	7.83 (2.99)	8.20 (2.43)	3.53 (1.08)	4.28 (1.73)	0.18 (0.05)	0.25 (0.13)	7.25 (2.21)	6.17 (1.78)	13.31 (5.48)	1.88 (0.54)
22	7.50 (4.51)	5.50 (2.35)	0.87 (0.26)	1.11 (0.66)	0.06 (0.06)	0.07 (0.02)	2.82 (0.86)	2.22 (0.74)	7.66 (1.60)	0.68 (0.22)

Table 2. Means and standard deviations of channel substrate characteristics in control reaches of 22 Oregon Coast Range Streams.

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
1	0	0	6 (13)	0	20 (12)	44 (6)	64 (25)	44 (8)	10 (14)	12 (12)
2	10 (20)[1]	23 (45)	0	16 (15)	10 (20)	46 (34)	40 (8)	15 (17)	40 (25)	0
3	0	0	3 (8)	30 (31)	10 (11)	40 (26)	42 (22)	26 (17)	45 (24)	4 (8)
4	0	0	0	0	7 (10)	34 (34)	52 (23)	30 (21)	42 (26)	36 (44)
5	0	12 (25)	5 (12)	10 (13)	25 (20)	44 (21)	52 (24)	34 (24)	18 (24)	4 (8)
6	0	13 (22)	4 (9)	15 (16)	20 (12)	40 (19)	50 (16)	33 (11)	26 (6)	0
7	0	0	5 (12)	24 (37)	18 (18)	40 (37)	38 (26)	24 (23)	38 (28)	12 (20)
8	0	45 (7)	0	34 (27)	15 (18)	44 (27)	45 (14)	25 (17)	40 (21)	10 (0)
9	0	0	10 (20)	30 (0)	10 (12)	10 (0)	50 (35)	88 (19)	30 (12)	0
10	3 (8)	0	0	18 (10)	28 (17)	72 (28)	42 (17)	20 (17)	27 (8)	0
11	0	0	0	0	20 (22)	39 (8)	40 (25)	46 (11)	40 (19)	42 (10)
12	57 (50)	87 (12)	8 (13)	38 (26)	18 (20)	18 (8)	15 (16)	20 (10)	0	0
13	0	0	0	0	0	0	0	0	100 (0)	100 (0)
14	0	10 (0)	10 (14)	21 (10)	12 (16)	39 (21)	42 (16)	33 (23)	36 (25)	25 (21)
15	0	0	0	2 (4)	28 (24)	45 (33)	38 (30)	31 (19)	33 (25)	23 (28)
16	0	25 (45)	0	5 (9)	0	8 (13)	40 (26)	20 (22)	60 (26)	43 (45)
17	0	23 (40)	0	3 (5)	0	8 (10)	28 (19)	30 (42)	72 (19)	38 (39)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 2 Continued

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
18	0	0	17 (32)	22 (40)	3 (8)	24 (24)	33 (45)	42 (30)	47 (52)	12 (17)
19	0	0	0	0	5 (12)	12 (18)	25 (22)	14 (17)	70 (24)	74 (34)
20	0	0	0	57 (33)	7 (10)	29 (15)	38 (13)	39 (9)	55 (12)	39 (33)
21	17 (41)	0	8 (20)	30 (19)	20 (17)	32 (21)	42 (25)	34 (21)	17 (14)	2 (4)
22	0	0	0	10 (25)	18 (18)	0	52 (20)	28 (20)	30 (28)	58 (30)

Table 3. Total number of wood pieces and wood jam volume in control reaches of 22 Oregon Coast Range streams. Low wood is below bankfull depth; high wood is between bankfull depth and 1.8 m above bankfull depth.

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest HighWood (#)	Post-Harvest HighWood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
1	43	32	30	63	3	23
2	67	56	25	54	0	330
3	54	95	58	44	10	8
4	50	67	62	33	143	204
5	19	8	10	6	0	0
6	25	32	23	22	4	47
7	27	19	24	26	0	0
8	40	43	49	21	63	208
9	27	32	24	1	31	945
10	30	36	16	9	0	4
11	116	49	74	22	70	1035
12	21	4	23	7	0	0
13	20	18	7	2	0	0
14	16	76	36	15	0	5
15	25	85	90	96	315	708
16	83	52	31	49	0	34
17	96	41	36	27	100	69
18	87	71	55	85	282	439

Table 3 Continued

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest High Wood (#)	Post-Harvest High Wood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
19	59	30	46	41	2	0
20	99	54	81	27	18	68
21	3	8	14	18	3	31
22	74	33	19	49	7	89

Table 4. Means and standard deviations of selected channel characteristics for treatment reaches of 22 Oregon Coast Range streams.

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Depth (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
1	2.00 (0.71)[1]	3.43 (0.38)	1.34 (0.96)	0.93 (0.61)	0.11 (0.05)	0.09 (0.13)	4.20 (1.01)	3.24 (0.59)	1.28 (0.39)	10.57 (9.43)
2	13.19 (7.51)	14.31 (10.13)	3.09 (1.61)	3.56 (2.22)	0.23 (0.13)	0.24 (0.14)	8.26 (3.25)	6.18 (2.12)	2.52 (0.77)	14.12 (9.79)
3	9.46 (6.24)	9.14 (2.57)	2.03 (0.89)	1.87 (0.63)	0.22 (0.06)	0.13 (0.09)	3.63 (0.98)	2.87 (1.10)	1.11 (0.34)	5.30 (3.83)
4	3.17 (1.17)	2.50 (0.82)	1.66 (0.41)	2.25 (0.67)	0.12 (0.08)	0.12 (0.05)	3.72 (1.23)	3.28 (0.98)	1.13 (0.35)	11.09 (4.85)
5	7.38 (5.41)	7.94 (7.31)	2.07 (0.58)	2.36 (1.39)	0.17 (0.10)	0.19 (0.11)	3.62 (0.89)	3.92 (1.76)	1.10 (0.34)	12.90 (14.44)
6	6.90 (7.62)	1.40 (0.45)	3.93 (1.36)	4.17 (1.53)	0.21 (0.15)	0.21 (0.10)	5.53 (2.88)	6.48 (1.85)	1.69 (0.51)	16.83 (9.08)
7	5.50 (1.87)	5.14 (2.07)	1.20 (0.53)	1.58 (0.36)	0.11 (0.05)	0.14 (0.02)	2.77 (0.91)	2.93 (1.21)	0.85 (0.26)	12.83 (6.80)
8	6.73 (2.97)	3.83 (1.71)	2.23 (0.41)	3.50 (1.05)	0.23 (0.16)	0.20 (0.07)	4.97 (1.27)	6.29 (1.56)	1.52 (0.46)	12.55 (6.93)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 4 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Depth (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
9	3.15 (3.67)	4.38 (6.92)	2.99 (1.74)	6.33 (3.33)	0.18 (0.19)	0.40 (0.28)	7.10 (2.73)	8.66 (3.31)	2.17 (0.66)	19.23 (6.45)
10	4.33 (2.35)	3.11 (1.27)	2.74 (0.87)	3.80 (1.00)	0.18 (0.12)	0.20 (0.06)	3.88 (0.71)	5.00 (1.14)	1.18 (0.36)	10.32 (4.88)
11	8.00 (3.93)	10.25 (5.65)	2.25 (1.19)	3.20 (1.55)	0.17 (0.11)	0.18 (0.04)	3.96 (0.86)	5.05 (3.21)	1.21 (0.37)	8.89 (4.29)
12	5.81 (3.29)	8.56 (2.53)	1.85 (1.00)	3.36 (1.04)	0.10 (0.08)	0.18 (0.09)	4.69 (1.25)	5.39 (1.71)	1.43 (0.44)	10.19 (2.34)
13	1.00 (0.00)	1.00 (0)	1.55 (0.60)	1.81 (0.58)	0.13 (0.10)	0.21 (0.15)	3.88 (0.71)	3.00 (0.77)	1.18 (0.36)	32.71 (37.96)
14	6.50 (3.62)	5.33 (1.21)	1.81 (0.56)	2.78 (1.20)	0.08 (0.08)	0.18 (0.06)	3.28 (1.84)	3.51 (1.64)	1.00 (0.31)	7.11 (4.09)
15	22.50 (9.34)	14.22 (6.53)	1.54 (0.97)	1.59 (1.02)	0.14 (0.18)	0.07 (0.05)	4.19 (3.71)	2.95 (0.81)	1.28 (0.39)	9.00 (5.85)
16	9.20 (3.63)	9.83 (3.78)	1.71 (0.92)	1.32 (0.35)	0.12 (0.06)	0.12 (0.07)	3.78 (1.58)	1.49 (0.61)	1.15 (0.35)	9.75 (5.60)
17	8.00 (2.45)	8.67 (4.53)	0.88 (0.39)	1.32 (0.38)	0.08 (0.04)	0.14 (0.07)	2.23 (1.10)	2.94 (1.17)	0.68 (0.21)	9.71 (5.59)

Table 4 Continued

Site	Pre-Harvest Gradient (%)	Post-Harvest Gradient (%)	Pre-Harvest Wetted Width (m)	Post-Harvest Wetted Width (m)	Pre-Harvest Maxi-mum Depth (m)	Post-Harvest Maxi-mum Depth (m)	Pre-Harvest Bank full Width (m)	Post-Harvest Bank full Depth (m)	Pre-Harvest Flood prone Width (m)	Post-Harvest Flood prone Width (m)
18	4.13 (2.17)	5.11 (5.21)	2.30 (0.69)	1.88 (0.61)	0.16 (0.08)	0.13 (0.02)	3.39 (0.91)	3.56 (0.84)	1.03 (0.32)	19.23 (9.77)
19	2.10 (0.97)	1.00 (0)	2.18 (0.91)	2.13 (1.03)	0.13 (0.10)	0.18 (0.15)	4.08 (1.31)	3.17 (1.44)	1.24 (0.38)	10.29 (8.57)
20	4.60 (2.07)	14.63 (13.46)	1.35 (1.03)	2.28 (1.50)	0.08 (0.06)	0.13 (0.03)	4.44 (2.44)	3.44 (1.96)	1.35 (0.41)	6.55 (7.39)
21	6.65 (2.62)	5.71 (2.38)	3.27 (1.16)	3.22 (1.63)	0.19 (0.10)	0.14 (0.07)	6.43 (2.39)	5.08 (2.16)	1.96 (0.60)	8.42 (2.17)
22	4.83 (1.72)	3.00 (1.55)	1.48 (0.83)	0.99 (0.28)	0.09 (0.06)	0.09 (0.05)	3.09 (0.80)	1.67 (0.49)	0.94 (0.29)	3.19 (0.89)

Table 5. Means and standard deviations of channel substrate characteristics for treatment reaches of 22 Oregon Coast Range streams.

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
1	17 (37)[1]	0	0	16 (15)	12 (15)	34 (17)	52 (32)	23 (22)	19 (23)	27 (33)
2	6 (15)	10 (25)	13 (18)	27 (26)	24 (13)	33 (23)	48 (19)	22 (24)	10 (13)	8 (16)
3	0	10 (27)	0	13 (14)	24 (21)	38 (20)	35 (19)	33 (10)	42 (27)	6 (23)
4	0	0	0	3 (0)	12 (20)	44 (31)	53 (26)	38 (24)	35 (12)	14 (13)
5	9 (26)	11 (21)	0	11 (19)	17 (15)	34 (20)	41 (24)	34 (19)	33 (22)	11 (15)
6	0	3 (22)	4 (9)	0	22 (15)	62 (21)	30 (7)	31 (14)	44 (9)	4 (9)
7	0	11 (33)	12 (29)	23 (27)	23 (19)	37 (27)	32 (23)	34 (18)	33 (5)	3 (8)
8	0	60 (0)	8 (12)	21 (17)	23 (15)	47 (32)	32 (21)	27 (22)	37 (20)	30 (21)
9	3 (11)	0	8 (16)	53 (42)	6 (13)	15 (7)	61 (17)	93 (18)	24 (13)	0
10	0	0	0	10 (0)	23 (11)	81 (15)	41 (12)	19 (15)	36 (7)	20 (0)
11	0	0	0	29 (17)	9 (13)	40 (18)	41 (15)	56 (32)	50 (13)	15 (7)
12	41 (48)	73 (30)	4 (10)	38 (20)	21 (20)	34 (14)	23 (19)	39 (20)	11 (15)	0
13	0	0	0	0	0	0	3 (8)	0	97 (8)	100 (0)
14	13 (33)	42 (15)	0	0	18 (10)	35 (11)	38 (20)	32 (10)	30 (9)	47 (25)
15	0	11 (33)	0	26 (28)	43 (33)	38 (26)	40 (32)	23 (25)	18 (13)	2 (7)
16	0	0	0	0	4 (9)	1 (2)	24 (15)	32 (33)	72 (22)	66 (35)
17	0	0	0	2 (5)	8 (11)	20 (29)	30 (22)	23 (22)	62 (30)	54 (40)

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 5 Continued

Site	Pre-Harvest Bedrock (%)	Post-Harvest Bedrock (%)	Pre-Harvest Boulder (%)	Post-Harvest Boulder (%)	Pre-Harvest Cobble (%)	Post-Harvest Cobble (%)	Pre-Harvest Gravel (%)	Post-Harvest Gravel (%)	Pre-Harvest Fines (%)	Post-Harvest Fines (%)
18	0	0	13 (18)	36 (41)	38 (29)	38 (26)	30 (27)	25 (18)	20 (26)	0
19	0	0	0	0	0	18 (21)	52 (25)	23 (18)	48 (27)	60 (35)
20	0	0	0	50 (0)	26 (9)	54 (27)	36 (11)	22 (14)	38 (15)	32 (15)
21	1 (5)	5.88	8 (15)	30 (18)	29 (9)	33 (18)	40 (14)	31 (17)	22 (17)	1 (2)
22	0	0.00	0	0	3 (8)	31 (21)	38 (17)	43 (9)	58 (15)	27 (16)

Table 6. Total number of wood pieces and wood jam volume in treatment reaches of 22 Oregon Coast Range streams. Low wood is below bankfull depth; high wood is between bankfull depth and 1.8 m above bankfull depth.

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest High Wood (#)	Post-Harvest High Wood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
1	17	32	29	63	5	23
2	31	56	27	54	220	330
3	57	95	49	44	0	8
4	38	67	43	33	37	204
5	33	8	21	6	1	0
6	35	32	34	22	0	47
7	58	19	38	26	0	0
8	34	43	35	21	4	208
9	51	32	40	1	5	945
10	17	36	10	9	0	4
11	72	49	50	22	10	1035
12	13	4	23	7	0	0
13	31	18	11	2	0	0
14	17	76	26	15	0	5
15	63	85	49	96	256	708
16	75	52	26	49	19	34
17	103	41	26	27	6	69

Table 6 Continued

Site	Pre-Harvest Low Wood (#)	Post-Harvest Low Wood (#)	Pre-Harvest High Wood (#)	Post-Harvest High Wood (#)	Pre-Harvest Wood Jams (m^3)	Post-Harvest Wood Jams (m^3)
18	21	71	19	85	17	439
19	45	30	31	41	0	0
20	59	54	49	27	18	68
21	23	8	50	18	5	31
22	55	33	23	49	7	89

Table 7. Individual site conditions for 22 Oregon Coast Range headwater streams. CC = clearcut, PC = partial cut.

Site	Name	Location	Owner	Harvest Beyond RMA	Pre-Harvest Data Collection	Post-Harvest Data Collection	Control Length (m)	Treatment Length (m)
1	Argue Creek	T21S, R8W, S6	Roseburg Forest Products	2 sided CC	2003-2004	2005	253	418
2	Cook East	T2N, R8W, S14&15	State Forest	1 sided CC	2002-2004	2005	183	1261
3	Wolf's Foot	T1N, R7W, S7&8	State Forest	1 sided CC	2002-2004	2005	305	401
4	Bale Bound	T10S, R8W, S1	State Forest	1 sided PC	2003-2004	2005	305	384
5	Smith Creek	T1N, R10W, S17	Simpson Timber Company	2 sided CC	2002-2004	2005	305	976
6	Nettle Meyer	T5N, R6W, S20	State Forest	1 sided PC	2002-2004	2005	232	293
7	West Creek Combo	T7N, R6W, S 1, 11, 12&14	State Forest	1 sided PC	2002-2004	2005	305	366
8	Big South Fork	T6N, R9W, S28&29	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	305	671

Table 7 Continued

Site	Name	Location	Owner	Harvest Beyond RMA	Pre-Harvest Data Collection	Post-Harvest Data Collection	Control Length (m)	Treatment Length (m)
9	Ice Box	T4N, R10W, S10	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	213	793
10	Shangrila	T6N, R10W, S26,27,34&35	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	305	549
11	Section 27 Center	T5N, R10W, S27	Weyerhaeuser	2 sided CC	2002-2003	2004-2005	305	488
12	Toad Creek	T3N, R7W, S3	Longview Fibre Company	1 sided CC	2002-2003	2004-2005	305	963
13	Siletz River Trib.	T8S, R11W, S26	Boise	2 sided CC	2002-2003	2004-2005	168	793
14	Upper Mary's River	T10S, R7W, S5	Starker Forests	2 sided CC	2002-2003	2004-2005	244	327
15	East Fork Buck Creek	T8S, R9W, S33	Plum Creek	2 sided CC	2003-2004	2005	305	488
16	Elk Creek North	T8S, R9W, S14	Plum Creek	2 sided CC	2003-2004	2005	305	305

Table 7 Continued

Site	Name	Location	Owner	Harvest Beyond RMA	Pre-Harvest Data Collection	Post-Harvest Data Collection	Control Length (m)	Treatment Length (m)
17	Elk Creek South West Fork	T8S, R9W, S14	Plum Creek	2 sided CC	2003-2004	2005	244	287
18	Silver Creek	T24S, R11W, S12&13	Weyerhaeuser	1 sided CC	2003-2004	2005	244	477
19	Knapp Knob	T17S, R7W, S18	State Forest	1 sided PC	2002-2004	2005	305	1178
20	Eck Creek	T3N, R9W, S28&33	State Forest	1 sided PC	2002-2003	2004-2005	274	305
21	Cezanne	T1N, R6W, S22, 23&27	State Forest	2 sided PC	2003-2004	2005	976	976
22	North Nelson	T17S, R7W, S6	State Forest	1 sided PC	2002-2004	2005	305	393

Table 8. Mean warm-season (July 15th – August 31st) maximum temperature gradients and standard deviations for 22 Oregon Coast Range streams. Missing values indicate streams not installed with temperature probes; * indicates probe loss; bold indicates post-harvest value.

	2002		2003		2004		2005	
Site	Control	Treatment	Control	Treatment	Control	Treatment	Control	Treatment
1			2.7 (0.1)	-3.1 (3.6)	2.2 (0.6)	-0.3 (0.5)	**1.0 (0.2)**	**1.4 (0.6)**
2	-0.4 (0.4)[1]	0.4 (0.1)	1.6 (0.5)	0.2 (0.1)	0.5 (0.5)	0.4 (0.2)	**0.6 (0.2)**	**0.3 (0.1)**
3	0.4 (0.1)	0.1 (0.1)	0.4 (0.1)	0.0	0.7 (0.1)	0.2 (0.1)	**0.4 (0.1)**	**0.1 (0.0)**
4			-0.1 (0.2)	0.8 (0.1)	0.4 (0.4)	0.7 (0.2)	**-1.0 (0.4)**	**0.8 (0.1)**
5	0.0	0.0	-0.6 (0.1)	0.1 (0.1)	-0.2 (0.1)	0.1 (0.0)	**-0.2 (0.1)**	**0.3 (0.0)**
6	0.3 (0.2)	-0.1 (0.1)		-0.1 (0.0)	0.4 (0.2)	-0.1 (0.2)	**0.0**	**-0.4 (0.0)**
7	0.1 (0.1)	-0.1 (0.1)	-0.5 (0.0)	0.2 (0.1)	-0.6 (0.1)	0.2 (0.0)	**-0.8 (0.1)**	**0.2 (0.0)**
8	0.6 (0.1)	0.5 (0.1)	*	*	**0.6 (0.2)**	**1.0 (0.2)**	**0.4 (0.1)**	**1.0 (0.1)**
9	-0.4 (0.1)	2.0 (0.2)	-0.6 (0.1)	2.7 (0.4)	**1.4 (0.7)**	**-0.1 (0.2)**	**1.1 (01)**	**0.1 (0.1)**
10	0.1 (0.0)	0.0	0.2 (0.0)	0.0	**0.1 (0.2)**	**1.1 (0.3)**	**0.2 (0.1)**	**1.2 (0.2)**
11	0.2 (0.1)	0.6 (0.1)	0.0	0.3 (0.1)	**0.0**	**0.8 (0.2)**	**-0.1 (0.0)**	**0.6 (0.1)**
12	-0.1 (0.2)	-0.4 (0.2)	0.6 (0.5)	-0.7 (0.3)	**0.2 (0.1)**	**-0.4 (0.2)**	**-0.3 (0.3)**	**-0.3 (0.1)**
13	-0.6 (0.2)	0.6 (0.4)	-0.7 (0.7)	0.3 (0.1)	**-0.5 (0.3)**	**0.1 (0.1)**	**-0.9 (0.2)**	**0.2 (0.1)**
14	0.3 (0.1)	-0.1 (0.1)	0.3 (0.1)	-0.1 (0.1)	**0.0**	**0.5 (0.2)**	**0.1 (0.1)**	**0.6 (0.0)**
15			-0.1 (0.3)	2.6 (3.6)	1.1 (0.7)	-1.0 (0.6)	**0.1 (0.2)**	**0.0**
16					-0.5 (0.1)	0.1 (0.3)	**-0.4 (0.1)**	**2.2 (0.2)**
17			1.1 (0.1)	-0.2 (0.2)	1.2 (0.1)	0.0	**1.3 (2.0)**	**1.0 (0.1)**

[1]Numbers in parentheses indicate one standard deviation of the mean.

Table 8 Continued

Site	2002 Control	Treatment	2003 Control	Treatment	2004 Control	Treatment	2005 Control	Treatment
18			-0.3 (0.4)	-0.2 (0.0)	-0.3 (0.1)	-0.2 (0.1)	**0.6 (0.2)**	**0.0**
19	0.5 (0.2)	0.6 (0.1)	0.3 (0.4)	0.7 (0.1)	0.3 (0.1)	0.5 (0.2)	**0.1 (0.0)**	**0.3 (0.0)**
20	1.7 (0.1)	-0.7 (0.3)	2.0 (0.1)	-1.5 (0.3)	**1.5 (0.2)**	**-0.3 (0.3)**	**0.2 (1.5)**	**0.6 (1.5)**
21			0.6 (0.2)	0.1 (0.1)	**0.6 (0.2)**	**0.3 (0.1)**	**0.5 (0.0)**	**0.3 (0.1)**
22	-0.2 (0.1)	0.3 (0.0)	0.0 (0.0)	0.2 (0.0)	**0.1 (0.1)**	**0.4 (0.0)**	**0.0**	**0.4 (0.0)**