Evaluation of the Effectiveness of the Current TFW Shade Methodology for Measuring Attenuation of Solar Radiation to the Stream

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

Cooperative Monitoring
Evaluation & Research

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Washington State Forest Practices Adaptive Management Program

The Washington State Forest Practices Board (FPB) has established an Adaptive Management Program (AMP) by rule in accordance with the Forests & Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

> *Provide science-based recommendations and technical information to assist the FPB in determining if and when it is necessary or advisable to adjust rules and guidance for aquatic resources to achieve resource goals and objectives. The board may also use this program to adjust other rules and guidance.* (Forest Practices Rules, WAC 222-12-045(1)).

To provide the science needed to support adaptive management, the FPB established the Cooperative Monitoring, Evaluation and Research (CMER) committee as a participant in the program. The FPB empowered CMER to conduct research, effectiveness monitoring, and validation monitoring in accordance with WAC 222-12-045 and Board Manual Section 22.

Report Type and Disclaimer

This technical report contains scientific information from research or monitoring studies that are designed to evaluate the effectiveness of the forest practices rules in achieving one or more of the Forest and Fish performance goals, resource objectives, and/or performance targets. The document was prepared for the Cooperative Monitoring, Evaluation and Research Committee (CMER) and was intended to inform and support the Forest and Fish Adaptive Management program. The project is part of the Eastside Type F Riparian Effectiveness Program, and was conducted under the oversight of the Riparian Scientific Advisory Group.

This document was reviewed by CMER and was assessed through the Adaptive Management Program's independent scientific peer review process. CMER has approved this document for distribution as an official CMER document. As a CMER document, CMER is in consensus on the scientific merit of the document. However, any conclusions, interpretations, or recommendations contained within this document are those of the authors and may not reflect the views of all CMER members.

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Full Reference

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Evaluation of the Effectiveness of the Current TFW Shade Methodology for Measuring Attenuation of Solar Radiation to the Stream

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
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March 12, 2012

This technical report contains scientific information from a research study designed to evaluate the effectiveness of the Forest Practices Rules in achieving one or more of the Forests & Fish performance goals, resource objectives, and/or performance targets. The document was prepared for the Cooperative Monitoring, Evaluation and Research Committee (CMER) and was intended to inform and support the Forest and Fish Adaptive Management Program. The project is part of the Eastside Type F Riparian Effectiveness Program, and was conducted under the oversight of the former Bull Trout Scientific Advisory Group (BTSAG), which is now a part of the Riparian Scientific Advisory Group (RSAG). This document has been developed in response to review by CMER and the Adaptive Management Program's independent scientific peer review process

Reference:

McGreer, Dale[1], Michael Bonoff[2], John Gravelle[3], Dennis Schult[4], Sean Canavan[5], 2011. Evaluation of the Effectiveness of the Current TFW Shade Methodology for Measuring Attenuation of Solar Radiation to the Stream Study. Report to the Washington Department of Natural Resources Timber Fish and Wildlife Program Cooperative Monitoring, Evaluation and Research group. CMER Contract 02-189 with Mason, Bruce & Girard, Inc. Washington Department of Natural Resources, Olympia, WA.

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Eastern Washington riparian timber harvest prescriptions pertaining to shade differ depending on whether or not a harvest unit is within the Bull Trout Habitat Overlay (BTO). When a harvest unit is located within the BTO, “all available shade” must be retained within 22.9 m (75 feet) of the stream.[6] With the “all available shade” rule, trees may be harvested within the 75-foot zone if they are not determined to provide shade using the densiometer, and are not needed to meet basal area requirements. When a harvest unit is located outside the BTO, prescriptions fall under the standard shade rule, which may allow for harvest of a portion of shade trees within 22.9 m (75 feet), depending on elevation and canopy cover existing prior to harvest.

This study evaluated whether there was a significant change in the amount of solar radiation reaching the stream following harvest under the “all available shade” rule. Trees contributing to canopy shade were identified using a densiometer as prescribed by forest practices rules. The amount of solar radiation reaching the stream was measured using an Eppley pyranometer. Measurements of solar energy were collected before and after harvest. In each case, simultaneous measurements were collected over the period of a day in upstream reference reaches (no-harvest) and downstream treatment (harvested) reaches. A third instrument placed on an unobstructed hilltop measured total available solar radiation. Change associated with the application of the all available shade rule was determined by comparing differences in solar radiation reaching the stream in the control and treatment reaches before and after harvest.

Based on the average response at 16 sites, forest harvest conducted in accordance with the all available shade rule does not significantly alter the amount of solar radiation reaching the stream. The average increase in solar radiation was +3.0 W m^{-2}, which is within the instrument measurement error. Canopy attenuation decreased by an average of 0.43%, which was not statistically significant and was also within the instrument measurement error. Individual site responses were highly variable about the mean response, with 56% of sites having a reduction in solar energy after harvesting, and 44% of sites having an increase in solar energy.

[6] A complete discussion of the rule is found at WAC 222-30-040, www.dnr.wa.gov/BusinessPermits/Topics/ForestPracticesRules/Pages/fp_rules.aspx

1.0 INTRODUCTION

In the spring of 2002, the Cooperative Monitoring Evaluation and Research Committee (CMER) initiated two separate, but related, projects to better understand the effects of eastern Washington timber harvest prescriptions on shade, solar radiation, and stream temperature. The first was a study referred to as the Bull Trout Overlay Temperature Program - Eastern Washington Riparian Shade/Temperature Effectiveness Project (Shade/Temperature Study). The Shade/Temperature Study utilizes the two Eastside riparian shade prescriptions for the protection of stream temperature as treatments, and compares and assesses the effectiveness of each. The two shade prescriptions (Board Manual Section 1) include the standard shade rule (which uses the shade nomographs) and the "all available shade rule," which is applied within the bull trout habitat overlay (BTO) (WAC 222-16). Both shade prescription methodologies use the densiometer for measuring canopy cover.

The subject of this report is the second study initiated by CMER in 2002, the Evaluation of the Effectiveness of the Current TFW Shade Methodology for Measuring Attenuation of Solar Radiation to the Stream (Solar Study). The Solar Study only utilized sites that were treated with the "all available shade" rule, and thus a subset of sites used within the Shade/Temperature Study. The all "available shade rule" requires that "all available shade must be retained within 22.9 m (75 feet) of bankfull width or outer edge of the CMZ (whichever is greater) along (Type S or F waters)" (WAC 222-30-040). The Solar Study was designed to determine whether the application of the rule results in no net increase in solar radiation to the stream and to help address questions related to the adequacy of the Board Manual methodology for achieving "all available shade."

The Solar Study was designed to address a number of questions when paired with data from the Shade/Temperature Study which currently remains ongoing. The findings included in this report are limited to the following question:

Does the removal of trees that lie within 22.9 m (75 feet) of the stream, that don't qualify as providing shade according to the "all available shade rule", affect solar energy reaching the stream?

The null hypothesis is that there is no significant difference in solar energy reaching the stream, based on a comparison of control and treatment reaches measured before and after application of the all available shade rule.

1.1 Shade, Solar Radiation, and Energy Transfer Processes

The effect of timber harvest on water temperature is a key watershed management issue for water quality and aquatic biology (Beschta and Taylor 1988, Gravelle and Link 2007). Increases in stream temperature following complete removal of riparian vegetation through harvest and site preparation have been documented for decades (e.g., Brown 1969), and substantial increases of 2°C to 10°C in June-August have been reported (Beschta et al. 1987, Moore et al. 2005b). Increases in summer stream temperature can cause stress and mortality of aquatic species, including endangered fish species (Beschta et al. 1987).

Stream temperature is affected by multiple energy transfer processes including direct solar short-wavelength radiation, long-wavelength radiation, conduction, convection, and evaporation (Dent et al. 2008, Moore et al. 2005a). Complex sets of factors are known to govern stream temperature dynamics (Gravelle and Link, 2007, Moore et al. 2005a). For example, conductive transfer of energy via groundwater inflow and hyporheic exchange of surface and subsurface waters can substantially affect temperature regimes both at local and watershed scales (Johnson 2004, Johnson and Jones 2000, Poole and Berman 2001). While the influence and magnitude of these processes are difficult to examine independently, direct solar radiation has been shown to be the primary contributor to maximum daily summer stream temperature at the site level (Ice 2000, Johnson 2004). Because of the relatively large influence of direct solar radiation on stream temperature, changes to this variable alone can be used to develop estimates of maximum potential increases in temperature (Ice 2000).

Maintaining shade is an effective means of reducing direct solar radiation and summer maximum stream temperature, but transmission of solar radiation through forest canopy can affect stream temperature even in cases where a riparian buffer is retained if it is not sufficiently wide, dense, or tall (DeWalle 2010, Moore et al. 2005b). Transmission of solar radiation through vegetative canopies is a complex process (DeWalle 2008, Moore et al. 2005b) and the effectiveness of stream protection zones of various widths and leave tree requirements is not completely understood (Gomi et al. 2006). Simplified models based on extinction coefficients or the spatial distribution of gaps in the canopy have been employed to predict transmission through canopies (Hardy et al. 2004) and to simulate effective shade of streams (Chen et al. 1998). Measurement of solar radiation beneath canopies is difficult owing to the extremely variable effect of canopy density on the transmission of solar radiation and the expense of multiple sensors (Link et al. 2005). Moore et al., (2005a) report that dense canopies can block more than 90 percent of solar radiation, while open stands block less than 25 percent.

Despite these complexities, this study evaluated whether there was a significant change in the amount of solar radiation reaching the stream by comparing pre-harvest measurements of solar radiation to those following harvest under the all available shade rule. Ultimately, these measures will be related to canopy cover, shade, and temperature effects measured in the companion shade and temperature study.

2.0 METHODS

2.1 Site Selection and Measurement Dates

Sites and the exact location of measurement transects for both the solar and temperature studies were determined as part of the Shade/Temperature study.

Given the high level of landowner participation required for this study, sites could not be randomly selected, and thus may not be representative of bull trout overlay streams throughout eastern Washington. Sites were selected from a pool of small eastern Washington streams located within the bull trout overlay, and on lands where landowner cooperators, including the WDNR, had committed to conducting timber harvest within a timeframe acceptable to CMER. The group of study sites was further refined to provide a sample of streams that were relatively sensitive to the effects of tree removal on solar radiation by applying a set of specific site selection criteria. These site selection criteria were established to minimize the influence of other variables (e.g., roads, non-forested areas, groundwater, etc.) on stream temperature effects. The site selection criteria for these study streams are found in the original study plan for the Shade/Temperature study (Light, et. al. 2002):

- A study reach at least 600 m long on a small (< 15 ft. (4.6 m) bankfull width[7] fish-bearing stream.[8]

- A relatively consistent stand of timber with sufficient basal area to meet the minimum requirements for commercial harvest under the Forest and Fish rules.

- Pre-harvest canopy closure levels > 50%.

- Absence of tributaries that enter or influence the study reaches.

- Absence of a channel migration zone (CMZ).

- Limited amounts of non-forested areas (i.e., pastures). Generally, non-forested areas were not to occur within the riparian zone, especially within the core or inner zone of the Riparian Management Zone (RMZ) as defined by WDNR Forest Practices Rules (WAC 222-30-022). Sites with > 10% of the inner zone occupied by non-forested areas required a special review and approval process to be considered for inclusion in the study.

- Limited amounts of wetlands, beaver ponds, or other secondary surface water bodies.
    - Ideally, none were to be present; however, inclusion of a limited amount of these areas could be acceptable. If secondary surface waters occupied greater than 10% of the riparian area at a site then a special review and approval process was required in order to be considered for inclusion in the study.

- Continuous surface flow during the monitoring period (no intermittent sections within the study reaches).

- Absence of stream-adjacent roads within the riparian zone.

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[7] Not all of the sites in this study met the 15-foot bankfull width requirement per the CMER approved Study Plan; however, streams that did not meet this criterion typically had a bankfull width less than 20 feet. To reduce variability associated with harvest prescriptions, CMER applied RMZ prescriptions for streams less than or equal to 15 feet wide to all streams in this study (see the Washington Forest Practices Rules, Dec. 2002, pg. 30-18, first table). Before being included in the study, any sites having exceptions to the pre-defined site selection criteria were first approved by the project's scientific advisory group (Table 2.1-1).

[8]Fish presence was not verified. However, the study streams had the physical characteristics typical of smaller fish bearing streams in this region.

- Road crossings within the sample area were to be avoided if possible; however, a sample site with a road crossing was not automatically removed from consideration. Any stream-adjacent roads or road crossings required independent review and approval.

- Absence of significant groundwater inputs within the study reaches.
    - Sites were examined for groundwater influence using spot temperature checks throughout the sample reach and by discharge measurements at the upper and lower boundaries of the reference and treatment reaches. Sites with noticeable differences in groundwater influence between treatment and reference reaches were reviewed and approved independently for inclusion.

- Absence of recent major disturbance from:
    - debris torrents
    - livestock grazing that had significantly altered stream morphology or bank vegetation
    - other channel disturbance

- Committed landowner.
    - The landowner had to be willing to design the timber harvest unit to fit the experimental design and be willing to maintain the reference site in an unmanaged condition for at least 3 years (and preferably longer).
    - Landowner had to agree to harvest along both sides of the stream.
    - Timber harvest and related activities had to comply with forest practices rules and had to have the maximum allowable volume removed during harvest.

In order to reduce the potentially confounding effect of elevation on stream temperature, sites were chosen for each of the two treatments (i.e., all available shade and standard rule) to be representative of the different elevation bands. Sites were also not to have had any recent harvest within 30.5 m (100 feet) of the stream within 305 m (1,000 feet) upstream of the reference reach.

After identifying the landowner, a list of candidate sites was sent to appropriate managers to solicit cooperation in the study. Sites were visited in the field to assess stream and forest conditions, and to confirm that the site matched the selection criteria. Early site visits included preliminary stand plots to ensure sufficient basal area and stem density for harvest entry. The location for the treatment reach at each candidate study site was established to best meet the site selection criteria. Details regarding sites and their concurrence with selection criteria are provided within the documentation for the companion Shade/Temperature Study.

The study plan for the Solar Study called for a total of 20 BTO study sites. The original plan called for field measurements to be made over the course of three years: pre-treatment measurement of 10 sites in year one, pre-treatment measurement of 10 additional sites plus post-treatment measurement of the first 10 sites in year two, and post-treatment measurement of the second set of 10 sites in year three. Pre- and post-treatment solar measurements for all study sites were made as sites were identified and approved for pre-treatment measurements and approved for post-treatment measurements following harvest to acceptable standards. Due to various circumstances (timber market conditions, changing harvest decisions, etc.) timing of pre- and post-treatment measurements differed from the original study plan and required data collection to extend beyond year three. As a result, as many as six years elapsed between pre- and post-treatment measurements for some sites. In addition, some sites where pre-treatment measurements were collected were dropped from the study, due either to poor market conditions that prevented harvest, or because sites were later judged to not have satisfactorily met the site selection criteria. As a result, the total number of study sites where both pre- and post-treatment measurements met the study design criteria was reduced to a total of 16 sites. Of these 16 sites, three were located on the east slope of the Cascade Mountains in south-central Washington, while the remaining sites were located in the northeastern portion of the state (Figure 2.1-1). Table 2.1-1 provides basic characteristics for each site, and Table 2.1-2 shows the pre- and post-treatment measurement dates for all sites.

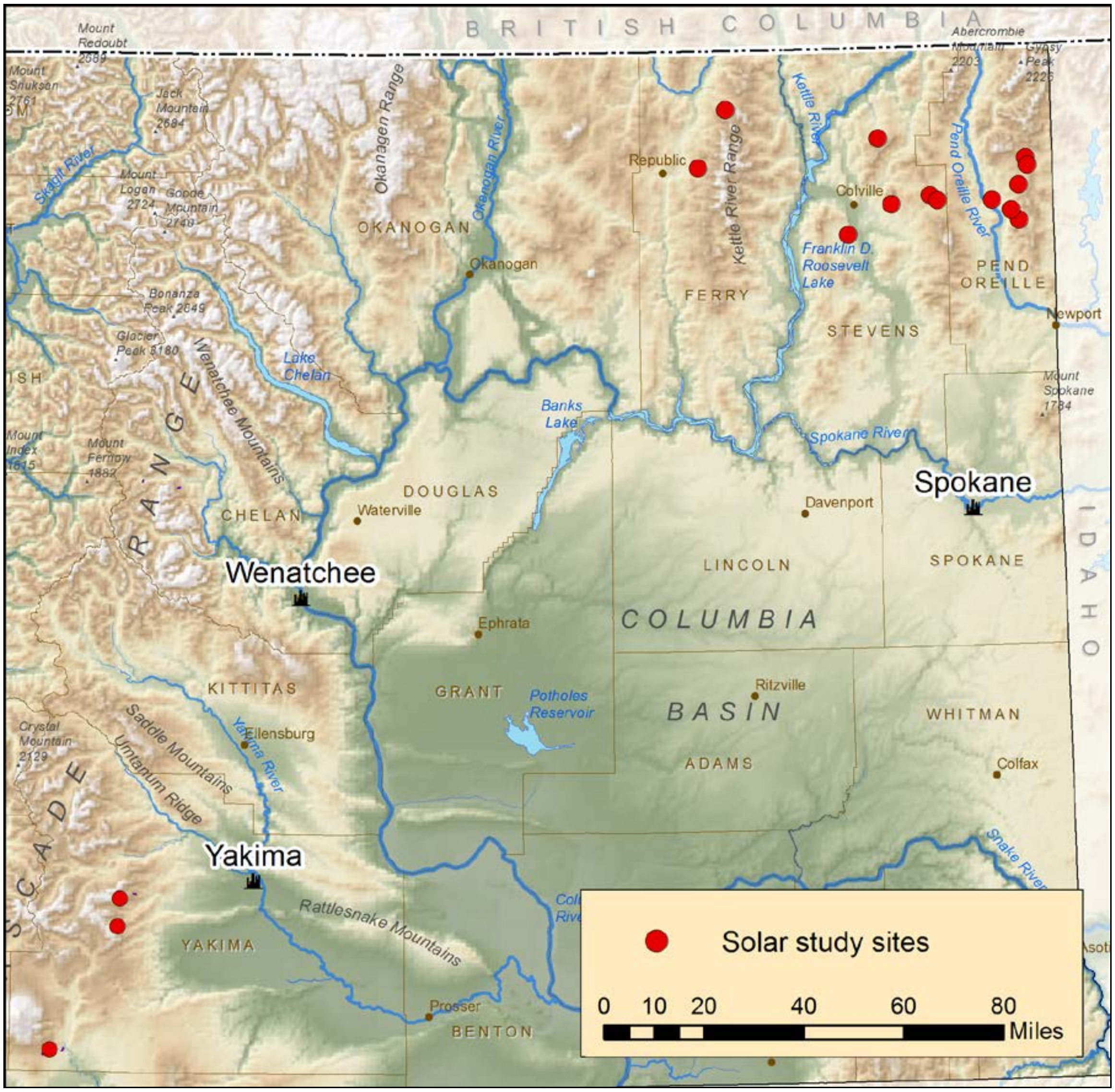

Figure 2.1-1. Solar study site locations.

Table 2.1-1. Summary of basic site characteristics.

	Site	Latitude	Longitude	Elevation (m)	Bankfull Width (m) Treatment[9]	Bankfull Width (m) Reference[7]
1	SF Ahtanum	46.465	-121.077	1376	6.3	6.0
2	Moses Creek Trib	48.545	-117.742	934	2.3	2.0
3	Mill Creek	48.489	-117.188	1070	1.8	1.4
4	Dry Canyon	48.549	-117.303	658	2.0	1.7
5	Long Alec	48.830	-118.458	1268	2.6	3.2
6	NF Foundation	46.546	-121.067	1452	3.9	3.6
7	Cole Creek	48.459	-117.933	577	4.4	5.4
8	Lotze Creek	48.736	-117.793	1051	4.5	3.7
9	Clark Creek	48.568	-117.572	1009	1.8	1.9
10	Upper Bacon Creek	46.105	-121.351	1007	3.9	4.4
11	Seco Creek	48.590	-117.183	1063	2.4	2.4
12	Sema 2	48.647	-117.143	1076	2.0	1.8
13	Sema 1	48.650	-117.144	1069	1.6	1.3
14	Flodelle	48.552	-117.541	1027	3.0	2.5
15	Tungsten	48.519	-117.220	1005	1.2	1.0
16	Sanpoil	48.662	-118.582	1024	1.9	1.5

Table 2.1-2. Pre- and post-harvest measurement dates and solar angles.

	Site	n	Pre-Harvest Date Measured	Pre-Harvest Mean Solar Angle	Treatment Completed	Post-Harvest Date Measured	Post-Harvest Mean Solar Angle	Difference in Solar Angle
1	SF Ahtanum	20	7/9/2003	52.24	2008	7/13/2008	51.82	-0.42
2	Moses Creek Trib	30	7/15/2003	50.46	2009	7/17/2009	50.19	-0.27
3	Mill Creek	30	7/17/2003	50.24	2005	8/15/2006	44.20	-6.04
4	Dry Canyon	30	7/22/2003	49.44	2006	7/19/2006	49.89	+0.45
5	Long Alec	29	7/24/2003	48.94	2008	8/04/2008	46.72	-2.22
6	NF Foundation	29	8/1/2003	48.71	2008	7/28/2008	49.50	+0.79
7	Cole Creek	30	7/15/2004	50.52	2009	7/13/2009	50.76	+0.23
8	Lotze Creek	30	7/21/2004	49.49	2008	7/20/2008	49.67	+0.18
9	Clark Creek	30	7/22/2004	49.42	2009	7/18/2009	50.06	+0.63
10	Upper Bacon Creek	30	7/27/2004	49.91	2006	8/17/2006	45.07	-4.84
11	Seco Creek	30	8/11/2004	45.18	2007	8/1/2007	47.52	+2.34
12	Sema 2	30	7/13/2005	50.66	2009	7/15/2009	50.40	-0.26
13	Sema 1	29	7/14/2005	50.54	2008	7/16/2009	50.29	-0.25
14	Flodelle	30	8/9/2005	45.69	2009	8/18/2009	43.31	-2.38
15	Tungsten	29	7/18/2006	50.09	2006	7/30/2007	47.99	-2.10
16	Sanpoil	29	7/19/2006	49.86	2008	7/19/2008	49.86	0.00

[9] Average of channel width measured at the 5 transects.

2.2 Experimental Design

Using the same approach and study sites selected in the companion Shade/Temperature Study for the bull trout overlay portion of that study, the Solar Study employed a before/after, control/impact (replicated BACI) design to test for effectiveness of the "all available shade" prescription. An unharvested upstream reach provided control (reference) for a downstream impact (treated) reach. The length of each treatment and reference pair was 600 m (300 m for the reference and 300 m for the treatment). The treatment reach was located immediately downstream of the reference reach. The harvest treatment was carefully controlled so that treatment effects could be determined from the all "available shade rule" when applied to minimum tree retention requirements. This involved consistent removal of all trees within 22.9 m (75 feet) of the adjacent study stream identified as not providing shade to the adjacent study stream at any time. Identification of these removal trees was done in conjunction with the companion Shade/Temperature Study.

As part of the companion Shade/Temperature Study, reach transects were monumented. Wooden stakes were installed on both sides of the channel at 25 m increments along the entire study site, which consisted of the 300 m downstream treatment and 300 m upstream reference. Pink flagging was securely placed on woody vegetation near the wooden stakes for ease of relocation. A measuring tape was stretched tightly across the channel between the station monument stakes. The solar measurements were taken in the center of the wetted channel along the tape (the same location as the canopy closure and Hemiview measurements were taken in the companion study). The companion study (Shade/Temperature) also recorded the distance from the right bank stake to the associated canopy closure measurement position to facilitate relocating measurement stations along the study site in subsequent sample years.

Simultaneous (paired) measurements were made in reference and treatment reaches to assess changes in solar radiation following harvest. Measurements were made during a single day prior to harvest and during a single day following harvest. All measurements were made during the mid-summer months of July and August (July 9 to August 18). Measurements were made at five locations spaced at 50 meter intervals within each reach (reference and treatment, see Figure 2.2-1). In addition to the two instruments used on the streambed, a third instrument operated simultaneously (unattended) at a nearby clearcut, meadow, or open field (hereafter referred to as the "hilltop" instrument). The hilltop instrument measured sunlight unobstructed by vegetative canopy or topography, and simultaneous to the in-stream instruments, and in combination with the in-stream pyranometers, allowed calculation of attenuation, or the interception by the canopy of incoming solar radiation. Each crew member remained at a given in-stream monitoring location for five minutes, recording data at one-minute intervals, before moving to the next location. Over the course of the day, each location was visited six times, resulting in a total of 30 observations in each reference and treatment reach.

At the beginning of a measurement day, the hilltop instrument was deployed and set to record readings at one-minute intervals. The two-man crew then traveled to the stream site and positioned themselves separately at the +50m and -50m stations (Figure 2.2-1).

Once placed in the stream on its tripod (0.5-1.0 m above the surface of the water) a gimble device was used to level the pyranometer[1]. Using a schedule based around solar noon, each crew member started the data logger timing programs for both treatment and reference units. Each unit then simultaneously recorded solar radiation for a total of five minutes at its respective station. The five-minute period consisted of five one-minute readings calculated from averages of one-second measurement intervals. On completion of the five-minute period, the two crew members had eight minutes to move in opposite directions to the +100m and -100m stations, where they again recorded five minutes of solar radiation data. This procedure was repeated at 50 meter intervals until the +250m and -250m stations were reached. The crew members then had 20 minutes to return to the +50m and -50m stations where they started the second loop. After three loops were completed in one direction, and following an interval of 20 minutes, three more loops were completed in the opposite direction beginning at the +250 and -250 stations, resulting in a total of six loops. Using this procedure, a total of 150 minutes of solar radiation data were recorded both upstream and downstream of the site center, and 30 5-minute observations were distributed both spatially and temporally throughout the day.

A customized data collection program using audible alarms and synchronized internal clocks ensured that observations were made on schedule, that they were simultaneous in the treatment and reference reaches, and that the set of observations were centered on solar noon (which was pre-determined for a given sample date and location). Observations were made at the same time of day in the reference and treatment reaches, and as close as possible to the same day of the year for both pre- and post-harvest measurements.

The sampling design described above was used for calculation of two key parameters: Difference in Watts per meter squared (DiffWm^{-2}) and difference in attenuation (DiffAtten). DiffWm^{-2} is the difference in incoming solar radiation reaching the stream surface, and DiffAtten is the difference in percent solar radiation blocked by canopy from reaching the stream surface (attenuation). As described in Section 2.4, differences in solar radiation and attenuation pre- and post-harvest were based on the “difference of the differences”, where:

$$\textbf{Difference} = [(\textbf{Treat}_{\textbf{post}} - \textbf{Reference}_{\textbf{post}})] - [(\textbf{Treat}_{\textbf{pre}} - \textbf{Reference}_{\textbf{pre}})]$$

2.3 Instrumentation/Quality Assurance

Solar radiation measurements, recorded as Watts/square meter (W m^{-2}), were made with Eppley Precision Spectral Pyranometer (PSP) sensors and Data Electronics DT50 dataloggers. Eppley PSP sensors are high quality pyranometers used for extremely accurate solar radiation measurements. Eppley PSP sensors are often used as a standard to calibrate other pyranometers (Campbell Scientific 2001).

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[1] A pyranometer is a sensor that is designed to measure the solar radiation flux density from a field of view of 180 degrees.

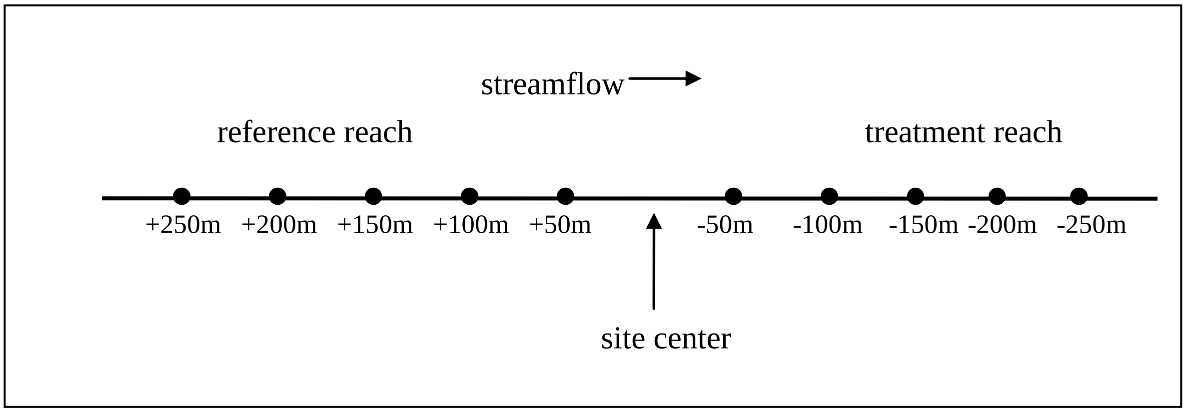

Figure 2.2-1. Schematic illustration of solar radiation measurements in a study reach.

Three identical sets of equipment (pyranometer/data logger combination), were employed on any given day at a study site: one in the reference stream reach, another in the treatment stream reach, and a third at a nearby hilltop.

Both pyranometers and datalogger units were calibrated by the manufacturer at the beginning of the project prior to pre-harvest data collection. Calibration following the 2003 and 2007 field seasons was completed by sending the units to J&S Instruments, Inc. in Springfield, OH for testing and maintenance. All instruments in all years remained within acceptable calibration limits which are based on Eppley PSP specifications (http://www.eppleylab.com) for temperature dependence (±1.0%), linearity (±0.5%), and cosine response (±1.0%). Calibration was also checked prior to each field season with side-by-side tests to cross-check readings between the four units (three plus the spare unit). If all readings in the side-by-side tests averaged within 2 percent of each other, the units were deemed to have remained in calibration.

System Accuracy

Based on the PSP sensor calibration constant (in mV W^{-1} m^{-2}) and the DT50 datalogger capability to measure pyranometer voltages to an accuracy of ±0.1% at the 25mV scale (Carr 2005), datalogger accuracy was determined with the following equation (Campbell Scientific 2001):

DT50 accuracy = ±(% datalogger accuracy * 25mV) * (1 W m^{-2} / PSP calibration constant in mV W^{-1} m^{-2})

With DT50 datalogger specifications and an average project PSP calibration value of 0.0084 mV W^{-1} m^{-2}, this yielded:

DT50 accuracy = ±(0.001 * 25mV) * (1 W m^{-2} / 0.0084 mV W^{-1} m^{-2}) = ±3.0 W m^{-2}

Individual pyranometers with differences in calibration constants resulted in estimated DT50 accuracy ranges of ±2.7 W $m^{-2}$to ±3.2 W m^{-2}, with an average DT50 accuracy of ±3.0 W m^{-2}.

For the stream units, using an average radiation measurement of 65.5 W m^{-2}, average PSP sensor accuracy related to temperature dependence, linearity, and cosine response yielded:

PSP temperature dependence accuracy = ±(0.01 * 65.5 W m^{-2}) = ±0.655 W m^{-2}

PSP linearity accuracy = ±(0.005 * 65.5 W m^{-2}) = ±0.3275 W m^{-2}

PSP cosine response accuracy = ±(0.01 * 65.5 W m^{-2}) = ±0.655 W m^{-2}

The system accuracy of DiffWm^{-2} using the two stream instruments was calculated by taking the square root of the sum of squares of component accuracies:

$(3.0\ W\ m^{-2})^2 + (0.655\ W\ m^{-2})^2 + (0.3275\ W\ m^{-2})^2 + (0.655\ W\ m^{-2})^2 = 9.965$

$\sqrt{9.965} = 3.2\ W\ m^{-2}$

Based on an average hilltop measurement value of 750 W m^{-2}, the system accuracy for the hilltop instrument was:

DT50 accuracy = ±(0.001 * 25mV) * (1 W m^{-2} / 0.0084 mV W^{-1} m^{-2}) = ±3.0 W m^{-2}

PSP temperature dependence accuracy = ±(0.01 * 750 W m^{-2}) = ±7.50 W m^{-2}

PSP linearity accuracy = ±(0.005 * 750 W m^{-2}) = ±3.75 W m^{-2}

PSP cosine response accuracy = ±(0.01 * 750 W m^{-2}) = ±7.50 W m^{-2}

$(3.0\ W\ m^{-2})^2 + (7.50\ W\ m^{-2})^2 + (3.75\ W\ m^{-2})^2 + (7.50\ W\ m^{-2})^2 = 135.56$

$\sqrt{135.56} = 11.6\ W\ m^{-2}$

Limits of Detectability

In order to quantify limits of detection, system errors related to each pyranometer instrument were considered. Since the BACI design requires the use of at least two sensors to detect treatment effect, combined error from both sensors must be considered. Due to the independence of the sensors, this combination of error uncertainty can be quantified by using the square root of the sum of squares of the individual errors. The uncertainty is said to be added “in quadrature” (Taylor 1997, Mount and Louis 2005). Calculating the combined uncertainty in quadrature for two pyranometer instruments gave:

$$(3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 = 20.48$$
$$\sqrt{20.48} = 4.5 \text{ W m}^{-2}$$

Given the above, the limit of detectability using two pyranometer instruments simultaneously is ±4.5 W m^{-2}. However, since DiffWm^{-2} is based on differences of differences (i.e. using two pyranometer instruments simultaneously both pre-harvest and post-harvest), the limit of detectability when calculating for DiffWm^{-2} equated to:

$$(3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 = 40.96$$
$$\sqrt{40.96} = 6.4 \text{ W m}^{-2}$$

For DiffAtten, which required the use of three pyranometer instruments, the system accuracy for the hilltop instrument needed to be included for the three instrument system accuracy:

$$(3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 + (11.6 \text{ W m}^{-2})^2 = 155$$
$$\sqrt{155} = 12.4 \text{ W m}^{-2}$$

Since DiffAtten was based on pre-harvest and post-harvest measurements, the limit of detectability when calculating for DiffAtten must account for both pre- and post-harvest measurements:

$$(3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 + (11.6 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 + (3.2 \text{ W m}^{-2})^2 + (11.6 \text{ W m}^{-2})^2 = 310$$
$$\sqrt{310} = 17.6 \text{ W m}^{-2}$$
$$17.6 \text{ W m}^{-2} / 750 \text{ W m}^{-2} = 2.3\%$$

The limit of detectability with three pyranometer instruments, using an average hilltop value of 750 W m^{-2}, was calculated to be ±2.3% for DiffAtten.

Full Sun Screening Criteria

In addition to providing data on total available incident solar radiation reaching the stream at a given time, the hilltop instrument also served a screening function in helping to ensure that data were collected during days with primarily cloud-free, full sun conditions. This screening criterion required a hilltop instrument average daily recording of at least 75 percent of potential full sun (as defined below). A typical daily measurement period was from approximately 09:15 am to 16:45 pm, depending on the specific location.

Although unobstructed full sun solar radiation can be determined based on site latitude, longitude and elevation, such values are theoretical; water vapor (haze), smoke, or any form of particulate that may be present, interferes with these theoretical values. Instead, the approach used for this study relied upon the data actually observed for each day of measurement at each site. Accordingly, the criterion of 75 percent of potential full sun was assessed by first generating a full sun curve with the recorded hilltop data. Using only the hilltop observations that occurred during the portion of the day during which stream observations were taken, a second-order polynomial was fit through the observations to obtain a curve that defined "full sun" for the particular day and location in question. The hilltop measurements taken during the daily measurement period were averaged. If the hilltop average was equal to or greater than 75 percent of the "full sun" curve, the data "passed" this test. This approach allowed determination of whether the criterion had been satisfied at the end of each observation day. An example of the hilltop radiation recorded during partially cloudy conditions at one of the sites, Lotze Creek, and the curve developed to represent full sun radiation used for the 75% full sun QA test is shown below (Figure 2.3-1). These data for Lotze Creek also demonstrate that radiation recorded at some points in time actually exceed theoretical full sun radiation. This occurred during the course of this study particularly when cumulus thunder storm-associated clouds reflected short-wave radiation, increasing the quantity of radiation received by the pyranometers to values greater than 100% of theoretical clear sky values, or those as represented by the fitted-to-the-data representations of full sun conditions.

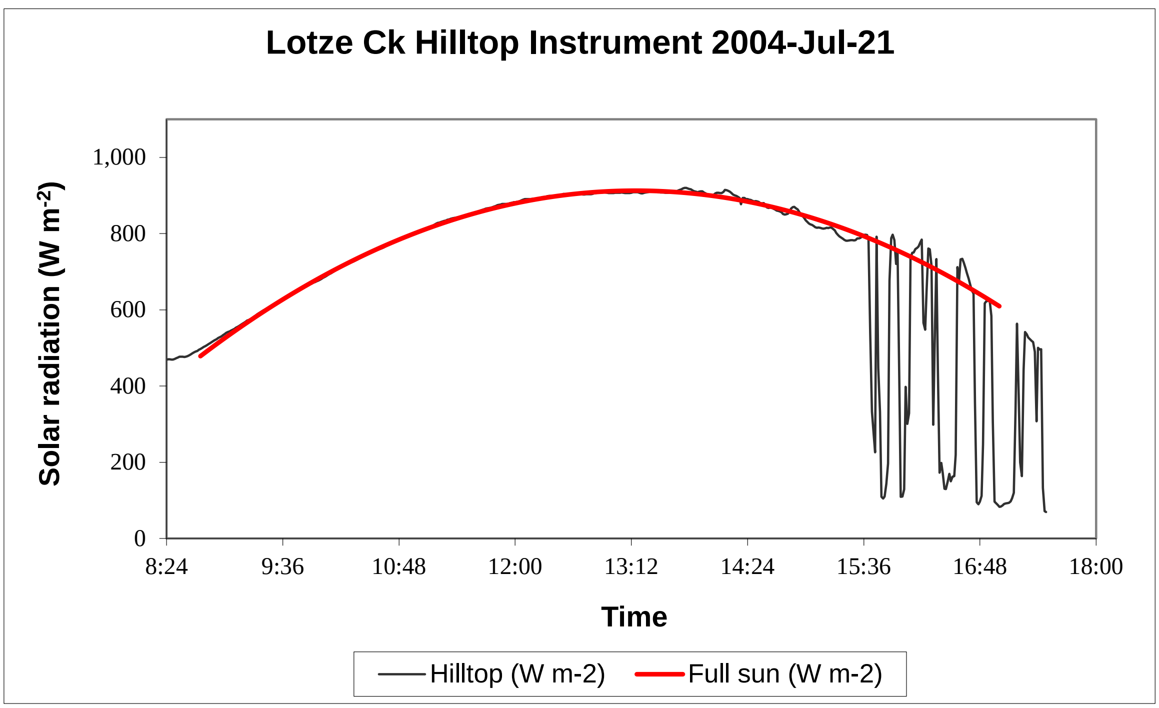

Figure 2.3-1. Hilltop data relationships for Lotze Creek illustrating actual solar radiation recorded and the second-order polynomial representing the full sun condition.

Calculation of percent of full sun for a given day is given as:

Percent full sun = R_{hill}/SR_{hill}
where,
R_{hill} = radiation recorded at the hilltop instrument (W m^{-2})
SR_{hill} = simulated full sun radiation (W m^{-2})

This percent full sun calculation was assessed over the course of the entire observation period where in-stream treatment and reference instruments recorded measurements. The hilltop instrument was placed as close to the stream reaches as possible without compromising the hilltop unobstructed sunview requirement. It was then assumed that hilltop radiation measurements were identical to above canopy levels for the stream reaches ($R_{hill} = R_{stream\ above\ canopy}$). While this assumption could be violated at some measurement times where sporadic cloudiness affects hilltop and stream reaches variably, this assumption is deemed valid for periods of full sun. As illustrated above, on July 21, 2004, the sky above Lotze Creek was clear until some cumulus clouds developed later in the afternoon. However, this site met the 75 percent criterion, with 94.6% percent of full sun recorded during the observation period (~09:15 to 16:45). Topographic shading could also invalidate the assumption, but was not observed during the course of the solar observations at any of the sites measured.

Because cloud cover reduces the ratio of direct solar radiation to diffuse solar radiation incident upon stream surfaces, the 5-minute data, i.e., the sets of 5-minute observations in treatment and reference reaches, were further examined by removing data pairs collected when the hilltop received less than 85 percent full sun. This was an exploratory approach designed to retain the preponderance of observations while examining the effect of clouds on computed treatment effects. This analysis was reported for each site within the July 2008 interim report for this study, but reviewers judged it most appropriate to include all data in the analysis for this final report.

2.4 Data Analysis

In order to test for statistically significant differences in solar energy reaching the stream pre- and post-treatment, results were analyzed using the before-after/control-impact (BACI) experimental design. Since the objective of this analysis was solely to determine if there were overall differences in incoming short-wave radiation to the stream surface following BTO harvest prescriptions, this pooled evaluation required the use of site means for variables at each study site. These site means were analyzed using paired Student's t-tests between pre- and post-treatment measurements for the 16 solar sites (n=16). A method where mean site values were calculated using a 'differences of the differences' approach was selected where effects from treatment would be determined by changes in the relationship between the treatment and reference reaches. This differences calculation can be characterized by the following general equation:

$$\textbf{Difference} = (\textbf{Treat}_{\textbf{post}} - \textbf{Reference}_{\textbf{post}}) - (\textbf{Treat}_{\textbf{pre}} - \textbf{Reference}_{\textbf{pre}})$$

For the purpose of analyzing treatment effects, the two variables were calculated using this differences equation to evaluate the following:

1) DiffWm^{-2}: Difference in incoming solar radiation reaching the stream surface.
2) DiffAtten: Difference in percent solar radiation blocked by canopy from reaching the stream surface. Attenuation was first derived for each measurement period by dividing the in-stream pyranometer measurement by the hilltop pyranometer measurement and is calculated as 1 - (In-stream Wm^{-2} / Hilltop Wm^{-2}).

These variables were calculated as follows:

$$\textbf{DiffWm}^{-2} = (\textbf{Treat W m}^{-2}_{post} - \textbf{Reference W m}^{-2}_{post}) - (\textbf{Treat W m}^{-2}_{pre} - \textbf{Reference W m}^{-2}_{pre})$$

$$\textbf{DiffAtten} = (\textbf{TreatAtten}_{post} - \textbf{ReferenceAtten}_{post}) - (\textbf{TreatAtten}_{pre} - \textbf{ReferenceAtten}_{pre})$$

If there was no treatment effect, the difference between reaches pre-treatment ($Treat_{pre}$ – $Reference_{pre}$) would be equal to the difference between the reaches post-treatment ($Treat_{post}$ - $Reference_{post}$). If the DiffWm^{-2} or DiffAtten values as calculated in the equations above were significantly different from 0, this would indicate the treatment prescription did have an effect.

Before site means could be calculated for the DiffWm^{-2} and DiffAtten metrics, each site's data were screened for missing/erroneous sensor measurements, mismatched-in-time readings between Treatment and Reference pyranometers, and overall validity of each measurement period (each loop, each station). Missing/erroneous sensor measurements were considered time periods where pyranometer readings did not collect accurate data due to equipment malfunctions or user error, and resulting unpaired measurement periods were excluded from the analyses. After site measurement period data were verified (up to n = 30; see Table 2.1-2) for each site by treatment period, DiffWm^{-2} and DiffAtten were calculated by measurement period. Each of the six time loops at each of the 5 station locations were averaged to derive station values for each site (n=5). These five station location values were then averaged to calculate a site mean value for DiffWm^{-2} and DiffAtten variables.

Statistical computations were preceded by diagnostic testing for assumptions of normality and were conducted using the commercial statistical package "R" (R Development Core Team 2009, Ripley 2001). The null hypothesis was that riparian zone harvest would not increase the amount of solar energy reaching the stream ($H_O \Delta = 0$). Given there are no direct mechanisms for riparian harvest to increase riparian shade, treatment effects in DiffWm^{-2} and DiffAtten were evaluated with one-tailed tests. These one-tailed paired t-tests were done with a significance level of α=0.05 for increases in DiffWm^{-2} and DiffAtten following harvest treatment.

3.0 RESULTS

Results described in this section focus on determining whether statistically significant increases in incoming solar radiation or decreases in attenuation exist following treatment. As described below, all analyses were conducted on site means; paired t-test results are presented followed by a summary of measured values.

3.1 Pooled Analysis

Using the pooled site means from the 16 BTO solar sites (n=16), there was no statistically significant change ($\alpha = 0.05$) between pre- and post-harvest time periods for both the DiffWm^{-2} (p=0.349) and DiffAtten metrics (p=0.347, Table 3.1-1). Looking at site means, the net treatment increase in incoming solar radiation of 3.0 W m^{-2} (DiffWm^{-2}) was not statistically significant. For attenuation (DiffAtten), the net treatment decrease of 0.0043, or 0.43%, was not statistically significant.

The limit of detectability using two pyranometer instruments simultaneously is ±6.4 W m^{-2} for DiffWm^{-2}, which is greater than the ±3.0 W m^{-2} net treatment effect. Below this detectability threshold, small increases in solar radiation equate to no treatment effect, and this is confirmed by the one-tailed test (p=0.349). The limit of detectability with three pyranometer instruments, using the average hilltop value of 750 W m^{-2}, is ±2.3% for DiffAtten. Since the -0.43% net treatment effect is below this detectability threshold, this change equates to no treatment effect, which is also confirmed statistically (p=0.347).

Box whisker plots for DiffWm^{-2}, Figure 3.1-1, and DiffAtten, Figure 3.1-2, show the median net treatment effect and quartile values. Note that median values (middle line through the box) are near zero for both metrics, illustrating the lack of significant treatment effects for pooled data, and that most values lie near the median (within the shaded-box quartiles).

Table 3.1-1. Summary of DiffWm^{-2} and DiffAtten values used in pooled paired t-tests.

Site	Reference Reach		Treatment Reach		Treatment Effect	
	DiffWm^{-2}	DiffAtten	DiffWm^{-2}	DiffAtten	DiffWm^{-2}	DiffAtten
SF Ahtanum	101.6	-0.1390	32.3	-0.0427	-69.3	0.0963
Moses Creek Trib	0.7	0.0011	-6.6	0.0055	-7.4	0.0044
Mill Creek	1.7	-0.0030	3.0	-0.0072	1.3	-0.0041
Dry Canyon	-8.1	0.0027	15.9	-0.0341	23.9	-0.0367
Long Alec	-17.9	0.0272	-53.0	0.0720	-35.1	0.0448
NF Foundation	-13.2	0.0321	9.5	-0.0006	22.7	-0.0326
Cole Creek	-50.6	0.0899	-2.5	0.0375	48.1	-0.0524
Lotze Creek	-22.8	0.0276	-9.5	0.0255	13.4	-0.0021
Clark Creek	15.1	0.0009	14.6	-0.0101	-0.5	-0.0110
Upper Bacon Creek	-2.1	-0.0022	1.1	-0.0031	3.2	-0.0009
Seco Creek	-20.1	0.0494	40.5	-0.0198	60.5	-0.0692
Sema 2	-15.4	0.0560	2.7	-0.0129	18.1	-0.0689
Sema 1	10.5	-0.0276	-3.6	0.0049	-14.2	0.0325
Flodelle	3.6	0.0110	2.5	0.0190	-1.1	0.0080
Tungsten	-6.7	0.0057	-11.2	0.0106	-4.5	0.0049
Sanpoil	-17.3	0.0063	-28.4	0.0249	-11.1	0.0186
Pooled Average	**-2.6**	**0.0086**	**0.4**	**0.0043**	**3.0**	**-0.0043**

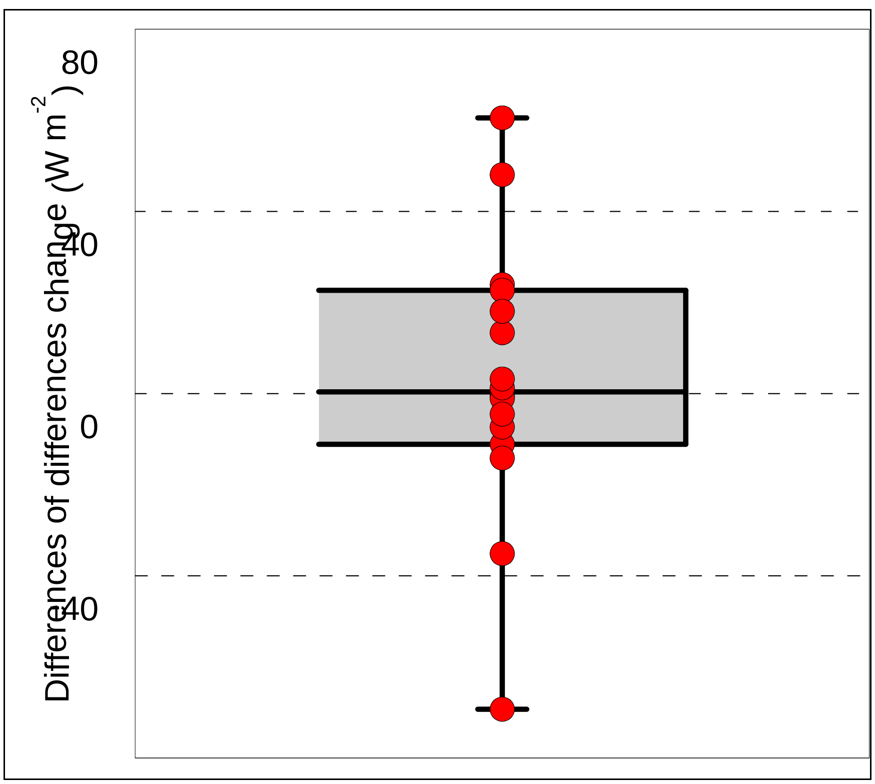

Figure 3.1-1. Box whisker plot showing net treatment effect for DiffWm^{-2}.

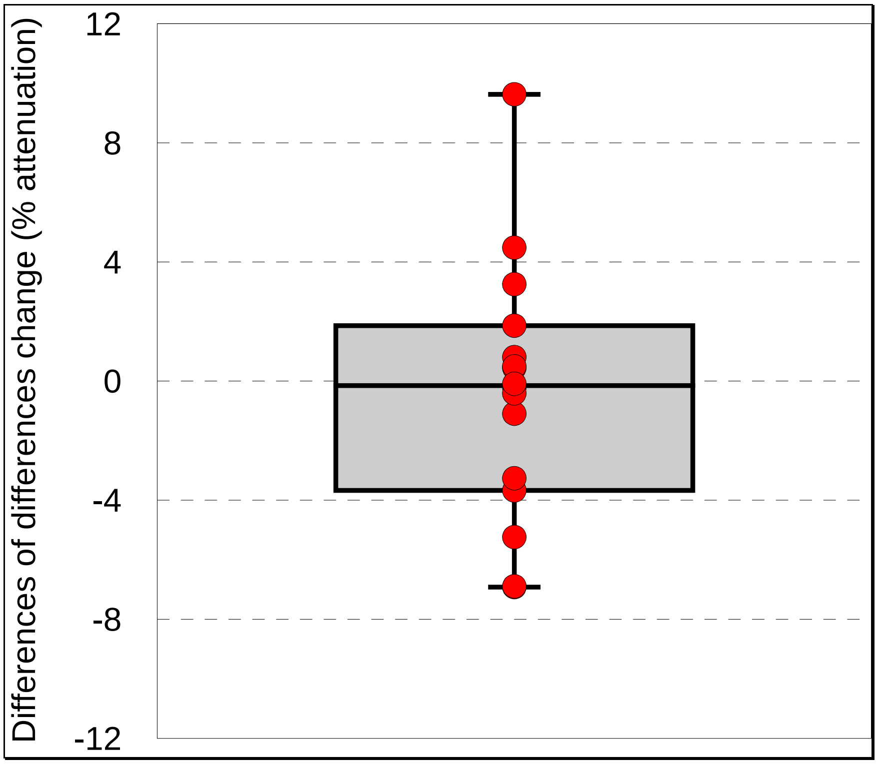

Figure 3.1-2. Box whisker plot showing net treatment effect for Attenuation %.

3.2 Summary of Measured Values

Pre- and post-harvest treatment reach values are listed below (Table 3.2-1), with corresponding solar radiation measurements for the reference reach (Table 3.2-2). Looking at the pooled values for the 16 sites, hilltop values of 745.2 (pre-harvest) and 760.2 (post-harvest) were similar between periods. In the treatment reach, incoming solar radiation to the stream averaged 63.1 W m^{-2} pre-harvest, and it increased slightly to 63.6 W m^{-2} post-harvest. However, percent attenuation also increased slightly, from 91.3% (pre-harvest) to 91.7% (post-harvest), indicating slightly more effective shade. In the reference reach, incoming solar radiation to the stream decreased from 68.8 W m^{-2} (pre-harvest) to 66.3 W m^{-2} (post-harvest). This pooled average decrease across the reference reaches also corresponded to an increase in attenuation from 90.4% (pre-harvest) to 91.3% (post-harvest). These values, slight rounding aside, correspond with a net treatment increase (DiffWm^{-2}) of 3.0 W m^{-2} and an attenuation decrease of 0.43%. Incoming solar radiation values ranged from 20.2 W/m^2 to 134.0 W m^{-2} across all pre-harvest stream reaches, and this range was 21.9 W m^{-2} to 148.6 W m^{-2} in the post-harvest reaches.

Table 3.2-1. Solar radiation at the treatment reach, hilltop, and attenuation (mean values for the day of measurement).

Site	Pre-Harvest Treatment Reach			Post-Harvest Treatment Reach		
	Stream ($W m^{-2}$)	Hilltop ($W m^{-2}$)	Attenuation (%)	Stream ($W m^{-2}$)	Hilltop ($W m^{-2}$)	Attenuation (%)
SF Ahtanum	87.1	857.2	89.8	119.4	850.2	85.5
Moses Creek Trib	81.1	807.0	90.1	74.5	802.5	90.7
Mill Creek	21.2	710.4	97.1	24.2	710.9	96.4
Dry Canyon	32.8	775.3	95.8	48.7	713.4	92.4
Long Alec	98.5	764.1	87.3	45.5	794.6	94.5
NF Foundation	117.4	742.8	85.4	126.9	831.1	85.3
Cole Creek	106.9	660.3	82.8	104.3	753.6	86.5
Lotze Creek	52.0	777.3	92.3	42.6	810.1	94.8
Clark Creek	36.2	750.0	93.9	50.8	752.8	92.9
Upper Bacon Creek	33.6	765.8	95.7	34.7	714.2	95.4
Seco Creek	59.2	606.4	90.2	99.7	776.4	88.2
Sema 2	27.3	755.9	95.4	29.9	709.0	94.1
Sema 1	30.1	730.6	95.7	26.5	772.5	96.2
Flodelle	31.0	635.9	92.2	33.5	665.9	94.1
Tungsten	71.9	791.4	91.5	60.7	780.6	92.5
Sanpoil	123.8	793.4	85.5	95.4	725.5	88.0
Pooled Average	**63.1**	**745.2**	**91.3**	**63.6**	**760.2**	**91.7**

Table 3.2-2. Solar radiation at the reference reach, hilltop, and attenuation (mean values for the day of measurement).

Site	Pre-Harvest Reference Reach			Post-Harvest Reference Reach		
	Stream ($W m^{-2}$)	Hilltop ($W m^{-2}$)	Attenuation (%)	Stream ($W m^{-2}$)	Hilltop ($W m^{-2}$)	Attenuation (%)
SF Ahtanum	34.5	857.2	95.6	136.1	850.2	81.7
Moses Creek Trib	63.0	807.0	92.2	63.7	802.5	92.3
Mill Creek	20.2	710.4	97.3	21.9	710.9	97.0
Dry Canyon	37.8	775.3	95.2	29.8	713.4	95.4
Long Alec	84.7	764.1	88.6	66.8	794.6	91.4
NF Foundation	134.0	742.8	83.4	120.8	831.1	86.6
Cole Creek	115.2	660.3	82.7	64.6	753.6	91.6
Lotze Creek	48.8	777.3	94.2	26.0	810.1	97.0
Clark Creek	133.5	750.0	82.3	148.6	752.8	82.4
Upper Bacon Creek	34.8	765.8	95.5	32.7	714.2	95.3
Seco Creek	91.3	606.4	85.6	71.3	776.4	90.5
Sema 2	54.7	755.9	87.6	39.3	709.0	93.2
Sema 1	31.2	730.6	95.6	41.7	772.5	92.9
Flodelle	27.5	635.9	93.9	31.1	665.9	95.0
Tungsten	114.3	791.4	86.5	107.6	780.6	87.1
Sanpoil	76.1	793.4	90.6	58.8	725.5	91.3
Pooled Average	**68.8**	**745.2**	**90.4**	**66.3**	**760.2**	**91.3**

4.0 DISCUSSION

Changes to incoming solar radiation and effective shade metrics (W m^{-2} and Attenuation) following treatment were not found to be statistically significant. Net treatment effects were +3.0 W m^{-2} and -0.43% Attenuation, i.e., a small increase in solar radiation and decrease in shade. The following discussion explores these net treatment results in more detail and provides perspective on what these values mean from the standpoint of stream water heating/energy budget.

4.1 Study Limitations

The Solar Study was subject to constraints that have the potential to affect the results. This report is limited to an examination of the net change between treatment and reference reaches following the application of the all available shade rule using a pooled analysis. Questions related to the relationship between solar radiation and specific site conditions are relegated to a follow-up report.

The use of a replicated BACI design provides the ability to control for many potentially confounding effects (e.g., differences in vegetation), but the design also makes it possible for changes in reference reaches to mask treatment effects. Solar radiation was measured once pre-harvest and once post-harvest and, because of harvest delays, the period between measurements ranged from 1-6 years. If during that period, windthrow or other non-treatment related changes in canopy density affected the reference reaches disproportionately, the effect of the treatment could be masked. Conversely, false positive treatment effects could occur if non-treatment changes in canopy density affected the treatment reaches disproportionately.

Because of the specific site selection criteria used for this study, sites selected effectively represent small eastern Washington bull trout overlay streams that are thermally sensitive to increases in solar radiation. The study sites were not drawn at random from the bull trout overlay, and thus may not be representative of the wide range of streams subject to the “all available shade rule”.

4.2 Pooled Analysis

The mean differences for DiffWm^{-2} and DiffAtten yielded no statistically significant treatment effect. This is not unexpected given that pooled averages in DiffWm^{-2} and DiffAtten were only +3.0 W m^{-2} and -0.43%, respectively. Evaluation of confidence intervals (C.I.) offers additional insight (Figure 4.2-1). Confidence intervals in the figure show no treatment effect even at the 33% confidence level. The figure also shows that an average treatment effect of at least 19.2 W m^{-2} would be required to detect a treatment effect at the $\alpha = 0.05$ significance level.

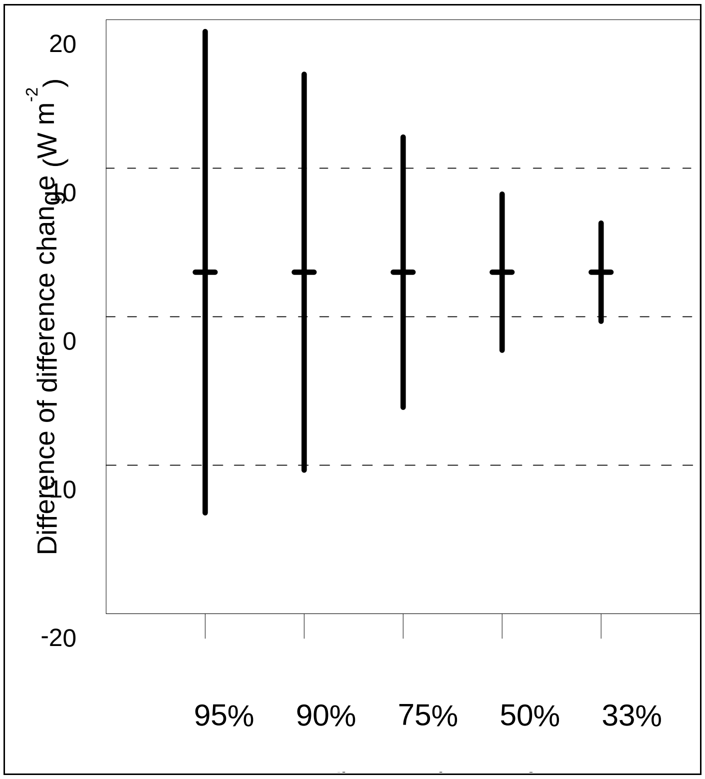

Figure 4.2-1. Confidence intervals of DiffWm^{-2} showing how the pooled data showed no treatment effect, even at the 33% confidence interval.

4.3 Factors Affecting Results for Individual Sites

Overall differences in DiffWm^{-2} and DiffAtten were small. However, considerable variability in DiffWm^{-2} (-69.3 W m^{-2} to +60.5 W m^{-2}) and DiffAtten (-6.92% to +9.63%) was observed when looking at individual site responses. These ranges in responses could be produced by actual treatment effect, other anthropogenic activities, or natural factors. Possible factors explaining the variability could include differences in the extent of treatment (harvested basal area), age and species composition of the riparian zone, stream aspect, stand growth and mortality between pre- and post-treatment measurements, and other disturbance factors (e.g., proximity to roads, road construction following the pre-treatment measurements, harvest history). Treatment effects were not related to the magnitude of the pre-harvest radiation values in the reference and treatment reaches (Figures 4.3-1, 4.3-2, and 4.3-3). That is, higher or lower shade levels prior to harvest did not appear to affect treatment response.

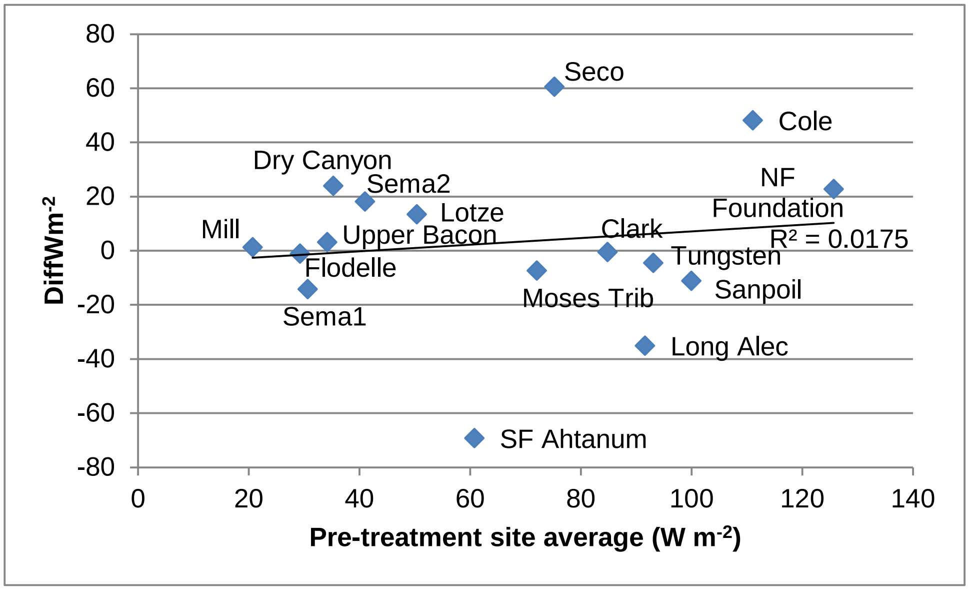

Figure 4.3-1. Scatterplot of net treatment effect (DiffWm^{-2}) and pre-harvest site averages (reference+treatment / 2).

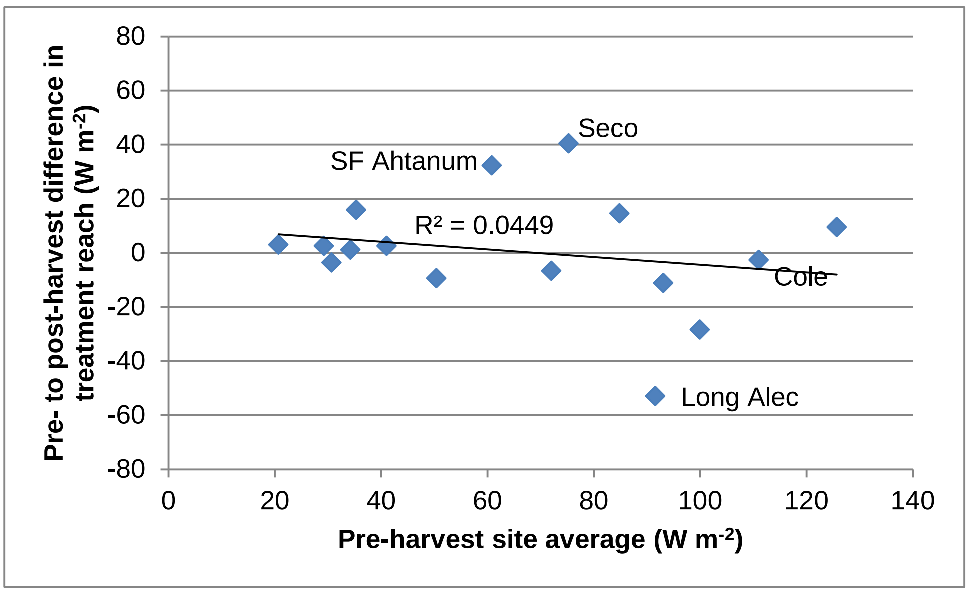

Figure 4.3-2. Observed differences (W m^{-2}) in treatment reaches and pre-harvest site averages (reference+treatment / 2).

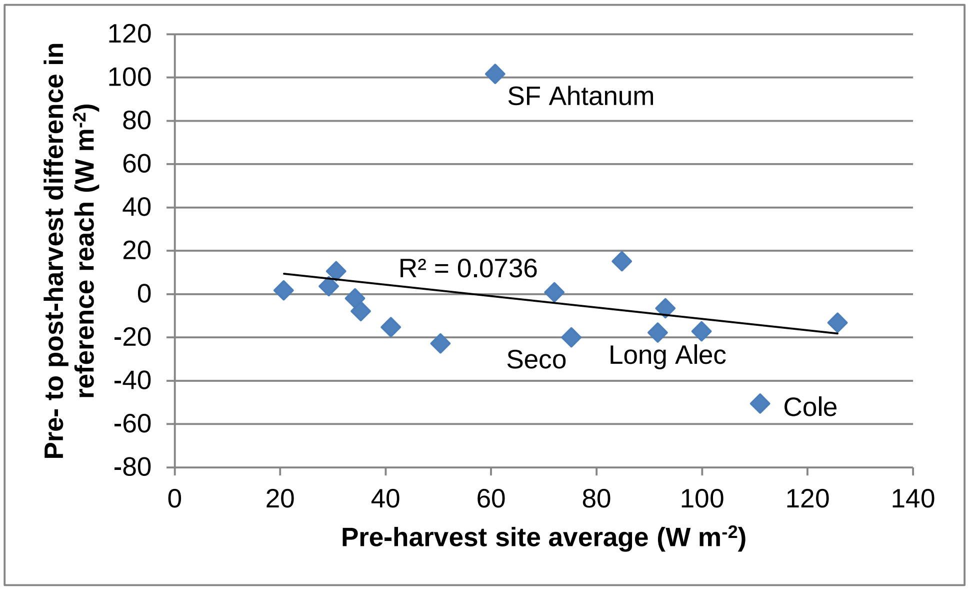

Figure 4.3-3. Observed differences (W m^{-2}) in reference reaches and pre-harvest site averages (reference+treatment / 2).

As much as six years elapsed between pre- and post-harvest measurements due to delayed harvest of private lands and state timber sales, increasing the potential for non-treatment effects. This was examined by plotting elapsed time between pre- and post-harvest measurements and net treatment effects (DiffWm^{-2}) (Figure 4.3-4), differences (W m^{-2}) in treatment reaches (Figure 4.3-5), and differences (W m^{-2}) in reference reaches (Figure 4.3-6). This examination revealed no systematic effect of elapsed time on treatment effects. However, data are insufficient to fully evaluate this concern, and delayed harvest may have reduced the ability to detect a treatment effect.

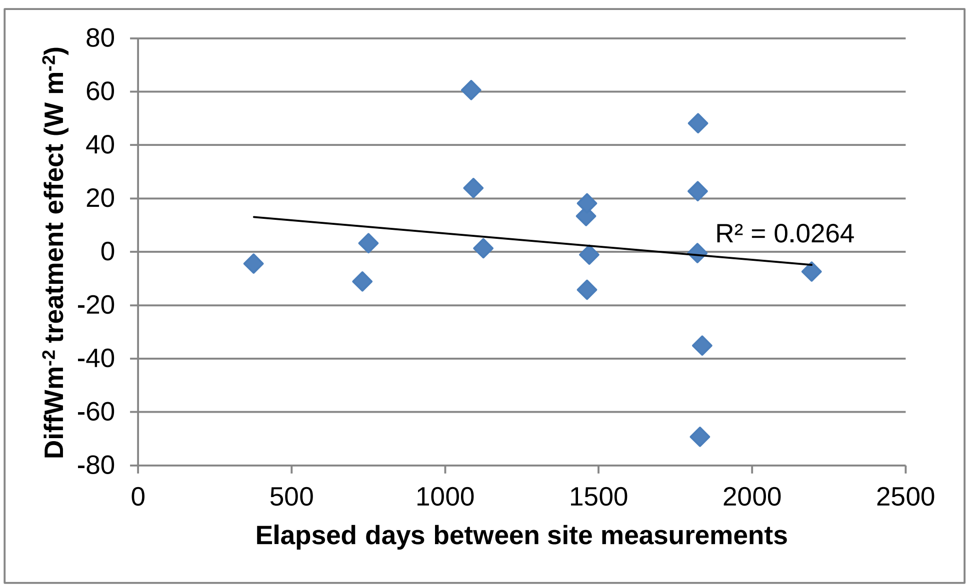

Figure 4.3-4. Relationship between net treatment effect (DiffWm^{-2}) and elapsed time between pre- and post-harvest measurements.

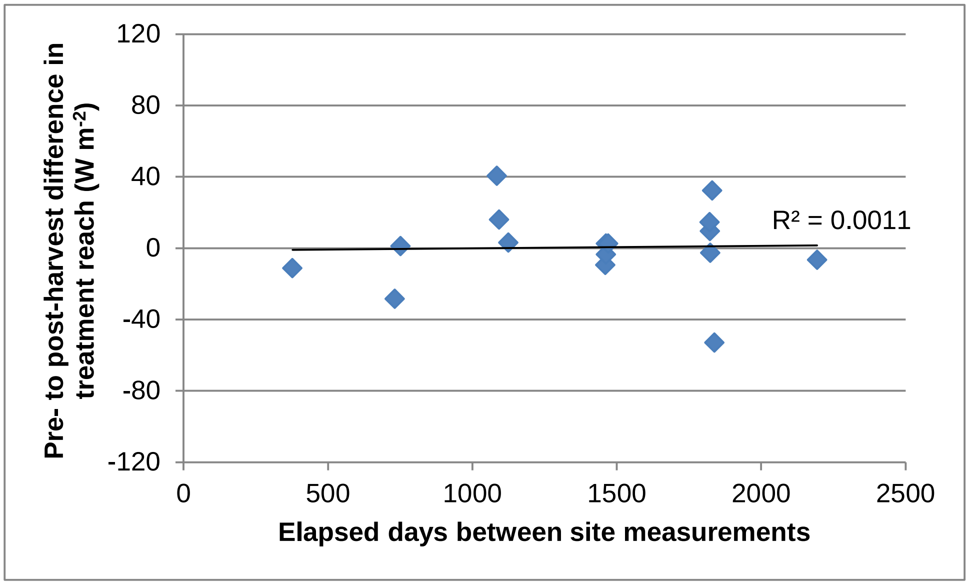

Figure 4.3-5. Relationship between observed differences (W m^{-2}) in treatment reaches and elapsed time between pre- and post-harvest measurements.

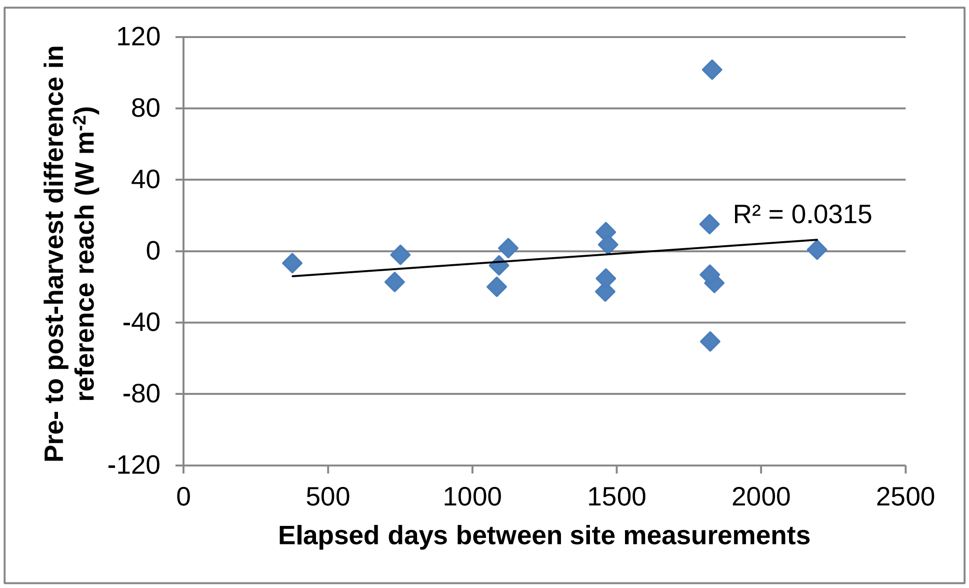

Figure 4.3-6. Relationship between observed differences (W m^{-2}) in reference reaches and elapsed time between pre- and post-harvest measurements.

Although all measurements were taken mid-summer, differences between pre- and post-harvest measurement dates potentially affected actual solar angle for a given site (see Table 2.1-2). This potential effect on results was reviewed by plotting difference in solar angle and net treatment effects (DiffWm^{-2}). Figure 4.3-7 shows this relationship. Negative difference in solar angle values indicate that the post-harvest measurement was taken later in the summer when solar angles are less than for the pre-treatment measurement. No systematic effect of solar angle differences on treatment effects is indicated by these data.

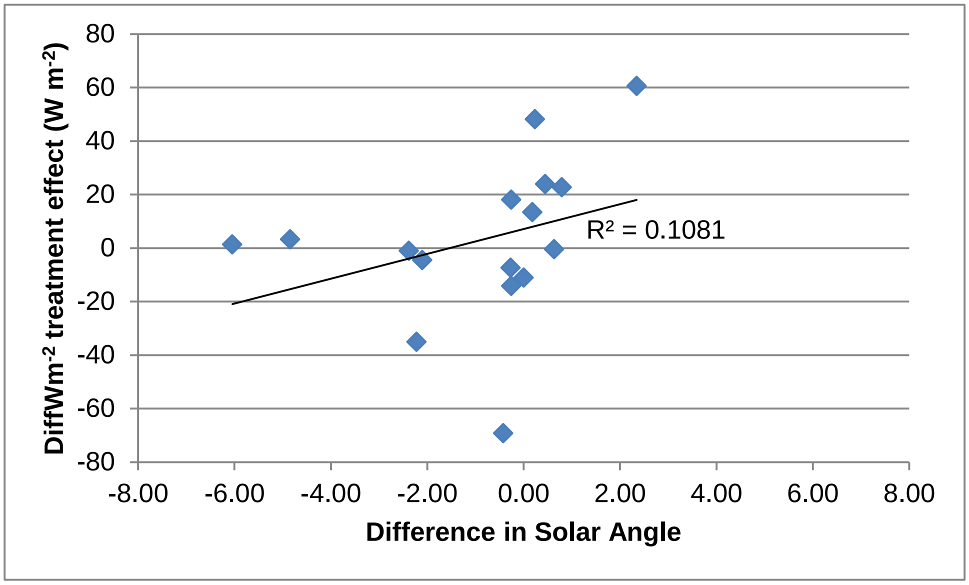

Figure 4.3-7. Relationship between net treatment effect (DiffWm^{-2}) and difference in solar angle between pre- and post-harvest measurements.

The potential for non-treatment effects related to changes in stand characteristics that may have occurred between pre- and post-harvest measurements was further examined via relationships between elapsed time and basal area, a stand metric provided from the companion temperature study. For this examination, changes in basal area between the pre- and post harvest measurements within the riparian management zone (RMZ) core area, where no trees were removed via harvest, were plotted versus changes in attenuation (DiffAtten%). Figure 4.3-8 demonstrates no relationship to treatment effects as represented by DiffAtten% to changes in core zone basal area between the pre- and post- harvest measurements. Although this current examination was constrained to basal area, shade is known to be more closely correlated with tree height and canopy closure (Beschta and Wethered 1984; Boyd 1996; Chen et al. 1998; Doughty et al. 1991). Relationships of additional stand characteristics to shade may be examined when these solar study results are combined with the Shade/Temperature Study.

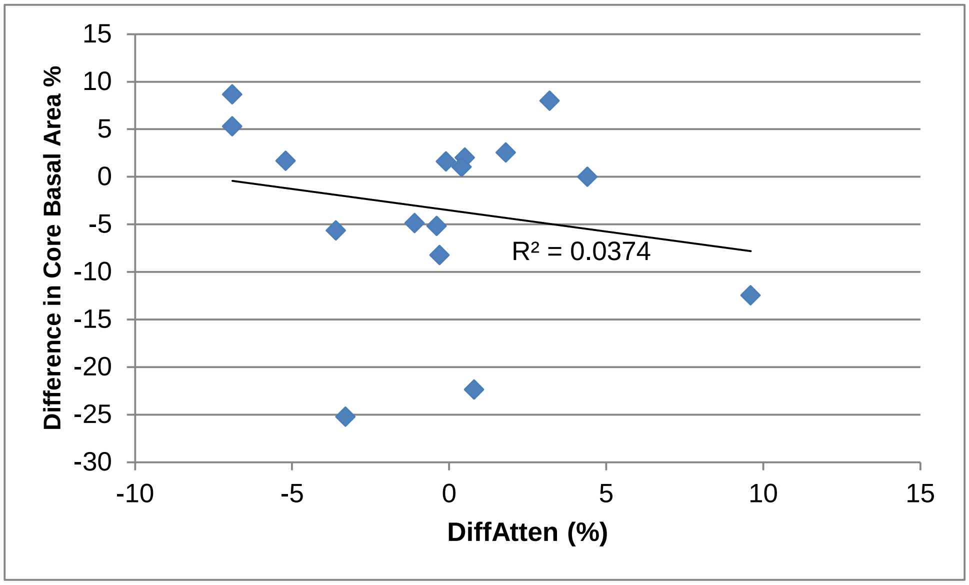

Figure 4.3-8 . Relationship between change in net core basal area and attenuation net treatment effect (DiffAtten).

Potential effects of stream azimuth were also examined. Stream azimuth, represented by categorizing stream aspect into cardinal direction quartiles, was found to be nearly equally distributed. No relationship of stream azimuth to differences (W m^{-2}) in treatment effect was apparent in either treatment or reference reaches (Figures 4.3-9 and 4.3-10).

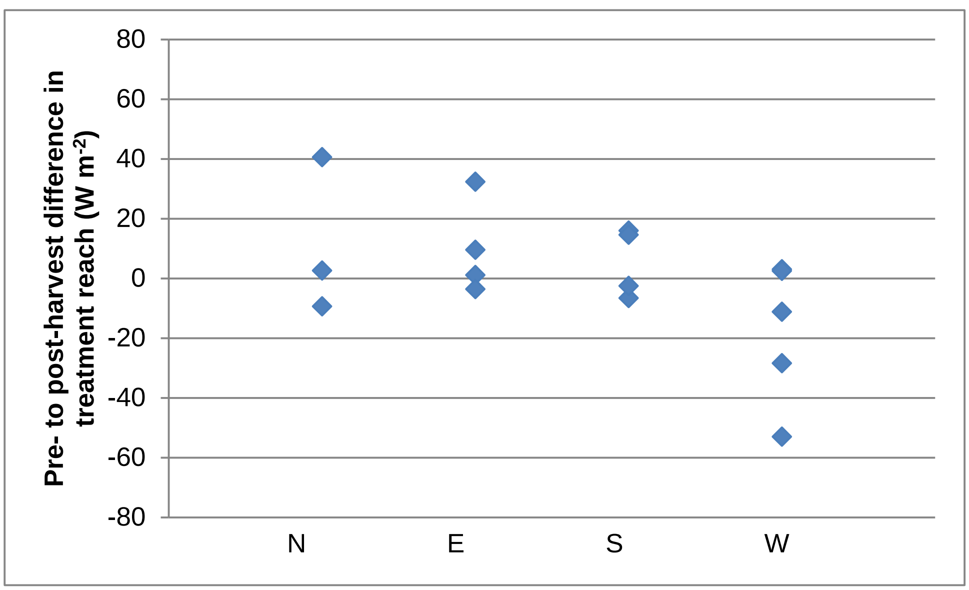

Figure 4.3-9. Relationship between observed differences (W m^{-2}) in treatment reaches and stream azimuth (i.e. N=315 to 45; E=45 to 135; S=135 to 225; W=225 to 315).

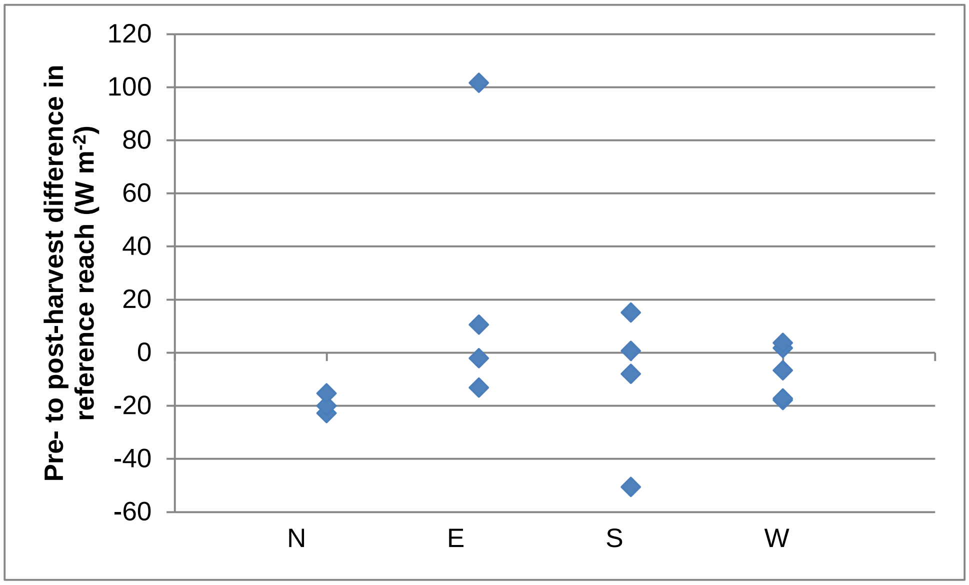

Figure 4.3-10. Relationship between observed differences (W m^{-2}) in reference reaches and stream azimuth (i.e. N=315 to 45; E=45 to 135; S=135 to 225; W=225 to 315).

The objective of this analysis was to determine if there were overall differences in incoming solar radiation to the stream surface following BTO harvest prescriptions. The scope of the study did not include quantitative measurements of factors that could cause or contribute to changes in solar radiation reaching the streams, pre- to post-harvest. However, conditions were observed that potentially affected results, particularly at the following four streams:

- South Fork Ahtanum
- Cole Creek
- Sema 1
- Sema 2

Observations at each of these sites are summarized below for DiffWm^{-2}:

South Fork Ahtanum: The largest apparent treatment effect occurred at the South Fork Ahtanum, a decrease in DiffWm^{-2} of 69.3 W m^{-2}. Field observations suggest that considerable stand mortality occurred during the five years between pre- and post-harvest measurements, a factor supported by increases in radiation observed in both the treatment and reference reaches post-harvest. The treatment reach increased from 87.1 W m^{-2} pre-harvest to 119.4 W m^{-2} post-harvest, and the reference reach increased from 34.5 W m^{-2} pre-harvest to 136.1 W m^{-2} post-harvest.

Cole Creek: Five years also elapsed between the pre- and post-harvest measurements at Cole Creek, where markedly increased riparian vegetation was observed post-harvest. This site had substantial streamside alder/hardwood vegetation, and most of the change (48.1 W m^{-2}) resulted from a 50.6 W m^{-2} decrease in solar radiation reaching the stream within the reference reach pre- to post-harvest, whereas the treatment reach only showed a 2.6 W m^{-2} decrease. Like the South Fork Ahtanum site, net treatment response was more a reflection of reference reach changes rather than treatment reach changes.

Sema 2: A road was constructed through the treatment reach between the pre- and post-harvest measurements, causing increased exposure to solar radiation for at least one station during two measurements made during the morning post-harvest period. Despite the effect of the road, the net increase of 18.1 W m^{-2} was almost entirely attributable to a decrease in radiation measured within the reference reach (-15.4 W m^{-2}); net change within the treatment reach was only 2.6 W m^{-2}.

Sema 1: The stream flowed subsurface beneath large glacial boulders and accumulated logs and forest floor debris. Although the differences measured resulted in a decrease of 14.2 W m^{-2}, changes to stream temperature attributable to changes in solar radiation may be masked by other energy transfer processes.

4.4 Summary of Measured Values

Beyond statistical significance tests and sensor detection limits, it is also useful to examine the measured values observationally to assess a potential treatment effect to both incoming solar radiation and effective shade (Attenuation). Solar radiation incident on stream surfaces averaged 65 W m^{-2} across the 16 sites (Figure 4.4-1). When compared to the hilltop average (750 W m^{-2}), this equates to greater than 90 percent attenuation; i.e., very little incoming solar radiation reached the streams.

Another interesting note involves the source of calculated treatment effect in DiffWm^{-2} and DiffAtten. As discussed, the measured changes are not statistically significant and the calculated treatment effects are below the detection limits of the pyranometers. Moreover, much of the observed change can be attributed to differences within the untreated reference reaches. Of the 3.0 W m^{-2} pooled net treatment effect, most (87 percent) is due to the -2.6 W m^{-2} decrease in the difference calculations from the reference reaches (Figure 4.4-1). The net treatment increase for DiffAtten is also caused by a decrease in the reference reaches. The mean DiffAtten_{treat} value was a decrease (-0.43%), but the $\text{DiffAtten}_{reference}$ value was a larger decrease (-0.86%). Although mean attenuation within the treatment reaches actually increased following harvest, by using the differences of the differences approach, the larger change in the reference variable equated to a net treatment increase in attenuation of +0.43% [(-0.43% - (-0.86%)) = +0.43%].

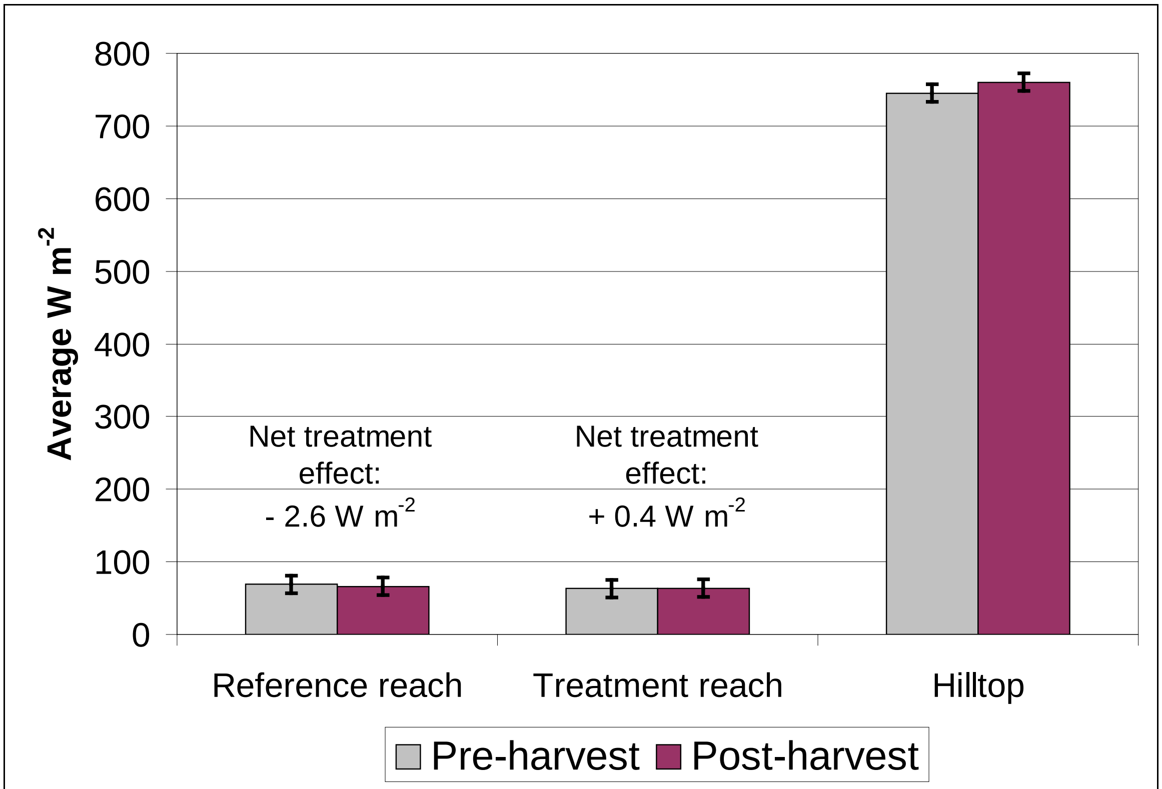

Figure 4.4-1. Pooled reference, treatment, and hilltop DiffWm^{-2} values along with calculated DiffWm^{-2} net treatment effects by reference reach (-2.6 W m^{-2}) and treatment reach (+0.4 W m^{-2}). Standard error bars (±1 S.E.) are included.

4.5 Energy Budget Considerations

Changes in solar radiation discussed above are in absolute terms, without reference to potential changes in stream temperature. Solar radiation/temperature relationships within the 16 reaches that are the subject of this study will be assessed following completion of the companion Shade/Temperature Study. Nonetheless, it is useful to consider, at least on a theoretical basis, the extent to which changes in solar radiation observed during this study could increase stream temperature. Such a discussion begins to address the following question:

> *If solar energy input to the stream increases following application of the all available shade rule, do stream temperatures also increase after harvest?*

While direct solar radiation generally is the primary contributor to maximum daily summer stream temperature (Adams and Sullivan 1989), thermal response of stream waters is also affected by multiple energy transfer processes, including longwave radiation, conduction, convection, and evaporation. These processes in turn are dependent on reach-specific stream characteristics such as stream flow and velocity, width and depth of the water column, local hyporheic exchange, and any ground or surface water contributions (or losses) that may occur. Placing the results presented in this report within an energy budget context, when constrained by a pooled-site examination and without use of stream characteristics measured in the temperature response companion study, presents a challenge. However, energy budgets constructed by Johnson (2004) provide at least a crude means for comparison.

Johnson (2004) studied stream temperature and energy budgets within a small western Oregon Cascade stream. Detailed energy budgets were constructed for a bedrock reach with no vegetative shade and no visible groundwater input. Stream average wetted width was reported as 2.13 m, average water depth as 0.07 m, and discharge as 3.4 L s^{-1}; hydraulic characteristics that are all within the range of stream conditions observed during the solar measurements. Incoming solar radiation, measured with a pyranometer, was confirmed as the dominant energy transfer process; mid-day solar input (11:00 to 13:00) was approximately 860 W m^{-2}. Maximum temperature differences through a 150 m reach were +3.9^{o} C under two experimental conditions: with-shade (solar input of 4 W m^{-2}) and without shade (solar input of 860 W m^{-2}).

The pooled analysis from the 16 BTO sites yielded no statistical increase and no change in pooled mean solar radiation (within system error of ±6.4 W m^{-2}). If we disregard limits of detection, assume that the overall estimated change of +3 W m^{-2} is real, and assume that all other factors are equal, a proportional approach using Johnson's results can be applied. With the BTO results of an increase of +3 W m^{-2} solar input, and the available incoming solar radiation (~750 W m^{-2} from the pre- and post-treatment daily hilltop values), the estimated temperature increase based on daily values would be:

$$(3 \text{ W m}^{-2} / 750 \text{ W m}^{-2}) \times 3.9°\text{C} = 0.016°\text{C}$$

Adjusting for increased distance of exposure (300 m, solar study, versus 150 m used in Johnson (2004)) would yield:

$$(3 \text{ W m}^{-2} / 750 \text{ W m}^{-2}) \times 3.9°\text{C} \times (300 \text{ m} / 150 \text{ m}) = 0.03°\text{C}$$

This approximation is admittedly crude, as Johnson's (2004) shading experiment occurred in a bedrock reach compared to the mostly alluvial stream reaches studied within this project. However, Johnson also indicated that temperature response may be relatively high in bedrock reaches compared to other substrates, so temperature response may be more limited in alluvial stream reaches. Regardless, if the estimation of a +0.03°C stream temperature response based on empirical data is remotely close in an energy budget context, a small increase in solar radiation of 3 W m^{-2} would be expected to result in undetectable changes in stream temperature, especially when considering sensor errors of ±0.2°C found in typical thermographs. This estimate is based on pooled data results, and estimates will vary on a site-specific basis. From a thermodynamics standpoint, streams with less flow would generally experience larger changes in stream temperature.

5.0 CONCLUSIONS

Using a pooled site methodology for the 16 BTO solar radiation sites in eastern Washington, there were no statistically significant increases in incoming solar radiation following the prescribed harvest prescriptions over the period of measurement. The single hypothesis to be tested for this current report, "There is no significant difference in solar energy reaching the stream pre- and post-harvest when the "all available shade" rule is applied," was not rejected. There was an overall calculated change of +3.0 W m^{-2} in incoming solar radiation. This was not statistically significant and was within the range of system measurement error (±6.4 W m^{-2}). When looking at percent attenuation, there was a calculated change of -0.43%, which was also not statistically significant and was less than the limits of detectability (±2.3%). Application of an approach to gauge potential increases in stream temperature given the calculated changes in solar radiation (excluding potential measurement error) suggest that the +3.0 W m^{-2} of increased energy would result in thermal loading which would be far too small to detect using typical stream temperature sensors.

This report was constrained to a pooled site analysis. Consideration of factors affecting treatment response at individual sites was beyond the scope of the analysis for this study. However, pooled site examination of extraneous non-treatment effects demonstrated no relationship of these effects to solar energy (W m^{-2}) received at the stream surfaces and solar attenuation. Extraneous factors examined included elapsed time between pre- and post-harvest measurements, and changes in solar angle between pre- and post-harvest measurement dates. Also examined were pre- to post-harvest changes in stand characteristics as represented by RMZ core area basal area, stream azimuth, and pre-harvest levels of shade.

Sites selected for this study were not randomly located; they were selected to represent small BTO streams sensitive to changes in solar exposure. It was outside the scope of this study to assess the potential causes and implications of site specific variability on the pooled analysis. Better assessing the potential causes of the site level responses will be a topic examined more completely in the forthcoming Shade/Temperature companion study.

Based on this pooled site analysis, the authors conclude this study of 16 BTO streams adequately demonstrated that application of the "all available shade rule" did not cause a significant or detectable increase in average solar radiation reaching the stream surface or decrease in solar attenuation (shade).

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