Effectiveness of riparian management zone prescriptions in protection and maintaining shade and water temperature in forested streams of Eastern Washington

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WASHINGTON STATE DEPARTMENT OF
Natural Resources
PETER GOLDMARK - Commissioner of Public Lands

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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 Practices 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 (RSAG).

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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Executive Summary: We examined shade and stream temperature response to timber harvest at 30 study sites in eastern Washington over an eight year period (2003-2010). Study sites were examined for at least two years before implementation of riparian timber harvest in all but one site and for at least two years after riparian timber harvest in all sites. The timing of pre-harvest and post -harvest sampling was dictated by treatments completed by individual landowners. A replicated before–after-control-impact (BACI) study was used to test effectiveness of the two eastern Washington riparian prescriptions for protection of shade and stream temperature. 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" (ASR) must be retained within 75 feet of the stream. When a harvest unit is located outside the BTO, prescriptions fall under the standard rule (SR), which may allow for harvest of a portion of shade trees within 75 feet, depending on elevation and canopy cover existing prior to harvest. We focused on shade and maximum daily temperature from July through mid September. The ASR limited the mean decrease in shade to 1%, with a maximum decrease of 4%. Under the SR, shade was reduced by a mean of 4%, with a maximum reduction of 10%.

Stream temperature response was evaluated by fitting pre-harvest calibration relationships between the upstream and downstream daily maximum temperatures in both the treatment and reference reaches. Generalized least squares (GLS) regression was used to account for autocorrelation in the residuals. A prediction equation for the stream temperature at the downstream end of a study reach was developed based upon the stream temperature at the upstream end. The observed minus the predicted temperature was then computed in each treatment reach to determine the post-harvest stream temperature response. Differences in the observed and predicted temperatures for the reference reaches were used to establish the background responses in stream temperature. Daily maximum stream temperature responses in the post harvest period varied from -2.3 °C to 2.6 °C over the course of the entire study across treatment and reference reaches, with 98% of all of the daily responses value 1.0 °C or less. Site seasonal means of daily maximum stream temperature treatment responses in the first two years following harvest ranged from -0.7 °C to 0.5 °C in the ASR reaches and from -0.3 to 0.6 in the SR reaches. Site seasonal mean post-harvest background responses in reference reaches ranged from - 0.5 °C to 0.6 °C in the first two years following harvest. The site-specific evaluation results suggested that there were post-harvest treatment reach temperature responses, albeit small, in at least one sample period following harvest in 19 of the 30 study sites. Similar analysis on the reference reaches also indicated a significant post-harvest temperature response in 19 of the 30 study sites during at least one year. During the first two summers following timber harvest, minor differences in stream temperatures responses were observed in the no-harvest reference, ASR harvest, and SR harvest reaches. Mean daily maximum stream temperature increased 0.16 °C in the SR harvest reaches, whereas stream temperatures in both the ASR sites and in the no-harvest reference reaches increased on average by 0.02 °C. The seasonal variability observed in the no-harvest reference reaches set practical bounds on the magnitude of temperature changes that can reliably indicate a treatment response in our BACI designed study. Seasonal mean stream temperature responses of up to 0.5 °C in the no-harvest references were common during the post-harvest test period. Changes in canopy closure, shade, and stand attributes following harvest did not account for the variations observed in stream temperature responses. Processes not directly related to riparian forest canopy alteration may be primarily responsible for the small variations observed in stream temperature following timber harvest. Study results found the estimated temperature effects for both the All Available Shade Rule and the Standard Rule are similar to control conditions along our 1,000 ft test reaches for small streams in the mixed fir zone mid-successional forests of Eastern Washington.

1 Introduction

The effect of timber harvest on water temperature is a key issue for management of cold water fish species in the Pacific Northwest. Increases in summer stream temperature can cause stress and mortality of aquatic species, including threatened or endangered fish species (Beschta et al. 1987). Temperature regime is one of the most important water quality factors affecting bull trout (*Salvelinus confluentus)* distribution (Rieman and McIntyre 1995). Federal endangered species listings of trout and salmon species (*Oncorhynchus and Salvelinus spp.*) in the Pacific Northwest cite stream temperature increases due to logging as a limiting factor for population recovery (Bryant and Lynch 1996, Myers and Bryant 1998). Stream temperature increases following complete removal of riparian vegetation due to timber harvest and site preparation have been documented for decades (Brown 1969). Increases of 2°C to 10°C have been reported for daily maximums in June-August (Beschta et al. 1987, Moore et al. 2005b, Ice 2008, and Gomi et al. 2006). More subdued treatment effects have been reported with retention of riparian buffers where timber removal is limited (Gomi et al. 2006, Jackson et al. 2001, Groom et al. 2011; Moore et al 2005a).

Stream temperature is a function of multiple energy transfer processes, including direct solar radiation, longwave radiation, conduction, convection, and evaporation. Of these factors, direct solar radiation is the primary contributor to daily maximum summer stream temperature and has the most direct response to riparian canopy removal from forest harvest (Brown and Krygier 1970, Johnson 2004). Maintaining shade is an effective tool for minimizing stream temperature heat flux during the summer months when maximum stream temperatures are observed (Johnson 2004). Washington State enacted timber harvest regulations under the Washington Forest Practices Rules to maintain stream shade following timber harvest. Since removal of shade is strongly associated with stream temperature increases, forest practice rules in Washington have been established to minimize stream temperature increases following timber harvest near streams by application of minimum shade requirements.

Forest practices harvest prescriptions include minimum shade rules or requirements in eastern Washington that differ depending on whether a stream is located inside or outside of the mapped bull trout overlay (BTO) (WAC 222-16). If harvest is proposed within the BTO, the “All Available Shade Rule” (ASR) applies where all trees providing shade to the stream must be retained within 75 ft of bankfull width or channel migration zone (CMZ), whichever is greater, of fish-bearing streams (WAC 222-30-040). Under direction of the Forest Practice Board Manual, Section 1, all trees that contribute to canopy closure as determined by systematic hand-held densiometer measurements are considered to provide shade to the stream. No consideration is given to stream aspect and topography when determining which trees provide shade to the stream in the field. Elsewhere in eastern Washington, where timber harvest is conducted under what is referred to as the “Standard Rule” (SR), harvest of trees cannot reduce canopy closure below the minimum derived from the nomograph in Step 4 of Forest Practice Board Manual, Section 1. The nomographs depict canopy cover requirements based on elevation and water quality stream temperature classification. In summary, the ASR requires that all trees that contribute to canopy closure be retained during harvest, whereas the SR provides for varying canopy closure requirements depending on elevation of streams within a harvest area.

Although the knowledge of the current and potential distribution of bull trout is imprecise, large areas of forest land in eastern Washington are currently within the BTO and require application of the ASR (Figure 1.1). The ASR is based on the assumption that the SR is inadequate to maintain the cold water temperatures required by bull trout. It is further assumed that retention of all available shade within a 75-ft buffer width under the ASR is sufficient to prevent harvest-related increases in stream temperatures.

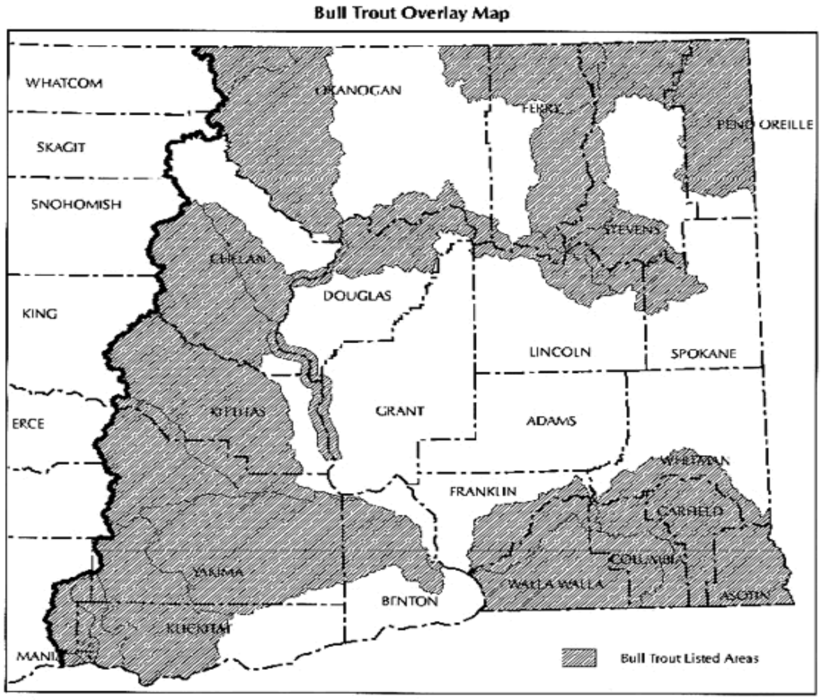
Bull Trout Overlay Map

Figure 1.1. The Bull Trout Overlay in eastern Washington (from Washington Forest Practices Board Manual).

The Cooperative Monitoring, Evaluation and Research Committee (CMER) implemented this study to compare and assess the effectiveness of the two eastern Washington riparian prescriptions for the protection of shade and stream temperature. The purpose of the study was to determine whether or not the ASR provides the shade and temperature protection intended by the rule, and whether or not it is more effective than the SR rule.

Stream temperature effects are defined herein as a change in the warming or cooling rate of water as it flows across a 1,000-foot-long reach following riparian timber harvest. Detecting stream temperature effects and attributing them to timber harvest can be difficult because of natural temporal and spatial variability in warming or cooling rates. Temperature variability is a function of several factors including basin size (Caissie, 2006), microclimatic and geologic processes (Kasahara and Wondzell, 2003), and annual and spatial hydrological variability (Poole and Berman 2001, Story et al. 2003). As such, longitudinal patterns (i.e. the rate of warming or cooling) in stream temperatures can be highly variable in small streams (Dent et al. 2008, Moore et al. 2005a). Study designs and analytical techniques must therefore be able to distinguish relatively small changes in stream temperature caused by riparian timber harvest from a wide range of background variability.

The study incorporates a modified before/after, control/impact (BACI) design to identify and account for the inherent variability that is commonly encountered in stream temperatures (Light et al. 2002). Multiple pre-harvest and post-harvest years of data collection allowed for the determination of within-site variability of stream temperatures across years. Control reaches permitted further evaluation of interannual temperature variability over the entire duration of the study. We anticipated that the study's sample size would assist in overcoming a degree of inter-site variability in temperature behavior. In this analysis, shade, canopy closure, air temperature, and stream temperatures were compared before and after harvest to quantify and compare differences in SR and ASR riparian prescriptions. In a companion study, solar radiation reaching the stream was also compared before and after harvest on the ASR sites to assess whether or not the ASR and densiometer methodology were actually achieving all available shade (McGreer et al. 2011).

The primary objectives of this study are to:

- Quantify and compare differences in post-harvest canopy closure between the SR and the ASR riparian prescriptions of eastern Washington.
- Quantify and compare differences in stream temperature effects of the two riparian prescriptions: the SR and the ASR.

In addition to the primary objectives, results from the companion solar study (McGreer et. al 2011) are combined with information collected in this study to address three key questions:

- Does removing trees that don't qualify as "all available shade" affect solar energy reaching the stream and/or stream temperature?
- Is canopy closure, as defined by the densiometer methodology used in the All Available Shade Rule, an adequate surrogate for the attenuation of solar energy to the stream needed to prevent stream temperature increases?
- What are the circumstances under which increases in solar energy to the stream significantly influence stream temperature?

The study is based on the premise that the primary mechanism for changing stream temperature following timber harvest is increased direct solar radiation. If the riparian prescriptions provide insufficient shade, the streams would receive increased amounts of solar radiation, which would in turn increase the warming rate of stream temperatures as it flows through the harvested area.

The effectiveness of the two prescriptions are evaluated for achieving stream shading objectives and maintaining stream temperature warming or cooling rates at pre-harvest levels. The physical characteristics of the study streams and attributes of the forest stands are described in order to extend the findings of this study to streams of similar settings, and to explore relationships between these characteristics and response variables.

2 Methods

2.1 Study Site Selection Criteria

During 2003, efforts were initiated to identify 40 study sites that would meet site selection criteria for inclusion in the study. This study was initiated with the intent of selecting a random representative sample from all of the potential sites meeting rigorous site selection criteria that were within the harvest planning horizon of landowners across eastern Washington. The criteria were established in the original study plan (Light et al. 2002) to minimize the anticipated influence of other environmental or anthropological factors on stream temperature responses to timber harvest. After first soliciting individual landowners for sites to include in the study, it soon became apparent that a random sampling approach was impractical due to the specificity of site selection criteria (Table 2.1). The selection criteria greatly limited the availability of study sites. Working with digital orthophotographs, topographic maps, and air photos, a total of 116 candidate study sites were identified that were believed to initially meet the site selection criteria. After confirmation of the landowner, a list of candidate sites was sent to appropriate property managers to solicit cooperation in the study. Each of the sites where landowners expressed willingness to being included in the study was visited in the field to assess site conditions in regards to harvest feasibility and consistency with site selection criteria. Early site visits included preliminary stand plots to ensure sufficient basal area and stem density thresholds for harvest entry. The location for the treatment and references reaches at each candidate study site was established to best meet the site selection criteria. Because of the difficulty in finding sites that met the entire suite of criteria, CMER agreed to broaden the criteria as follows.

Channel Widths

Rules for timber harvest in riparian areas of eastern Washington are different for streams that exceed 15 foot bankfull width as compared to streams that are less than 15 foot wide. Both stream size classes have similar shade/canopy requirements, no harvest core zones (30 feet from edge of bankfull or channel migration zone edge, whichever is largest) and tree retention rules for the inner and outer zone of the riparian management area. However, the inner and outer zone widths vary between the two stream sizes. Larger streams (exceeding 15 foot bankfull width) require management of an inner zone extending 70 feet from the core zone outer edge, whereas the smaller streams (15 foot and less bankfull width) require a 45 ft inner zone. Outer zones also vary in width between the two depending upon Site Class of the site. To limit the number of applied riparian prescriptions, the riparian prescriptions for streams less than or equal to 15 feet wide were applied (see Washington Forest Practices Rules, WAC 222-30-022) for all streams included in the study. Four sites were included, however, with streams exceeding 15 feet bankfull width (which exceeded an initial requirement in the study plan). Mean channel width in the four sites (Cole, SF Ahtanum, Dry, and EF Cedar) ranged from 16 to 22 feet. Riparian prescriptions for small streams were also applied to these four sites.

Tributary Inflow

The initial site selection criteria included the absence of tributaries. However, locating study sites with adequate timber resources for harvest with the complete absence of tributary channels became problematic. Seven sites were included in the study with at least seasonal tributaries (i.e., only surface flow during spring runoff period). Nine sites with tributary channels were initially included in the list of 37, but two were later dropped because of change in harvest plans. Seven sites included in the study (Bacon, Big Goosmus, EF Cedar, Heel, Sema 1, Sema 4, SF Ahtanum) contain at least seasonal tributary inputs. Tributary channels contributed to less than 10% of the total discharge as measured at the bottom of the reach.

Wetland / Seeps

Other selection criteria that proved to be difficult to completely adhere to included the preference for no wetlands or groundwater seeps/springs within the riparian area. Small, stream-adjacent seep channels and other small wetland pockets were situated within the treatment areas of ten sites (Big Goosmus, Dorchester, EF Cedar, Heel, Middle, Mill, NF Foundation, Sema 2, Sema 4, SF Ahtanum). In no case did the wetlands occupy more than 10% of the riparian management zone area at a given site and no sites had open standing water.

Roads

Eight of the original 116 sites were disregarded for further consideration due to existing riparian roads that significantly influenced both shade and/or availability of harvestable trees. Nine sites (Byers, Dorchester, Dry Canyon, EF Cedar trib, Floedelle, Heel, Prouty, SF Dairy, and Tungsten) with roads adjacent to or within at least a portion of the riparian zone on one side of the stream remained in the study. Roads were 1) limited to just a small portion of the outer edge of the riparian zone (Byers, Floedelle, Prouty, SF Dairy); 2) situated within the reference reach, either in the inner zone (EF Cedar trib), or outer zone (Dorchester, Tungsten); however, these roads did not appear to influence stream shading [shading exceeded 92% at all sampling locations throughout the entire reach]; or 3) characterized as narrow (≈ 20 feet wide), grown-over skid trails (Dry Canyon, Heel). New stream crossings, installed for timber harvest purposes, were situated just downstream of the upper end of the treatment reach in two study sites (Sema 2, Sema 4).

Discontinuous Flow

Selection criteria called for avoidance of streams with discontinuous flows and intermittent sections. After sites were established and monitored for two years, four sites (Little Goosmus, Prouty, Sema 1 and Sema 2) were found to contain stretches of intermittent flows beginning in mid to late summer during some years. In order to avoid the variability in stream temperature profiles associated with discontinuous channels and subsurface flows, a process described under Section 3.1 *Temperature Data Screening* was used to identify the periods when stream temperature may have been affected by the intermittent flows.

Many of the sites that were excluded from further consideration lacked adequate basal area for permitting harvest, or included presence of extensive wetlands and beaver ponds, wide channel migration zones, dry reaches, or inadequate stand conditions for the entire site length. The list of 116 sites was reduced to 37 (seven more were subsequently dropped due to changes in harvest plans) that met or came closest to meeting study design criteria (Table 2.2). None of the sites were dropped because landowners did not want to participate in the study.

Table 2.1. Criteria used to select study sites for inclusion in the Eastside Shade and Temperature Effectiveness Study

- A study reach at least 2,000-ft long on a small (<15-ft bankfull width) fish-bearing stream; 1,000 feet for the reference reach, and 1,000 feet for the treatment reach.
- No recent harvest within 200 feet of the stream in the reference reach.
- No recent harvest within 100 feet of the stream, 1,000 feet upstream of the reference reach.
- A relatively consistent stand of timber with sufficient basal area to meet the minimum requirements for commercial harvest under the forest practices rules.
- Pre-harvest canopy closure levels >50%.
- Absence of tributaries that enter or influence the study reaches.
- Absence of a channel migration zones.
- Limited amounts of unforested areas (i.e., pastures). Generally, unforested areas were not to occur within the riparian zone, especially within the core or inner zone. Sites with > 10% of the inner zone occupied by nonforested areas required special review and approval by CMER 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. If secondary surface waters occupied greater than 10% of the riparian area at a site, then review and approval by CMER was required.
- Continuous surface flow during the monitoring period (no intermittent sections within the study reaches).
- Absence of stream-adjacent roads within the riparian zone.
  - 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 review and approval by CMER.
- 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 required review and approval by CMER before inclusion in the study.
- Absence of recent major disturbance from:
  - debris torrents
  - livestock grazing that has significantly altered stream morphology or bank vegetation
  - other channel disturbance
- Committed landowner
  - Landowner must be willing to design the timber harvest unit to be consistent with the experimental design and be willing to maintain the reference site in an unmanaged condition for at least 3 years (and preferably longer).
  - Landowner must agree to harvest along both sides of the stream.
  - Timber harvest and related activities must comply with forest practices rules and have the maximum allowable volume removed during harvest.

Table 2.2. Summary of deviations from selection criteria in study sites of the Eastern Washington Riparian Shade and Temperature Effectiveness study.

Study Site	Selection Criteria Issues	Notes
All Available Shade Rule Sites		
Bacon	Tributary, CMZ	Seasonal tributary (dry during the entire study) enters at upper end of treatment reach; short CMZ (55 ft length by 18 ft width) in treatment reach
Clark	Roads	Active road on west side 130 ft from stream in treatment reach; abandoned skid road east side within 100 ft ; RMZ only harvest
Cole	CMZ, Channel Width	CMZ (650 ft length by 20 ft width) in treatment reach, dominated by hardwoods; channel width >15 ft.
Dry Canyon	Roads	Old skid road within inner zone on east side of reference and treatment reaches.
Floedelle	Roads	Road in inner zone, lower 250 ft of treatment reach on north side.
Long Alec	CMZ	Short CMZ (50 ft length by 13 ft width) in treatment reach ; RMZ only harvest
Lotze	Timber, Groundwater	Young forest regrowth in upland harvest block east side of treatment reach; small side seeps (<3 ft width) enter in reference reach.
Mill	Wetlands, Groundwater	Sidewall seeps in treatment reach
Moses	None	RMZ harvest only
NF Foundation	Wetlands	Seasonal seeps west side of reference; low density stand on east side uplands of treatment reach
Sanpoil	None	
Seco	None	
Sema 1	Tributaries, Flow	Discontinuous flows late summer in both reference and treatment reach; seasonal tributary enters in reference reach
Sema 2	Wetlands, Flow, Roads	Discontinuous flows late summer; new road crossing installed near middle of treatment reach; side seep enters west side treatment reach
SF Ahtanum	Tributaries, CMZ, Channel Width	low density upland stand on both sides treatment reach; basewall channel enter treatment reach on south side, contributes 1-2% of flow; short CMZ (75 ft length by 28 ft width) in treatment reach; channel width >15 ft.; RMZ only harvest
Tungsten	Roads	Road crossing at site center; abandoned road crossing middle of reference reach.

Table 2.2 (continued). Summary of issues associated with selection criteria during the establishment of study sites in the Eastern Washington Riparian Shade and Temperature Effectiveness study.

Study Site	Selection Criteria Issues	Notes
		Standard Rule Sites
Big Goosmus	Tributaries	Seasonal tributary north side of treatment reach (no surface flow observed entire study period)
Byers	Consistent timber	Uneven-aged forest stands in uplands of reference and treatment reach. RMZ only harvest
Dorchester	Wetlands, roads, groundwater	1/3 of reference reach bordered by shrub and hardwood; side seeps (moist all summer) north side of reference reach; road within 200 ft of channel on north side of reference reach
Dry	Channel Width	Channel width >15 ft
EF Cedar	Tributaries, CMZ, wetlands, groundwater, Channel Width	Tributary enters south side of reference, contributes 2% of flow; short CMZ (75 ft length by 28 ft width) in treatment reach; seeps in inner zone north side of treatment reach, outer zone north side wet area (75 ft); groundwater emerges from basewall in reference reach; channel width >15 ft
EF Cedar Trib	Roads	Stream adjacent road on north side within inner zone of reference reach; road crosses at site center; abandoned skid rd 0-300 ft length in inner zone north side of treatment reach
Heel	Tributaries, wetlands, roads	Streams/seeps enter on east side of treatment reach, contributing 1-2% of flow; stream enters east side of reference reach, contributing 5-10% of flow to study stream; abandoned skid road inner zone east side of treatment reach.
Little Goosmus	Flow, groundwater	Small side seeps at -500 ft in treatment reach; discontinuous flows in some years
Middle	Wetlands, roads	Seep areas on north side of treatment reach buffered with additional leave trees; road within inner zone for 50 ft on north side reference reach; outer zone road on north side in treatment reach for 100 ft.; RMZ only harvest
Prouty	Flow, roads	Discontinuous flows late summer; road within 200 ft north side of treatment reach.
Sema 3	None	
Sema 4	Tributaries, wetlands	Yarding corridor crosses stream near site center; small tributary enters reference reach just upstream of site center, contributes 5% of flow; side seeps on east side of reference reach for 75 ft length.
SF Dairy	Roads	Skid road in inner zone of treatment reach on south side; young regeneration stand in uplands south side of treatment reach.
Sylvus	Timber	Regeneration stand (clear-cut) in uplands on west side of upper reference reach, RMZ out to 170 ft has mature timber.

RMZ = Riparian management zone; CMZ = channel migration zone

2.2 Study Areas

The study was conducted at 30 sites in eastern Washington (Figure 2.1). Sites were situated along second- to fourth-order streams with harvest-regenerated or fire-regenerated forests between 65 and 110 years old on State owned and managed forestlands (18 sites), or private industrial forests (12 sites).

The study area is influenced by inland northwest climate patterns resulting in wet, cold winters and warm, dry summers. Mean annual precipitation across the study basins ranges from about 12 to 36 inches per year, of which approximately 75% falls between October and April. Snow fall accounts for nearly 50% to 70% of the mean annual precipitation. Forest cover is dominated by second growth western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), Engelmann spruce (*Picea engelmannii*), and Douglas-fir (*Pseudotsuga menziesii*). Hardwood tree species encountered at the study sites include three species of alder (*Alnus rubra, Alnus rhombifolia, Alnus sinuata*), black cottonwood (*Populus trichocarpa*), quaking aspen (*Populus tremuloides*), and birch (*Betula papyrifera*). Miscellaneous hardwood shrubs, including vine maple (*Acer circinatum*), Douglas maple (*Acer glabrum* var. *douglasii*), and red-osier dogwood (*Cornus stolonifera*), were never dominant in the stands and seldom reached diameters greater than 4 inches at breast height. Hardwoods are a minor component in all of the study sites. All sites had dense canopies over the stream channel. Prior to harvest treatments, canopy closure measurements ranged from 89% to 97%, with a mean of 93%.

Elevation for the study sites ranged from 1,872 to 4,762 feet above sea level (as measured at site center, mean = 3,346 ft). The study sites were representative across the range of elevations for both shade rules. Elevation drop within individual study sites ranged from 55 to 334 ft (mean = 156 ft) and study site channel gradients ranged from 3 to 17% (mean = 8.0 %). Bankfull widths ranged from 3.5 ft to 22 ft (mean = 9.7 ft). Gravel and cobble dominated channel beds in all study sites. The stream reaches had low baseflow discharge varying from less than <0.1 cfs to a high of 4.4 cfs. While all of the streams were perennial, sections with discontinuous flow were observed during summer dry periods in 4 of the 30 study sites (Table 2.3). Basin areas at the downstream ends of the study sites ranged from 316 to 11,814 acres. Appendix 1 and Appendix 2 provide reach specific summaries of channel characteristics and riparian conditions for each study site.

2.3 Study Design

Each study site consisted of a control (reference) reach with no harvest activity upstream of an impact (treatment) reach where the riparian harvest was applied (Figure 2.2). The treatment reach was located immediately downstream of the reference reach and harvested using one of the two (randomly assigned) riparian prescriptions. The reference reach had no active timber harvest or road construction within 200 feet of the stream during the course of the study. The length of each treatment and reference pair was 2,000 ft (the reference and treatment reach were each 1,000 ft).

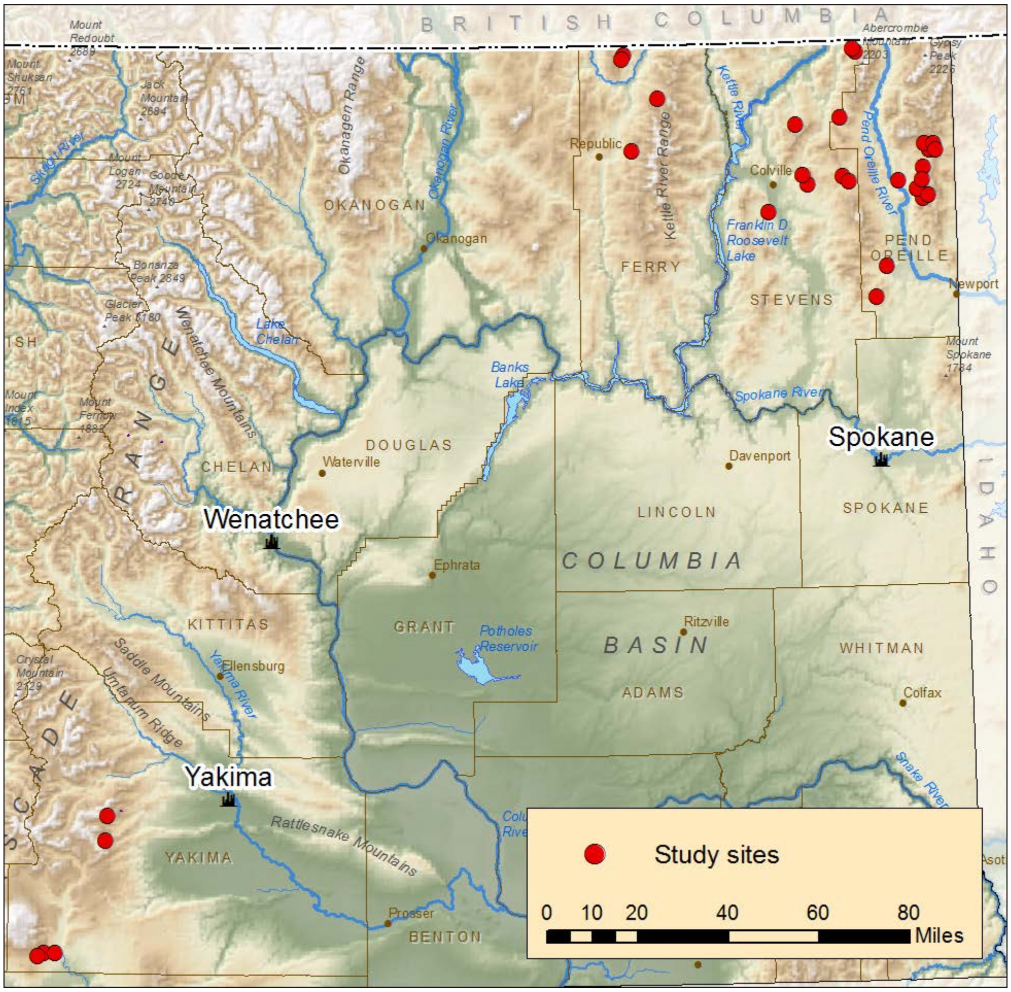

Figure 2.1. Location of 30 sites examined in the Eastern Washington Shade and Temperature Effectiveness Study.

Table 2.3. Characteristics of study sites included in the Eastern Washington Shade and Temperature Effectiveness study.

Study Site	Mean Bankfull Width (ft)	Basin Area (ac)	Mean Channel Gradient (%)	Elevation (ft)	Other Site Characteristics
All Available Shade Rule					
Bacon	13.5	2,614	13.6	3,234	small seasonal channel enters just below site center north side; no surface flow during sample periods
Clark	5.9	705	3.7	3,292	discontinuous flow for 200 ft of treatment reach in 2009 sample period only
Cole	16.0	11,814	3.8	1,872	narrow CMZ (15-20 feet wide) in treatment reach
Dry Canyon	6.1	2,426	4.1	2,146	
Floedelle	9.0	2,855	4.2	3,356	
Long Alec	9.5	2,199	6.4	4,133	
Lotze	13.1	1,809	5.3	3,414	
Mill	5.3	273	13.4	3,470	potential groundwater discharge at gradient jump in treatment reach
Moses	7.1	880	7.5	3,025	
NF Foundation	12.3	1,619	10.2	4,726	
Sanpoil	5.4	2,387	5.4	3,333	
Seco	7.9	1,318	5.7	3,466	
Sema 1	4.7	234	6.5	3,473	flow infiltrates in late summer in upper reference reach; flow submerged beneath boulders for 50m in treatment reach; small seasonal stream enters from west at midpoint in reference reach
Sema 2	6.3	333	9.0	3,490	discontinuous flows observed most seasons in vicinity of site center at steep boulder inflection; side seep near midpoint in treatment reach
SF Ahtanum	20.2	2,478	9.8	4,470	small stream enters south side of upper 100 feet below site center in treatment reach, contributes 1-2% of flow
Tungsten	3.5	316	7.9	3,264	
Standard Rule					
Big Goosmus	8.2	1,129	9.7	3,148	small seasonal channel enters just below site center north side
Byers	11.6	1,337	5.4	3,398	
Dorchester	9.9	2,082	5.0	2,173	
Dry	22.5	1,641	13.8	3,598	
EF Cedar	18.3	3,686	8.0	3,200	tributary enters from south side near midpoint of reference reach, contributes 2-3% of flow to study stream.
EF Cedar Trib	8.0	757	11.5	3,185	
Heel	5.2	298	10.3	3,844	tributary enters east side reference reach at +100m, contributes 10% of flow to study stream, side seeps enter east side in treatment reach
Little Goosmus	5.6	933	9.9	3,280	short intermittent segment (30 – 75 feet) in upper treatment reach some years.
Middle	11.5	2,251	10.3	3,744	side seeps on both banks of treatment reach
Prouty	8.8	349	17.4	4,048	discontinuous flow in late summer in treatment reach
Sema 3	7.9	922	2.4	3,457	short, steep boulder step inflection in reference reach
Sema 4	5.2	429	7.5	3,444	small tributary enters west side of reference reach just upstream of site center, contributes 5% of flow; seeps on east side reference reach
SF Dairy	13.6	2,009	6.8	2,305	split channel flow for short distances in reference and treatment reaches
Sylvus	8.6	1,789	5.4	3,312	

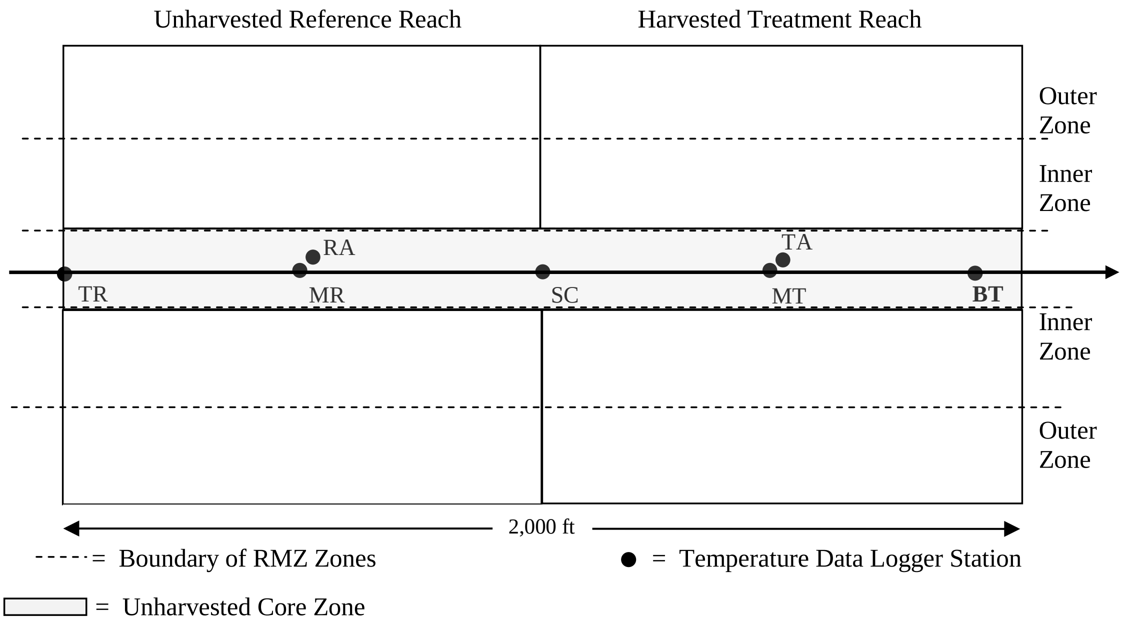

Figure 2.2. Schematic of a study site design used in Shade and Temperature Study. Stream temperature data loggers were placed starting upstream at Stations TR (Top Reference), MR (Middle Reference), SC (Site Center), MT (Middle Treatment) and BT (Bottom Treatment). Air temperature data loggers were placed at midpoint of the reference reach (RA) and midpoint of the treatment reach (TA). Forest stand data were collected in 12 strip plots (20 ft x 120 ft oriented perpendicular to the axis of the valley. Three plots were situated on both sides of the stream in each reach at 250, 500, and 750 ft upstream from the bottom of each reach.

In order to consistently relocate sample units throughout the duration of the study, a standard procedure for installing, referencing, and monumenting site and reach boundaries and sample locations for canopy, stand, and temperature measures was adhered to throughout the duration of the study. Wooden stakes were installed on both sides of channel at 75-ft increments along the entire study site, which consisted of the 1,000 ft downstream treatment reach and 1,000 ft upstream reference reach. Pink flagging was securely placed on woody vegetation near the wooden stakes for ease of relocation. The sampling station was identified on each ribbon (i.e. -500 ft is situated 500 ft downstream of site center). The upstream and downstream end of each site and individual reaches within the site were plainly and permanently marked near the channel margins on both sides of the stream. A general location map was prepared using Washington Department of Natural Resources (DNR) Base Maps. Each site was located on air photos, with the location of the site center and reach boundaries identified. Latitude and longitude coordinates were determined through use of a GPS unit.

2.4 Harvest Treatments

Sites were harvested consistent with the Washington State Forest Practices Rules (WAC 222-30-022), which require riparian buffers along fish-bearing streams to protect stream temperature, provide future large wood for streams, and retain other ecological functions. The two prescription treatments studied include the rules for harvesting along small (<15 ft wide) fish-bearing streams, the Standard Rule (SR) and the All Available Shade Rule (ASR). The SR includes shade retention requirements that differ depending on elevation. The ASR, which is applied when harvesting within the bull trout habitat overlay (BTO) (WAC 222-16), requires that all available shade must be retained within 75 feet of bankfull width or CMZ, whichever is greater, of fish-bearing streams (WAC 222-30-040).

Study sites were initially paired (two riparian prescriptions) based on similar elevations and stream width. Riparian prescriptions were randomly assigned within each pair except within known bull trout spawning areas. In these cases, the ASR was non-randomly selected in order to be protective of these sensitive areas.

Treatment site boundaries were marked within the riparian management zone (RMZ) following forest practices rules for Type F (fish-bearing) waters (WAC 222-30-022). The RMZ consists of three zones: The core zone is nearest to the edge of the stream and extends out 30 feet horizontally from the bankfull edge or outer edge of the channel migration zone (CMZ), whichever is greater. Five treatment reaches in this study had narrow CMZs (15-25 ft) for at least part of their length. The inner zone is situated immediately outside of the core zone. For streams with a bankfull width of less than or equal to 15 feet wide, the inner zone width is 45 feet wide (versus 70 feet for streams with bankfull widths greater than 15 feet wide). For this study, only small stream prescriptions were applied and assessed (with inner zone widths of 45 feet), even though four sites had bankfull widths ranging from 16.0 to 22.5 ft. The outer zone of the RMZ is the zone furthest from the water and its width varies according to stream width and site class for the land. For this study all treatment site outer zone widths were established according to rules for streams with bankfull widths of less than or equal to 15 feet wide. The specific site class (a measure of site productivity) at each treatment site would vary the outer zone width from 0 to 55 feet wide (Table 2.4).

No harvest was allowed in the core zone except for the purpose of road stream crossings (WAC 222-24-030, 222-24-050), or the creation and use of yarding corridors (WAC 222-30-060(1)), which occurred downstream of site center in two sites (Sema 2 and Sema 4). Inner and outer zone harvest opportunities for all treatment sites were determined according to forest practices rules (WAC 222-30-022). In order to ensure standard and consistent implementation of RMZ prescriptions, all treatment reaches were delineated and individual trees marked for harvest by the same field crew so that RMZ prescriptions would be interpreted consistently and sites would be laid out to the fullest extent of the forest practices rules. The treatment reach of each site was prepared for harvest as follows.

The core, inner, and outer zone boundaries of the treatment reach and a 200-ft wide no entry zone in the reference reach was first marked in the field. At site center, the division between the treatment and reference reach was clearly marked for the entire width of the RMZ to denote cutting boundaries. After boundary marking, all trees within the inner zone of the treatment reach were tallied by species and diameter at breast height (dbh). Each tree was individually marked with a unique identification number. The tally data included identification of individual trees that provided shade to the stream and/or leaned toward the stream. After the reach was tallied, regulations were consulted regarding leave tree requirements and trees were marked for harvest.

Harvest was permitted in the inner zone if the existing basal area for conifer and hardwood trees greater than 6 inches dbh was sufficient for the specific site index of the stand, ranging from 110 ft^2 / acre to 150 ft^2 / acre for low to high site indexes, respectively. If the basal area targets were met, the harvest treatment was to leave at least 50 trees per acre and a basal area ranging from 70 to 110 square feet per acre dependent upon site index. The appropriate prescription/shade rule was applied in addition to, and often required additional constraints to, the underlying riparian harvest prescriptions. The trees to be left had to include:

- The 21 largest trees per acre; and
- An additional 29 trees per acre that are 10-inch dbh or greater based on the priority order of:
    - Trees that provide shade to water;
    - Trees that lean toward the water;
    - Trees of the preferred species, as defined in WAC 222-16-010; or
    - Trees that are evenly distributed across the inner zone.

At some sites, more than 50 trees per acre were determined to be left in order to meet the minimum basal area for the site index (Table 2.4). Two sites (Cole and Long Alec) did not have sufficient existing basal area to harvest down to 50 trees per acre, but exhibited high stand density greater than 120 trees per acre. These sites were allowed to be harvested leaving a minimum of 120 trees per acre of which 50 were the largest and an additional 70 were greater than 6-inch dbh (WAC 222-30-022). For the outer zone, 15 dominant or codominant trees per acre were required to be left after harvest, thus the actual number of leave trees marked in the outer zone would vary dependent upon the width (based on site class) of the outer zone at each treatment site (Table 2.4).

After determining available trees for harvest in the inner zone based on basal area and leave tree requirements, a determination of adequate shade requirements to maintain water temperature (WAC 222-30-040) was made for each site according to the selected shade rule. For the ASR, all trees providing shade were retained within 75 feet from the edge of the bankfull width or outer edge of the CMZ (whichever is greater)(WAC 222-30-040(1)); therefore, each inner zone tree's contribution to canopy closure was determined at the time that individual trees were tallied. One crew member used the densiometer to determine which trees contributed to canopy closure while viewing the trees from the stream, while another crew member was responsible for measuring, marking, and tallying individual tree data. The crew member surveying for canopy closure relayed their specific tree data to the marking crew so that canopy contribution could be determined as individual trees were tallied.

For the SR prescription, the potential harvest of trees from the inner zone could not reduce canopy closure below the minimum derived from the nomograph (WAC 222-30-040(2)) in Step 4 of Forest Practice Board Manual, Section 1. The nomographs depict canopy cover requirements based on elevation and water quality stream classification (WAC 173-201A) existing prior to 2003[1] . In order to reduce variability in the prescriptions applied to the SR sites, the 18 °C nomograph was used for all study streams regardless of the actual temperature criteria assigned in the state standards.

After determining each potential inner zone tree's contribution to shade in the ASR sites, it was determined that harvest opportunities were greatly reduced in the inner zone of those sites as compared to the SR sites. In the SR sites, it was estimated that even under the maximum allowed harvest based on basal area and leave tree requirements, post-harvest canopy closure levels would not be reduced below the minimum requirements from the nomograph. Treatment in the uplands outside of the RMZ varied amongst sites between uneven age harvest, even age harvest, and no harvest (Table 2.4).

Following timber harvest, follow-up site surveys were conducted in the treatment reach to ensure that all trees marked for allowable harvest in the RMZ were harvested or at least felled. At some sites and for a variety of reasons, not all of the trees marked for harvest were removed. In these situations, a felling crew revisited the site to drop the trees that were inadvertently left standing during the initial harvest. The crew included research field staff accompanying a contractor timber faller to confirm the dropping of all standing trees that were marked for harvest. Some level of additional felling was required on 15 sites harvested in order to ensure consistency in implementation of the harvest prescriptions.

2.5 Data Collection

2.5.1 Sampling Periods

Due to staggered study entry and harvest schedules, data collection of temperature, canopy and shade, forest stand, and channel conditions occurred from 2003-2010. Some sites had prolonged pre-harvest monitoring. Seven sites had up to four years pre-harvest temperature data with only two years post-harvest data. Nine sites had three years pre-harvest data and one site had only one year pre-harvest data. The remaining 13 sites had two years pre-harvest data. Following harvest treatments, all 30 sites had at least two years post-harvest temperature data collection, although 21 of the 30 sites had at least three years post-harvest monitoring. Fourteen of the sites had up to four years post monitoring. Because of this imbalance, we assigned data collected at each site during each year to a specific sample period. Sample periods are defined as the season that data was collected relative to its harvest, where Post_1 = first sample season following harvest, Post_2 = second sample season following harvest, and so on. Pre-harvest sample periods are defined as Pre_1 = sample season immediately prior to harvest, Pre_2 = sampling conducted two sample seasons prior to harvest, and so on. Data collection included twice hourly stream and air temperature data during each sample period. Canopy, shade, riparian, and channel data were collected during the first year pre-harvest and the first year post-harvest. Table 2.5 provides the correspondence among calendar year, harvest, and data collected at each study site.

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[1] In 2003, substantial changes were made to the State temperature criteria. The shade nomographs in the Forest Practices Board manual have not been updated to correspond with state standards.

Table 2.4. Summary of harvest strategies for the 30 study sites treated in the Eastern Washington Shade and Temperature Effectiveness Study. E= even age harvest; U = uneven age harvest; and N = no upland harvest (riparian management zone harvest only). Canopy closure requirement indicates the amount of canopy closure that must be maintained following harvest and references the WAC 222-30-040(2) .

Study Site	**Site Class**	**RMZ Width (ft)**	**BA Retention Required Inner Zone (ft ^{2} / acre)**	**Outer Zone Width (ft)**	**Upland Harvest Strategy**	**Canopy Closure Requirement (%)Required (%)**	**Comments**
All Available Shade Rule							
Bacon	1	130	70	55	E	Retain All Shade	extra leave trees on north side to buffer seasonal stream
Clark	3	90	90	15	N		RMZ only harvest; re-entry into seed tree regeneration stand on east side of treatment reach
Cole	2	110	90	35	U		Low basal area/high density stand on east side of treatment reach
Dry Canyon	3	90	90	15	U		
Floedelle	2	110	90	35	N		RMZ only harvest
Long Alec	4	75	90	0	E, N		RMZ-only harvest on south side, Low basal area/high density stand, thinning prescription in RMZ on north side
Lotze	2	110	70	35	E		
Mill trib	2	110	90	35	U		extra leave trees buffer side seeps
Moses	3	90	90	15	N		RMZ-only harvest
NF Foundation	2	110	70	35	U		stand subject to insect damage mortality;
Sanpoil	4	75	90	0	U		
Seco	3	90	90	15	U		
Sema 1	2	110	110	35	U		
Sema 2	2	110	110	35	U		
SF Ahtanum	4	75	70	0	N		scattered post-harvest insect mortality through site; RMZ-only harvest
Tungsten	2	110	90	35	E		
Standard Rule							
Big Goosmus	3	90	70	15	U	39	extra leave trees north side to buffer regulatory type Np trib; mortality post-treatment period in reference reach
Byers	3	90	90	15	N	32	RMZ-only harvest
Dorchester	2	110	90	35	U	84	scattered post-harvest windthrow in inner zone south side of treatment reach
Dry	2	110	70	35	E	19	decadent stand susceptible to increased mortality from insect damage
EF Cedar	2	110	90	35	U	40	
EF Cedar trib	2	110	90	35	U	39	extra leave trees inner zone to meet basal area requirement.
Heel	2	110	110	35	E	2	extra leave trees to buffer seeps and meet basal area target in inner zone
Little Goosmus	3	90	70	15	U	36	6 trees removed illegally from reference reach RMZ and core zone of treatment reach post-treatment
Middle	3	90	90	15	U, N	13	RMZ-only harvest on north side; Seep areas on north side of treatment reach buffered with additional leave trees
Prouty	2	110	90	35	E, N	1	RMZ-only harvest on north side
Sema 3	2	110	110	35	U	25	narrow band of hardwood shrubs dominate core immediate streamside zone
Sema 4	2	110	110	35	U	26	yarding corridor crosses stream in treatment reach
SF Dairy	1	130	70	55	U, E	79	limited harvest in 25 yr old stand south side upland
Sylvus	2	110	90	35	E	34	extensive post-harvest windthrow

2.5.2 Stream and Air Temperature

Stream temperature data were collected at 30-minute intervals between 1 July and 15 September for a total of 77 days each year a site was investigated. Continuously recording temperature data loggers (Optic Stowaway Tidbit submersible data loggers, Onset Computer Corporation, Bourne, Massachusetts) were deployed at seven stations (5 instream, 2 air) in each study site. The accuracy of the Tidbit data loggers has been established as ±0.2°C by the manufacturer. Calibration of temperature loggers were validated in a controlled temperature ice water bath prior to deployment each season. Data loggers that exhibited departures from factory specifications were not used in the field.

Data loggers were placed in the stream at 500-ft intervals between the upper boundary of the reference reach and the lower boundary of the treatment reach (Figure 2.2). Data loggers were placed at depth of 0.3 – 1.0 ft depth in areas with well mixed, laminar flow. Stream temperature data loggers were placed in protective coverings of either perforated PVC or galvanized pipe, weighted, and deployed in shaded locations where stream flow was relatively constant at reliable summer depth and within a well-mixed water column. Air temperature dataloggers were placed at the midpoint of the reference reach (Station RA) and at the midpoint of the treatment reach (Station TA), suspended 4 to 6 ft above the stream channel and shaded by a Styrofoam cup.

Temperature data were recorded and computed separately for each data logger station during each sample season it was monitored. The daily mean (DMEAN), maximum (DMAX), and minimum (DMIN) stream and air temperature for each station were derived from 30-minute interval data recorded between July 1 and September 15 during all study years for each data logger. Diurnal fluctuation (DFLUX) was calculated from the daily statistics. The DFLUX is the daily maximum minus the daily minimum. The average DMAX, DMIN, and DFLUX were then computed separately for each season of study, referred to as the ADMAX, ADMIN, and ADFLUX.

We applied a quality assessment and quality control protocol to identify erroneous temperature data using a post-deployment accuracy check and field notes for the 30 sites. Exploratory graphical analyses were conducted to determine if any temperature measurements were clear outliers due to logger malfunction or discontinuous flow conditions. Data that were apparent anomalies due to malfunctioning loggers was excluded. We also used field notes and temperature plots to identify periods when the stream was dry or when data loggers were exposed to air. Daily temperature readings were screened to ensure that data reflected fully submerged temperature data loggers and that temperature patterns did not reflect peculiar increases or decreases associated with dewatering or erroneous measurements. The DFLUX of water temperature at the top, middle, and lower thermograph sites was plotted for each day and compared with a similar line plot of the DFLUX of air temperature. The temperature pattern at each logger station was examined for anomalies in daily fluctuation in relationship to other stations in the site. Daily temperature readings that exhibited increases and decreases in DMAX, DMIN, and DFLUX stream temperature that were not reflected in other probes during the same year were excluded from the analysis. A total of 4 sites were determined to have temperature anomalies during a portion of the days in one or more seasons. Temperature data during the days of these anomalies were excluded from further analysis with no attempt to impute missing data values. Results of the screening process are provided in Appendix 3.

2.5.3 Shade, Canopy Closure, and Solar Attenuation

Stream canopy closure and shade were quantified at 75-ft intervals within each reach using a hand-held densiometer (for canopy closure measurements) and a self-leveling fisheye lens digital camera (for shade measurements), respectively. Measurements were positioned in the center of the wetted channel. A measuring tape was stretched tightly across the channel between the pair of monument stakes. The distance from the right bank stake to the measurement position was recorded to facilitate relocating measurement stations along the study site in subsequent sample years. Canopy closure and shade values at all sites were measured once during the pre-harvest period in either the first or second year the site was established. Canopy closure was measured twice at four sites during the pre-harvest period (Clark, Cole, Floedelle, Moses) due to a four-year lag between the first measurement and RMZ harvest at these sites. All sites were measured twice for shade and canopy closure during the post-harvest period (Table 2.5).

Densiometer measurements and fish-eye photographs were taken three feet above the water level. An effort was made to take photos and densiometer measurements when the sun would not be in the picture. Densiometer measurements were used to compute canopy closure following methods described under Section 1 of the Forest Practice Board Manual. At each station, four densiometer readings were taken from the center of the stream while facing upstream, downstream, and towards the right and left banks. The surveyor assumed four equally spaced dots in each square of the spherical densiometer. The mean of the four dot counts per plot not covered by canopy was used to determine the percent canopy opening for the station. The mean number of dots was multiplied by 1.04 and the result was subtracted from 100 to obtain the percent of canopy closure. To estimate the reach canopy closure, the canopy closure calculations were repeated for all stations and a reach mean was calculated. Shade values were calculated from the photographs using HemiView™ 2.1 software (Delta-*T* Devices, Cambridge, UK) as daily mean percentage of pixels occupied by canopy within the portion of photograph where the sun path crosses the sky during the temperature measurement period of July 1 through September 15.

2.5.3.1 Evaluation of Upland Trees to Shade and Canopy Contribution

Although the focus of stream shade protection lies within 75 ft of the stream according to forest practices rules, trees outside of the RMZ (which ranges from 75 to 130 feet from the stream edge depending upon Site Class as described in Section 2.4 *Harvest Treatments*) could potentially influence shade in some situations and thus confound the temperature effects comparisons of the two RMZ prescription / shade rules. Post-harvest site inspections and follow-up timber felling ensured that all RMZ treatments were harvested (or trees at least felled) to the fullest extent allowable under the Forest Practice Rules. However, upland harvest treatments (timber harvest outside of the RMZ area) varied among the sites. Six sites included no harvest in the uplands on either side of the stream (RMZ-only harvest), whereas two sites included RMZ-only harvest on the north side of the stream. Upland tree retention levels varied in the 24 sites where upland harvest occurred on at least one side of the stream.

Table 2.5. Correspondence among calendar year, harvest of treatment reach, and data collected at each study site.

Study Site	2003	2004	2005	2006	2007	2008	2009	2010
				All Available Shade Rule				
Bacon	C,T,S	R,T,	**H**	C,R,T,S,	T	T	T	C,T
Clark	T	C,T,S,	R		T,	C,T,**H**	C,R,T,S	C,T
Cole	S	C,R,T	F,T			C,T,**H**	C,R,T,S	C,T
Dry Canyon	C,T,S	T,R	**H**	C,T,S	T	T	R,T	C,T
Floedelle		T	C,R,T,S	T	T	**C, H**	C,R,T,S	C,T
Long Alec	C,T,S	T		R	T	**H**,C,T,S	R,T	C,T
Lotze	C,T	T,R,S			T,**H**	C,T,S	R,T	C,T
Mill	C,R,T,S	T	**H**	C,T,S	T	T	R,T	C,T
Moses	C,T,S	T	R		T	**C,H**,T	C,R,T,S	C,T
NF Foundation	C,T,S	T	T	T,R	T,**H**	C,T,S	R,T	C,T
Sanpoil	C,T	R,T		S	T,**H**	C,T,S	R,T	C,T
Seco		T,S	C,R,T	**H**	C,T,S	T	R,T	C,T
Sema 1		T	C,R,T,S		T	T,**H**	C,R,T,S	C,T
Sema 2		T	C,R,T,S		T	T,**H**	C,R,T,S	C,T
SF Ahtanum	C,T,S	R,T			T	**H**,C,T,S	R,T	C,T
Tungsten				C,R,T,S	**H**,C,T,S	T	R,T	C,T
				Standard Rule				
Big Goosmus	C,T	R,T			**H**,T	C,T	R,T	C,T
Byers	C,T	T		L	R,T	T,**H**	C,R,T	C,T
Dorchester	C,T	R,T		T,**H**	C,T	T	C,R,T	C,T
Dry	C,T	R,T	**H**	C,R,T	T	T	T	C,T
EF Cedar	C,T	R,T	**H**	T,**H**	C,T	T	R,T	C,T
EF Cedar Trib	C,T	R,T		T,**H**	T	C,T	R,T	C,T
Heel		T	C,R,T		T,**H**	C,T	R,T	C,T
Little Goosmus	C,T	R,T	T	T	T,**H**	C,T	R,T	C,T
Middle		C,T	R,T	**H**	T	T,**H**	C,R,T	C,T
Prouty	C,T	R,T		**H**	T,**H**	C,T	R,T	C,T
Sema 3		T	C,R,T		T,**H**	T,**H**	C,T	C,R,T
Sema 4		T	C,R,T	**H**	T	T	C,R,T	C,T
SF Dairy	C,T	R,T		**H**	C,T	T	R,T	C,T
Sylvus	C,T	R,T	**H**	T	**H**,C,T	T	C,R,T	C,T

C = canopy and shade; T = temperature data loggers; R= riparian strip plots; H = timber harvest in treatment reach completed (including follow up felling); S=solar

Canopy and shade measurements preceded harvest for sites where a C and H are indicated for the same year. This occurred in sites where up to four years elapsed between the original pre-harvest canopy sampling and harvest treatment.

The four sites with two separate harvest periods (H) indicate that follow-up tree felling was conducted to drop trees that were designated for harvest but inadvertently left during the initial harvest. Post-treatment temperature analysis began after the follow-up tree felling was completed.

The influence of variable upland harvest treatments on stream shading following the RMZ treatment was investigated on 25 sites during 2010. All six of the two-sided RMZ-only harvest sites, the two one-sided RMZ-only harvest sites, and 17 of the sites that had standard operational upland harvests were investigated. Trees retained outside of the RMZ following harvest treatment that were visible from a sample of the post-harvest stream shading measurement stations were identified as follows. At each of the 25 study sites, five equally spaced stations in the treatment reach were sampled. The surveyor stood at the same location the hemispherical photographs were taken during the post-harvest sampling with the post-harvest photo in hand. Any visible canopy associated with trees situated outside of the RMZ was identified as an upland tree. Each of the individual upland trees were marked on the photo. The contribution of retained upland trees to stream shading at selected sample points was calculated from the re-analysis of the post-harvest hemispherical photographs using the HemiView Software. All of the upland trees visible from the sample station were identified on the photograph. Each upland tree was masked as visible sky on the hemiview photo for each station using photo editing software. The shade values for the edited hemiview photo were recalculated. Shade values with upland trees removed were compared to the shade values determined during the initial post-harvest shade sampling to estimate upland tree shade contribution.

2.5.3.2 Solar Radiation

McGreer et al. (2011) measured the amount of solar radiation reaching the stream using sets of Eppley pyranometers at each of the ASR study sites. 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 at five equally spaced locations in each reach. 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.

2.5.4 Forest Stand Conditions

Forest stand data were collected in 12 strip plots oriented perpendicular to the axis of the valley. Three plots were situated on both sides of the stream in each reach at 250, 500, and 750 feet upstream from the bottom of each reach. Each plot was 20 feet wide and extended out 130 feet horizontal distance from the channel edge. For each strip plot, a stake was positioned at a point near the bankfull channel edge. The location of the plot was defined by extending a nylon tape along the designated azimuth attached to a stake situated adjacent to the channel. Monuments were installed along the center line of each plot to enable plot relocation for post-harvest measurements. All standing trees equal or greater than 6-inch dbh were tallied. Species, dbh (to nearest inch), tree height, height to live crown, and distance from stream bank were recorded for each tallied tree. Standing dead trees were included in the tally but identified as such. Data were collected both pre-harvest and post-harvest. Windthrow, tree mortality, and trees that were felled as part of the harvest were determined in all plots during the post-harvest measurements.

2.5.5 Channel and Basin Characteristics

Channel data were collected at 75-ft intervals at the start of the study within each reach. Data included wetted width, bankfull width, stream gradient, and channel substrate. Visual estimate of the two dominant substrate size classes were collected at each 75-ft interval. The mean of each metric was computed separately for each reach. Site elevation, reach azimuth, and watershed area were determined from a geographic information system (GIS). Study site elevations were determined from examining GPS-determined logger locations against 10-m digital elevation models. Reach azimuth was calculated using GPS locations of the upstream and downstream loggers. We ‘‘folded’’ (rendered equivalent) the azimuth north to south by subtracting 180 degrees (Bartholow 1989) then folded the azimuth east to west by subtracting an additional 90 degrees. The result presents a 0–90° deviation from either east or west. Watershed area was calculated at the downstream end of the reference reach and at the downstream end of the treatment reach. Stream flow was calculated from measures of velocity and cross-section areas at three locations: (1) the upstream end of the reference reach; (2) the boundary between the reference and treatment reaches; and (3) the lower end of the treatment reach during summer base flow conditions (early September) in all years of the study.

2.6 Analytical Methods

We examined shade and canopy closure, stream temperature, riparian, and channel data with several analyses. The first analysis was constructed to make direct comparison of the effectiveness of the two prescriptions at achieving the intended level of shade protection. We then assessed the association among the changes in riparian stand attributes and post-harvest shade reductions after harvesting. The next analysis examined daily post-harvest stream temperature response at each site individually. Daily post-harvest stream temperature responses were then averaged for each sample reach and sampled period following harvest to compare differences between no-harvest, ASR harvest, and SR harvest prescriptions. And lastly, we conducted correlation analysis to examine the relationship of several riparian stand metrics, channel and basin channel characteristics, regional climate data, and post-harvest stream temperature response. In all analyses, we examined dependent variables to determine if the assumptions of the statistical tests were violated (normality, constant variance, independence) using histograms and residual plots using the statistical packages R (R Development Core Team 2009, Ripley 2001) and NCSS 2007 (Hintze 2007).

2.6.1 Canopy Closure and Shade Analysis

Reach-specific mean measurements from data gathered at stations placed at 75-ft increments were used to assess canopy closure and shade. We used a paired *t*-test to evaluate differences in pre-harvest canopy and shade levels between reference and treatment reaches. A two sample *t*-test was used to compare the pre-harvest treatment reach canopy and shade values of the ASR and SR sites.

2.6.1.1 Harvest Impacts on Canopy and Shade

Post-harvest changes in shade and canopy closure were examined by computing the differences between the measured values in the reference and treatment reaches (ShD = treatment reach mean canopy closure or shade – reference reach mean canopy closure or shade). This approach was taken due to the possibility that the canopy conditions and shading could change in the entire study site as a whole due to factors not related to the harvest (e.g., insect or disease infestation, windthrow, delayed timing between pre-harvest measurements and harvest, observation conditions, conditions of understory shrub canopy leaf out, observer error). The pre-harvest differences between reference and treatment reaches were then compared to post-harvest differences to determine a treatment effect. If the harvest prescription has no effect on canopy closure, then it is assumed that, for a study site, the difference between reference and treatment reaches pre-harvest (ShD_{Pre}) would be the same as the difference post-harvest (ShD_{Pst}).

If we define the effect of the prescription on the treatment reach relative to the upstream reference reach, then the dependent variable used to measure the effect of the prescription is:

$$ShE_i = ShD_{Pre\ i} - ShD_{Pst\ i}$$

where the subscript *i* refers to an individual study site. We can then calculate the mean effect ($Sh\bar{E}$) for all streams in the harvest prescription. If $Sh\bar{E}$ for shade and/or canopy closure is significantly greater than zero, than we would conclude that the harvest prescription has had no effect or a positive effect on canopy closure. If the mean effect is significantly less than 0, there has been a decrease in canopy closure in the downstream reach with respect to what was seen pre-harvest. The observations tested are the differences in canopy closure between the upstream and downstream reaches of a stream. Given there are no direct mechanisms for riparian harvest to increase shade and canopy closure in the short-term, we were concerned primarily about decreases in canopy closure or effective shading. Because we are concerned only about mean effects less than 0 for either harvest prescription, we test if $Sh\bar{E}$ is significantly greater than zero with a one sample *t*-test using a one-sided hypothesis for each harvest prescription separately and both harvest prescriptions combined. A two-sample *t*-test was used to test for significant differences of $Sh\bar{E}$ between the two harvest prescriptions. A two-sample *t*-test was used to examine if the shade contribution of retained upland trees following harvest differed between the RMZ-only harvest and the standard operational upland harvest.

2.6.1.2 Relationship among Riparian Stand Changes and Shade Impacts

Descriptive variables from the riparian stand plots included

- Tree Density (TD, trees/acre),
- Quadratic mean diameter (QMD)
- Basal area (BA, ft^2/ac)
- Mean tree height
- Mean crown ratio

All of the preceding metrics were computed for live trees equal to or greater than 6 inches diameter at breast height (DBH) separately for the treatment and reference reaches during both the pre-harvest and post-harvest period. We obtained reach specific site values for these variables by calculating mean values for the 6 strip plots located in each reach. Riparian stand metrics were computed for the core (0 – 30 feet from stream bank), inner (30 – 75 feet from stream bank), and outer zone (75 – 130 feet from stream bank) separately. Both pre-harvest and post-harvest stand conditions were summarized for the reference and treatment reach of each study sites. Changes to riparian descriptive variables were computed for each reach separately.

To verify the site selection criteria that each study site contained a relatively consistent stand of timber with sufficient basal area to meet the minimum requirements for commercial harvest under the forest practices rules, we used a paired *t*-test to evaluate pre-harvest differences between reference and treatment reaches. A two sample *t*-test was used to test for differences of pre-harvest stand conditions in treatment reaches between the ASR and SR sites.

We conducted correlation analysis between the post-harvest change in shade values and the descriptive riparian and channel variables to examine possible factors that may control harvest related reductions in shade. Specifically, we examined relationships between the change of treatment reach riparian attributes (trees per acre, basal area per acre, tree height, tree diameter channel gradient [both absolute and reach specific proportional change]) and the post-harvest change in treatment reach shade values. We also examined the relationship between the post-harvest changes of the aforementioned stand metrics and changes in incoming radiation values provided from the companion solar study (McGreer et al. 2011). A separate correlation matrix was prepared describing the relationships among channel width, channel azimuth, channel gradient, changes in BA, changes in tree density, post-harvest changes to shade, and post-harvest changes to solar energy inputs.

2.6.2 Temperature Analysis

We provided an approximate assessment of the statistical significance of the stream temperature response at the site level following an approach similar to Gomi et al. (2006). The site-level analysis computed DMAX stream temperature responses during the post-harvest period by development of upstream / downstream stream temperature regression relationships using pre-harvest data to predict downstream temperatures in both the reference and treatment reaches. Differences between predicted and observed temperatures during the post-harvest period provided a measure of stream temperature response. We then pooled the computed steam temperature responses of all of the sites and used linear mixed effects model analysis to quantify and compare treatment responses of the no-harvest, ASR, and SR prescriptions. Details on the analysis of site-specific and overall treatment responses follow.

2.6.2.1 Site-Specific Stream Temperature Response

We analyzed post-harvest changes in July 1 through September 15 DMAX stream temperatures. We developed regression relationships between DMAX stream temperatures measured at the downstream end of each reach (reference and treatment reaches separately) as a function of the corresponding values at the upstream end of the reach during the pre-harvest periods (calibration). Data from all pre-harvest sample periods were used to fit the reach specific regression models; all but one site (Tungsten) had at least 2 seasons of pre-harvest data for calibration (Table 2.5).

We first explored the data to look for extreme outliers in the daily stream temperatures by examining separate box plots for the upstream and downstream DMAX temperature reading in each site and reach. The initial temperature data QA/QC described in Section 2.5.2 *Stream and Air Temperature* identified and excluded anomalous values that were indicative of temperature sensor errors, loggers exposed to air, or discontinues flow conditions (Appendix 3). No outliers were omitted from the analysis following the initial QA/QC. Secondly, pair plots of the upstream and downstream temperatures in each reach of each site were examined. An ordinary least square regression line and a LOESS curve were overlaid on the pair plots to graphically assess the relationship. In nearly all cases, both the LOESS curve and OLS line closely corresponded to one another, indicating a strong linear relationship. Homogeneity of the OLS residuals was also assessed by plot of standardized residuals against fitted values for each reach. Although there were minor deviations in the spread of residuals across the fitted values in a few sites, plots indicate that there was no clear violation of heterogeneity. However, as is typical with daily time series data, auto-correlation function (ACF) plots indicated a clear violation of the independence of the OLS residuals for all site and reaches; various time lags had a significant residual autocorrelation.

Generalized least squares (GLS) regression was used to account for residual autocorrelation and heterogeneity of residuals, using the GLS procedure implementation in the software package R. The fitted model was:

$$y_t = \beta_0 + \beta_1 x_t + \varepsilon_t$$

where

y_t is the DMAX stream temperature at the bottom of a treatment reach on day t;

x_t is the corresponding DMAX stream temperature at the bottom of the upstream reference reach;

β_o and β_1 are coefficients to be estimated by regression,

ε_t is an error term modeled as an autoregressive process of order "k":

$\varepsilon_t = \rho_1\varepsilon_{t-1} + \rho_2\varepsilon_{t-2} + \dots\dots\dots. + \rho_k\varepsilon_{k-1} + u_t$,$\rho_d$ is the autocorrelation between error terms at

a lag of "d" days,

ρ_{1-k} are the lag d autocorrelation coefficients estimated by the GLS procedure,

ε_{t-d} is the error term "d" days before day "t", and

u_t is a random disturbance, assumed to be normally distributed with constant variance.

The order k for the autocorrelation was determined by examining partial autocorrelation functions and plots of the pre-treatment residuals and retaining only the terms with statistically significant partial autocorrelation coefficients. We investigated the inclusion of sinusoid functions to account for patterns observed in residuals for some sites. Regional seasonal climate data (air temperatures and accumulated precipitation) and reference DMAX air temperature (a surrogate for climate variability) were also examined to as predictor variables for stream temperature response in the calibration period. These adjustments did not improve model fit or account for patterns in the residuals in nearly all of the sites, so we opted to use the simpler GLS regression model across all sites. Our data was limited to just the summer season per sample year, so patterns associated with seasonal changes was not an issue at most sites.

Following selection and fitting of the appropriate auto-regression function (which at least in part verifies the assumption of residual independence), residuals corrected for the modeled auto-regressive structure were assessed to verify the assumptions of normality, homogeneity, and independence of residuals. Normality of residuals was assessed via QQ-plots. Homogeneity of residuals was assessed by plots of standardized residuals against plotted values. Residuals were plotted against the upstream temperature (predictor variable) to assess the independence assumption. Residuals were also plotted against reference DMAX air temperature values (another possible explanatory variable) to determine if the variable could be used to account for residual patterns and added to the regression relationship. In addition, Cooks distance leverage plots were examined to assess each model for influential observations. These diagnostic steps revealed no major violation of assumptions in nearly all cases.

The regression relationships between the upstream and downstream temperatures developed from the pre-harvest calibration period were used to predict expected DMAX stream temperature at the downstream end of the treatment and reference reaches during July 1 through September 15 of each year during the post-harvest period. Predicted daily maximum temperatures were subtracted from observed daily maximum temperature to compute the change in stream temperature during the post-harvest sample periods, hereafter referred to as the stream temperature response.

The DMAX stream temperature response on a given day in the post-harvest period was estimated as

$$\text{DMAX}_{Response} = y_t - \hat{y}_t$$

Where y_t and $\hat{y}_t$ are the observed and predicted DMAX temperatures on day t. Daily post-harvest temperature responses were computed for both the treatment and reference reaches. Estimates of temperature responses following harvest in the treatment reaches are referred to as treatment effects, whereas estimated temperature responses in the reference reach during the post-harvest period are referred to as background responses.

To provide an approximate assessment of the statistical significance of the stream temperature response at each study reach, we follow an approach similar to that of Gomi et al. (2006). The method compares pre- and post-harvest stream temperature responses within each treatment reach and each reference reach, separately. We first removed the autocorrelation from the residuals to provide an estimate of random disturbances:

$$\hat{u}_t = (y_t - \hat{y}_t) - \rho_1(y_{t-1} - \hat{y}_{t-1}) - \rho_2(y_{t-2} - \hat{y}_{t-2}) - \ldots - \rho_k(y_{t-k} - \hat{y}_{t-k})$$

where $\hat{u}_t$ is an estimate of the random disturbance on day t, and ρ_i is an estimate of the lag i autocorrelation coefficient for the GLS regression fit.

Given that these disturbances will be approximately independent, then if they are also approximately normally distributed, 95% prediction intervals can be estimated for each site reach separately as $\pm 1.96 s_u$, where s_u is the standard deviation of $\hat{u}_t$. Under the null hypothesis of no harvest impact on stream temperature, the distribution of $\hat{u}_t$ should be the same both pre-treatment and post-treatment. To assess the significance of $\text{DMAX}_{Response}$ in both the reference (background response) and treatment reaches (treatment response) following timber harvest, we applied the two-sample Kolmogorov-Smirnov (KS) test for the distribution of disturbances between the pre-harvest period and each post-harvest year. This test does not require normality or equality of variance. This analysis assumes that changes in distributions would also result in the changes in means and variances. Under the null hypotheses of no timber harvest impact (which is true in the case of the reference reaches), the distributions of the residuals (which are the autocorrelated temperature responses) and the uncorrelated random disturbances should be the same in both the calibration and test periods.

To further examine patterns of variability in the $\text{DMAX}_{Response}$, we fitted relations between DMAX air temperatures measured at the midpoint in the treatment reach as a function of the corresponding values at the mid-point of the reference reach during the pre-harvest periods (calibration). Data from all pre-harvest sample periods were used to fit 30 site-specific regression models. The differences between the observed and predicted DMAX air temperature in the treatment reach during the post-harvest period provide the air temperature response. The focus of this analysis was to compute a post-harvest air temperature response to use as an explanatory variable for post-harvest stream temperature response. We then use simple linear regression to examine the effects of changes in air temperature on $\text{DMAX}_{Response}$.

2.6.2.2 RMZ Prescription / Shade Rule Effectiveness – Pooled Analysis

To test for prescription/shade rule effectiveness in protection of stream temperature, we used the mean $\text{DMAX}_{Response}$ computed for each sample season at each sample reach as the dependent variable. Averaging the $\text{DMAX}_{Response}$ over a sample season removed the variability associated with temperature responses from shorter time periods, such as single days or individual weeks.

Stream temperature responses evaluated in this analysis therefore reflect prolonged alterations in stream conditions.

The pooled analysis was limited to include data from the first and second post-harvest years only ($Post_1$ and $Post_2$). This decision was made due to the staggered monitoring and harvest schedules and some prolonged post-harvest monitoring; some sites had up four to five years post-harvest data (Table 2.5). All sites had at least two years post-harvest data. We expected treatment effects to be most apparent within one to two years following harvest, as understory growth and crown expansion would be anticipated with increased time following timber harvest. We did not conduct tests on pre-harvest data due to the fact that the mean temperature response during the pre-harvest period is the mean of residuals from a site specific best fit model. Therefore the mean of the pre-harvest temperature response in all reference reaches is very close to zero in all in all reference and treatment reaches.

We tested for the effect of RMZ harvest on seasonal mean $DMAX_{Response}$ using linear mixed-effects (LME) models (Pineirho and Bates 2000). LME models incorporate both fixed effects associated with experimental factors and random effects associated with individual experimental units having more than one observation each. Initially, we examined a variety of random effects structures. We also examined a variety of site descriptor variables as fixed factors potentially controlling stream temperature response.

We report results from a simple LME that had the lowest AIC scores of all models examined. Our LME model used RMZ prescription type as the only fixed factor. The random effects structure included a random intercept model with data grouped by study site reach. Including study site reach as a random effect served to account for the two measures of $DMAX_{Response}$ at each study site used in the analysis (the mean $DMAX_{Response}$ of $Post_1$ and $Post_2$). The final model is represented as:

$$DMAX_{Response} = \text{RMZ Prescription Type} + (1|\text{Study Site Reach})$$

Planned comparisons were made to determine if the stream temperature responses observed under the ASR and SR harvest prescriptions (treatment responses) were each different from the temperature responses observed in the reference reaches (background response) or different from one another. These comparisons provided an estimate of the magnitude of stream temperature effects as a function of the RMZ harvest prescription.

2.6.2.3 Correlation of Descriptive Variables and Stream Temperature Response

The relationships between $DMAX_{Response}$, physical and vegetative descriptive variables, including shade and incoming solar radiation, were further examined for evidence of harvest-induced. Some measure of climatic conditions, stream and basin size, and other riparian and channel attributes may be useful in accounting for differences in stream temperature response within and between the two prescriptions (Groom et al. 2011, Gomi et al. 2006, Gravelle and Link 2007).We conducted a correlation analysis between the mean $DMAX_{Response}$ and each of the independent site descriptive variables to examine possible factors controlling stream temperature response. Except for reference reach air temperatures, baseflow discharge, change in shade following harvest, and air temperature response to harvest, all other potential covariates were static over all years. Specifically, we examined relationships between the descriptive variables (air temperature measured in the reference reach, watershed area calculated at site center, bankfull channel width, gradient, baseflow discharge, elevation, channel aspect, change in treatment reach shade following harvest) and the study site reach mean $DMAX_{Response}$. We also conducted correlation analysis of climate data measures observed at regional weather and stream flow gauging stations with $DMAX_{Response}$ to see if there were overall relationships to climate.

3 Results

3.1 Shade and Canopy Closure

Prior to harvest treatments, site canopy closure, as estimated by the handheld densiometer, ranged from 73% to 96%, with a mean of 89% at the ASR sites and 87% at the SR sites (Appendix 2). The four lowest pre-harvest canopy closure values occurred in sites with the largest bankfull channel widths. Pre-harvest canopy closure did not significantly differ between reference and treatment reaches or between the ASR and SR sites (Tables 3.1 and 3.2, respectively). Likewise, pre-harvest photographic-based shade values did not significantly differ between reference and treatment reaches within the ASR and SR sites. Shade measurements ranged from 89% to 97%, with a mean of 93% at the ASR sites and SR sites. Results from the companion solar study indicated that incoming solar radiation and radiation attenuation also did not differ significantly between the reference and treatment reaches prior to harvest (McGreer et al. 2011) at the ASR sites.

3.1.1 Harvest Impacts on Shade and Canopy Closure

Harvest prescription effects, defined as the change in shade/canopy closure in the treatment reach relative to the upstream reference reach, were small yet statistically significant in the SR sites (Figure 3.1). Shade values decreased in SR sites (mean effect of -2.8%, n_{SR}= 14, one-sided paired t = 3.557, p = 0.002), as did the canopy closure values (mean effect of -4.5%, n_{SR} = 14, one-sided paired t = 3.883, p < 0.001). Shade and canopy closure values did not significantly change in the treatment reaches of the ASR sites (mean shade decrease of 0.20%, n_{ASR} = 16, one-sided paired t = 0.332, p = 0.372; mean canopy closure decrease of 0.4%, n_{ASR} = 16, one-sided paired t = 0.634, p = 0.268). Shade reduction following harvest differed between the SR and ASR treatment reaches (n_{ASR} = 16, n_{SR} = 14, two-sample t = 2.988, p = 0.003). Shade reduction in the SR treatment sites exceeded the reduction in the ASR sites by 3%. Canopy closure reduction was also greater in the SR then in the ASR sites, (mean SR canopy reduction was 4% greater than that of the ASR sites (n_{ASR} = 16, n_{SR} = 14, one-sided, two sample t = 3.184, p = 0.002).

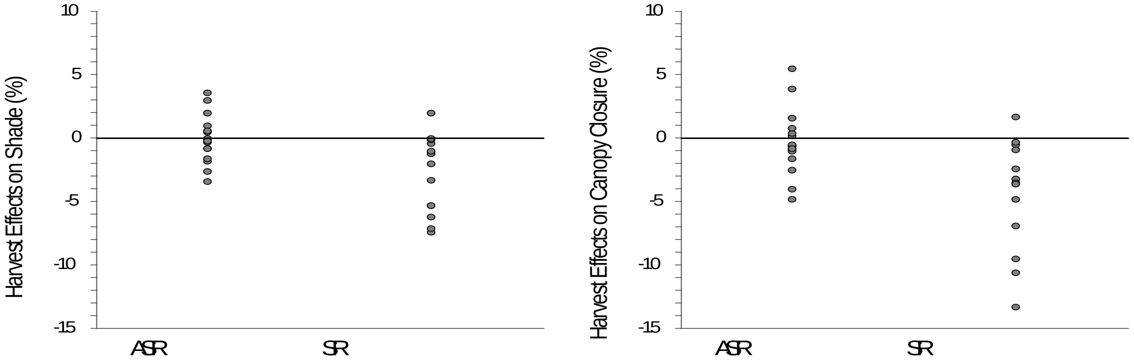


Figure 3.1. Plot of mean harvest treatment effects on shade and canopy closure value (%) for each site following riparian harvest, grouped by prescription type.

Table 3.1. Mean and standard deviation (in parentheses) of channel and pre-harvest riparian attributes for Reference and Treatment reaches for 30 streams included in the Eastern Washington Shade and Temperature Effectiveness Study. Riparian attributes include the area within 75 ft of the stream banks on both sides of the channel.

Attribute	Reference Reach		Treatment Reach	
Channel				
Basin Area (ac) *	1732	(2108)	1792	(2106)
Elevation (ft)*	3382	(626)	3305	(614)
Streamflow (ft^3/s)	0.5	(0.8)	0.5	(0.8)
Channel Gradient (%) *	8.4	(3.9)	7.6	(3.4)
Gravel (%)	53	(26)	53	(22)
Azimuth (°)	39	(31)	39	(31)
Bankfull Width (ft)	9.5	(5.1)	9.9	(4.6)
Riparian				
Basal Area (ft^2/ac)	190	(69)	205	(69)
Trees / Acre	221	(90)	237	(88)
Mean Tree Diameter (in) [a]	13	(3)	13	(3)
Live Crown Ratio (%)	57	(6)	55	(8)
Tree Height (ft)	72	(7)	73	(8)
Shade (%)	93	(2)	93	(2)
Canopy Closure (%)	88	(7)	88	(6)
Solar Attenuation (%)[b]	90	(5)	91	(4)
Solar Radiation (W/m^2)[b]	69	(39)	63	(35)

Note: For a given attribute, statistical difference (α = 0.05) between Reference and Treatment reaches is indicated with *.

[a] Value is the mean of quadratic mean diameter across all sites.

[b] Solar attenuation and radiation values are from McGreer et al. (2011) and were collected in the ASR sites only.

Table 3.2. Mean and standard deviation (in parentheses) of channel and pre-harvest riparian attributes in the treatment reaches of 16 ASR and 14 SR study sites included in the Eastern Washington Shade and Temperature Effectiveness Study. Riparian attributes include the area within 75 ft of the stream banks on both sides of the channel.

Attribute	ASR		SR	
	Channel			
Basin Area (ac)	2085	(2750)	1457	(966)
Elevation (ft)	3354	(706)	3248	(509)
Stream flow (ft^3/s)	0.6	(0.9)	0.5	(0.7)
Channel Gradient (%)	6.8	(2.7)	8.5	(4.0)
Gravel (%)	58	(10)	46	(29)
Azimuth (°)	43	(32)	35	(30)
Bankfull Width (ft)	9.3	(4.6)	10.6	(4.7)
	Riparian			
Basal Area (ft^2/ac) *	181	(62)	235	(68)
Trees / Acre	228	(84)	249	(94)
Mean Tree Diameter (in) [a]	12	(2)	14	(4)
Live Crown Ratio (%)	54	(8)	56	(8)
Tree Height (ft)	73	(7)	79	(9)
Shade (%)	93	(1)	93	(2)
Canopy Closure (%)	87	(6)	89	(6)
Solar Attenuation (%)[b]	91	(4)		
Solar Radiation (W/m^2) [b]	63	(35)		

Note: For a given attribute, statistical difference ($\alpha = 0.05$) between ASR and SR treatment reaches is indicated with *.

[a] Value is the mean of quadratic mean diameter across all sites.

[b] Solar attenuation and radiation values are from McGreer et al. (2011) and were collected in the ASR sites only.

Trees retained in the uplands beyond the outside edge of the RMZ were found to contribute little to effective shading in the 25 sites sampled. Mean shade contribution of upland trees per study site was calculated as < 1 %. Mean shade contribution of upland trees did not significantly differ between RMZ-only harvest sites and sites harvested under standard upland harvests operations ($n_{\text{RMZ Only}} = 7$, $n_{\text{Std Operations}} = 17$, two-sample $t = 0.224$, $p = 0.821$). Of the visible upland trees observed at each station, the number intersecting the effective shade solar path ranged from 0 to 10, with a mean of 1.33. The majority of trees found to intersect the effective shade solar path did so either in the early morning or early evening hours, and not when the sun was at its highest, the period of highest potential solar input. Shade reduction levels did not differ between the sites receiving a RMZ-harvest only and the sites receiving standard operational upland harvest (one-sided, two sample $t = 1.224$, $p = 0.12$).

3.1.2 Relationship among Riparian Stand Changes and Shade Impacts

Within 75 ft of the stream bank (core and inner zone combined), trees per acre (TPA), basal area per acre (BA), tree height, crown ratio (CRW), and mean tree diameter (QMD) of trees did not significantly differ between treatment and reference reaches prior to harvest (Table 3.1). Basal area within 75 ft of the stream banks in the treatment reach was slightly higher in the SR sites than in the ASR sites (two sample $t = 2.291$, $p=0.029$), while all other stand metrics were similar prior to harvest (Table 3.2). Higher BA in the SR site treatment reaches was due largely to the higher values observed in the core zone (Figure 3.2).

Tree densities and BA decreased slightly with increasing distance from the stream. TPA and BA for trees greater than or equal to 6 inches dbh were higher in the core zone compared to the inner and outer zones in the reference and the treatment reaches in both the SR and ASR sites, with the exception of the reference reaches in the SR sites, where the tree density was virtually identical in all three zones (Figure 3.2).

Over the course of the study, little change was detected in riparian stand attributes in the reference reaches. Tree density, tree height, and crown ratio within 75 ft and within 120 ft of the stream banks did not differ between pre-harvest and post-harvest measurements in either prescription. On average, BA did not differ in the reference reaches of the SR sites post-harvest, but increased slightly in the ASR sites (Figure 3.3). However, these changes represent less than a 5% change in the pre-harvest conditions and were due primarily to recruitment of small trees that were not tallied during the pre-harvest period because they previously did not meet the minimum 6-inch dbh criteria. Riparian stand attribute changes in the harvested treatment reach inner zone (a 45-ft wide band situated 30 ft from the stream bank) were readily apparent in both the SR and ASR sites (Figure 3.3). Because of the no-shade-removal requirement of ASR prescriptions, the SR prescription typically allowed for a higher proportion of the pre-harvest stand to be removed within 75 ft of the stream banks. In a band extending 75 ft from the stream bank out to 120 ft, post-harvest BA and TPA reductions were also greater in the SR then in the ASR. One of the five RMZ-only harvest sites (Long Alec, harvested in the RMZ only on one side) had no regulatory outer zones, so no harvest was conducted beyond 75 ft from the stream bank on the south side. Little change occurred within the core zone of the treatment reaches in either the ASR or SR sites during the post-harvest period.

Changes to riparian stand attributes following harvest were not significantly correlated with changes in stream shade (Table 3.3) or to changes in incoming solar radiation. Reductions that occurred in the amount and proportion of BA within 30-75 ft of the stream banks had little or no influence on the variation in shade reduction ($r^2 = 0.12$, $p = 0.061$, $n = 30$ and $r^2= 0.09$, $p =$

0.107, *n* = 30, respectively). Aside from the occasional tree mortality or windthrow in the core zone, the reduction in BA primarily occurred between 30 and 75 ft away from the stream, as harvest was prohibited within 30 ft of the stream bank.

Given that there was variability in harvest patterns beyond 75 ft from the stream bank, we also examined the relationships of changes in stand attributes in the outer zone situated between 75 ft to 130 ft from the stream bank. None of the pre-harvest to post-harvest changes in treatment reach stand attributes in the outer zone was significantly correlated with stream shade reduction (Table 3.3). We found no relationship among post-harvest changes in shade and the changes in incoming radiation (*r* = -0.19, *p* = 0.49) or changes in radiation attenuation (*r* = 0.31, *p* = 0.23) within ASR treatment reaches. No other site-specific factors accounted for differences in the changes in shade or solar radiation input following timber harvest (Table 3.4).

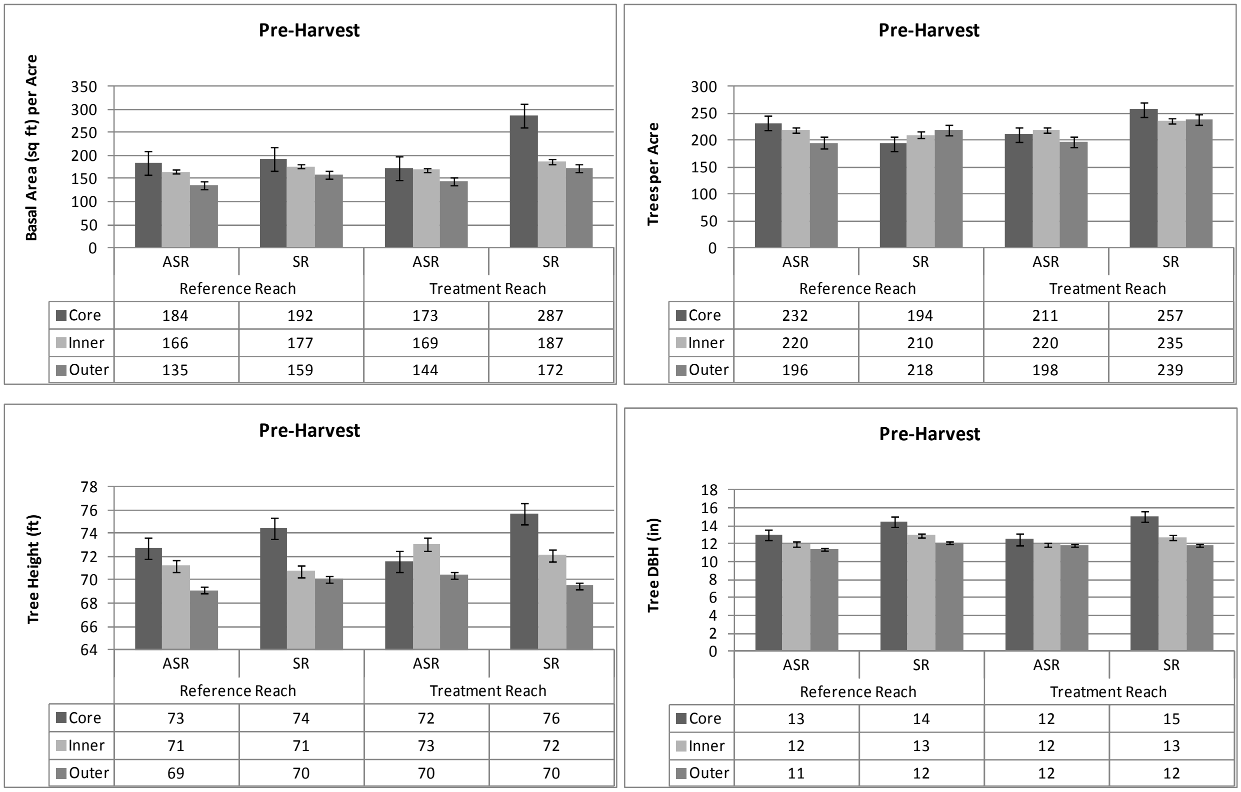
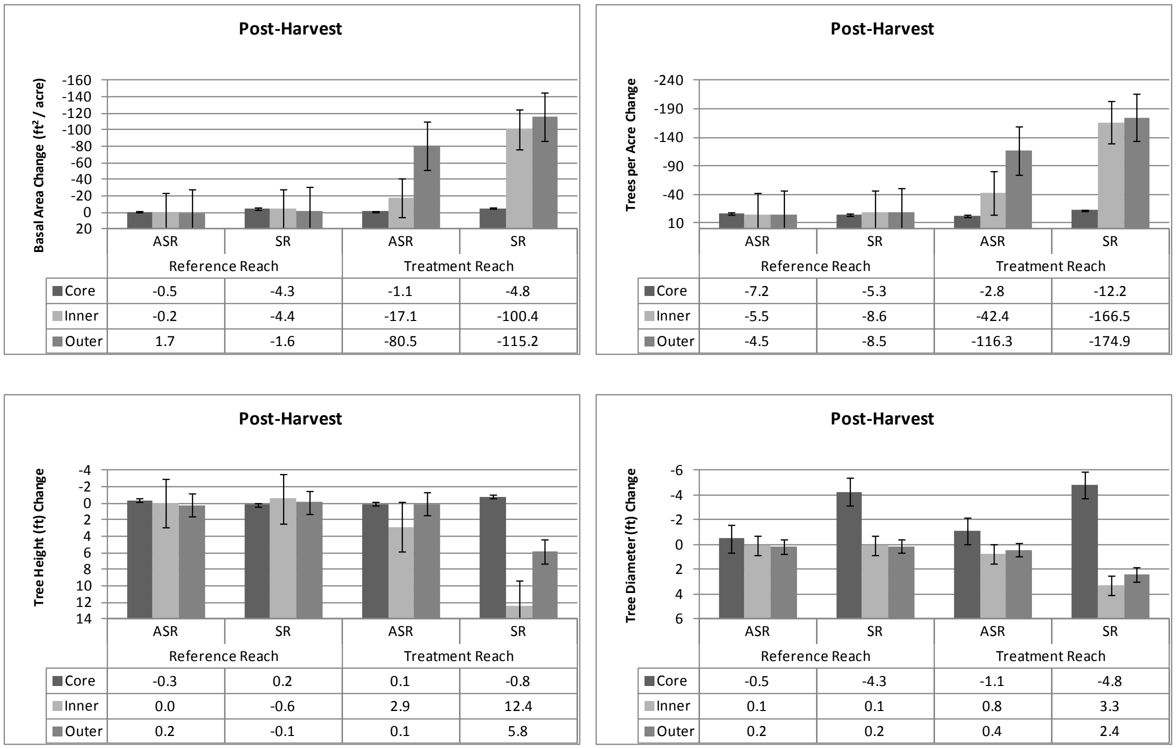


Figure 3.2. Stand attributes within riparian areas prior to timber harvest of study sites in the Stream Shade and Temperature Effectiveness Study in forest lands of eastern Washington. Core zone represents the area from 0-30 ft from the stream bank. Inner zone includes the area from 30-75 ft from the stream bank. Outer zone extends from 75 ft to 120 ft from the stream bank. All measurements are horizontal distance. Number of sample sites: All Available Shade Rule (ASR) =16, Standard Rule (SR) = 14. Vertical bars represent one standard error of the mean across prescription type.



Basal Area Change (ft^2 / acre)

	Reference Reach		Treatment Reach	
	ASR	SR	ASR	SR
■ Core	-0.5	-4.3	-1.1	-4.8
■ Inner	-0.2	-4.4	-17.1	-100.4
■ Outer	1.7	-1.6	-80.5	-115.2

Trees per Acre Change

	Reference Reach		Treatment Reach	
	ASR	SR	ASR	SR
■ Core	-7.2	-5.3	-2.8	-12.2
■ Inner	-5.5	-8.6	-42.4	-166.5
■ Outer	-4.5	-8.5	-116.3	-174.9

Tree Height (ft) Change

	Reference Reach		Treatment Reach	
	ASR	SR	ASR	SR
■ Core	-0.3	0.2	0.1	-0.8
■ Inner	0.0	-0.6	2.9	12.4
■ Outer	0.2	-0.1	0.1	5.8

Tree Diameter (ft) Change

	Reference Reach		Treatment Reach	
	ASR	SR	ASR	SR
■ Core	-0.5	-4.3	-1.1	-4.8
■ Inner	0.1	0.1	0.8	3.3
■ Outer	0.2	0.2	0.4	2.4

Figure 3.3. Average change in stand attributes within riparian areas following timber harvest of study sites in the Stream Shade and Temperature Effectiveness Study in forest lands of eastern Washington. Core zone represents the area from 0-30 ft from the stream bank. Inner zone includes the area from 30-75 ft from the stream bank. Outer zone extends from 75 ft to 120 ft from the stream bank. All measurements are horizontal distance. Number of sample sites: All Available Shade Rule (ASR)=16, Standard Rule (SR) = 14. Vertical lines represent one standard error.

Table 3.3. Mean pre- to post-harvest changes of riparian attributes in Core/Inner vs. Outer Zones of treatment reach within study sites of the Eastern Washington Stream Shade and Temperature Study. Proportional changes are presented in %. Pearson's correlation coefficient with pre-harvest to post-harvest change in shade is shown as *r* and probability level as *p*. Asterisks indicate sites that received an RMZ-only harvest on at least one side.

		0 – 75 feet from stream bank								75 to 120 feet from stream bank							
		Change Pre-Harvest to Post-Harvest				Proportional Change Pre-Harvest to Post-Harvest				Change Pre-Harvest to Post-Harvest				Proportional Change Pre-Harvest to Post-Harvest			
Site	% Change in Shade	Basal Area per Acre	Trees per Acre	Mean Height (ft)	Mean Tree Diameter (in)	Basal Area per Acre	Trees per Acre	Mean Height (ft)	Mean Tree Diameter (in)	Basal Area per Acre	Trees per Acre	Mean Height (ft)	Mean Tree Diameter (in)	Basal Area per Acre	Trees per Acre	Mean Height (ft)	Mean Tree Diameter (in)
All Available Shade Rule																	
Bacon	-1	-8	-10	0	0.3	-0.05	-0.08	0.00	0.00	-66	-26	-25	-6.6	-0.81	-0.50	-0.32	-0.08
Clark*	-1	-7	-19	0	0.4	-0.06	-0.11	0.00	0.00	-27	-40	-3	0.0	-0.23	-0.23	-0.04	0.00
Cole	-1	-7	-34	2	1.1	-0.05	-0.21	0.03	0.01	-82	-119	2	0.7	-0.69	-0.72	0.03	0.01
Dry Canyon	4	-27	-53	1	0.4	-0.19	-0.24	0.02	0.00	-171	-251	21	4.0	-0.95	-0.97	0.32	0.02
Floedelle *	-2	-23	-24	2	-0.2	-0.15	-0.13	0.03	0.00	-44	-59	-1	0.7	-0.39	-0.45	-0.01	0.01
Long Alec *	0	-3	-19	0	0.2	-0.02	-0.05	0.01	0.00	2	0	0	0.1	0.02	0.00	0.00	0.00
Lotze	-5	-21	-34	0	0.4	-0.09	-0.14	0.00	0.00	-128	-205	-3	0.1	-0.75	-0.76	-0.05	0.00
Mill	0	-13	-51	2	0.6	-0.05	-0.15	0.02	0.00	-189	-254	15	3.9	-0.52	-0.71	0.19	0.01
Moses*	-3	-28	-63	6	1.1	-0.11	-0.24	0.07	0.00	-115	-158	6	0.2	-0.60	-0.62	0.07	0.00
NF Foundation	-3	-39	-53	2	0.7	-0.19	-0.27	0.03	0.00	-33	-40	-10	-0.7	-0.43	-0.35	-0.17	-0.01
Sanpoil	-2	1	-5	1	0.4	0.01	-0.05	0.01	0.00	-82	-99	8	1.4	-0.61	-0.68	0.11	0.01
Seco	-1	-6	-24	-1	0.1	-0.03	-0.06	-0.02	0.00	-110	-231	1	1.4	-0.51	-0.63	0.02	0.01
Sema1	-3	11	15	-1	0.2	0.12	0.06	-0.02	0.00	-45	-92	-12	-0.8	-0.68	-0.61	-0.18	-0.01
Sema2	-1	9	0	-2	0.3	0.05	0.00	-0.02	0.00	-71	-158	-2	0.0	-0.60	-0.60	-0.03	0.00
SF Ahtanum *	-1	-17	-39	6	1.5	-0.08	-0.24	0.08	0.01	1	0	0	0.1	0.01	0.00	0.00	0.00
Tungsten	-3	-6	-24	4	0.9	-0.02	-0.12	0.05	0.00	-147	-152	3	2.3	-0.69	-0.77	0.04	0.01
r		**-0.01**	**-0.18**	**-0.09**	**-0.11**	**-0.22**	**-0.15**	**-0.05**	**0.09**	**-0.17**	**-0.18**	**0.49**	**0.33**	**-0.02**	**-0.06**	**0.54**	**0.15**
p		**0.98**	**0.51**	**0.75**	**0.68**	**0.42**	**0.59**	**0.86**	**0.75**	**0.52**	**0.50**	**0.05**	**0.22**	**0.95**	**0.84**	**0.03**	**0.57**
Standard Rule																	
Big Goosmus	-3	-96	-126	1	1.8	-0.27	-0.42	0.02	0.00	-147	-238	10	2.0	-0.89	-0.92	0.14	0.01
Byers *	-2	-60	-58	3	0.9	-0.29	-0.36	0.03	0.00	-29	-40	-3	0.0	-0.27	-0.27	-0.04	0.00
Dorchester	-5	-79	-97	10	1.5	-0.33	-0.45	0.13	0.01	-105	-158	8	1.8	-0.77	-0.83	0.13	0.01
Dry Creek	-10	-13	-10	1	0.6	-0.05	-0.10	0.01	0.00	-130	-125	33	7.6	-0.78	-0.90	0.39	0.05
EF Cedar	-3	-35	-58	8	6.2	-0.12	-0.48	0.11	0.02	-48	-86	12	7.7	-0.35	-0.72	0.16	0.06
EF Cedar trib	1	-33	-106	4	1.5	-0.21	-0.40	0.07	0.01	-118	-178	13	5.1	-0.92	-0.96	0.19	0.04
Heel	-5	-28	-73	2	1.3	-0.13	-0.28	0.02	0.01	-246	-323	4	2.6	-0.75	-0.83	0.06	0.01
Little Goosmus	-4	-55	-102	7	2.5	-0.44	-0.62	0.09	0.02	-93	-165	11	3.7	-0.81	-0.89	0.17	0.03
Middle	-2	-103	-111	0	0.4	-0.35	-0.38	0.00	0.00	-92	-73	-4	-1.2	-0.38	-0.24	-0.06	-0.01
Prouty *	-3	-112	-208	7	1.9	-0.37	-0.53	0.11	0.01	-221	-330	8	1.6	-0.86	-0.89	0.12	0.01
Sema3	-1	-35	-155	3	1.4	-0.18	-0.38	0.05	0.01	-108	-271	4	0.6	-0.64	-0.68	0.07	0.00
Sema4	-8	-37	-116	2	0.9	-0.25	-0.38	0.04	0.01	-96	-231	-3	1.0	-0.70	-0.76	-0.04	0.01
SF Dairy	-4	-13	-68	4	2.4	-0.07	-0.33	0.07	0.01	-42	-46	-2	1.0	-0.28	-0.37	-0.03	0.01
Sylvus	-8	-172	-184	0	0.8	-0.56	-0.61	0.00	0.00	-139	-185	-11	0.4	-0.76	-0.78	-0.15	0.00
r		**0.07**	**-0.23**	**0.27**	**0.25**	**0.03**	**-0.24**	**0.31**	**0.25**	**0.13**	**0.00**	**-0.12**	**-0.14**	**0.12**	**0.18**	**-0.04**	**-0.09**
p		**0.81**	**0.44**	**0.36**	**0.39**	**0.93**	**0.41**	**0.29**	**0.40**	**0.67**	**1.00**	**0.69**	**0.63**	**0.68**	**0.54**	**0.90**	**0.77**

Table 3.4. Correlation matrix describing the relationships among channel descriptives and post-harvest changes to shade, solar energy inputs, and riparian characteristics. Pearson's correlation coefficient with post-harvest change in shade during the first two post-harvest sample periods is shown as *r* and its significance level is shown as *p*.

Site		Shade Reduction	Change in Solar Radiation	Channel Gradient	Azimuth	Bankfull Width	Reduction Basal Area	Reduction Trees per Acres
Shade Reduction	***r***		-0.19	0.24	0.29	0.24	-0.31	-0.18
	p		0.49	0.20	0.12	0.20	0.10	0.34
Change in Solar Radiation	***r***			0.04	0.17	0.26	-0.26	-0.30
	p			0.87	0.54	0.32	0.34	0.26

3.2 Stream Temperature

Across all study sites and all sample periods, ADMAX temperatures ranged from 6.5 to 16.5 °C DMAX water temperatures ranged from 4.5 ° C to 19.5 °C. Appendix 5 provides a summary of water temperatures for each sample period measured at the bottom of the reference and treatment reaches in each site.

3.2.1 Site-Specific Stream Temperature Response

Significant ($p < 0.05$) residual autocorrelation in the pre-harvest regression was found for reference and treatment reaches in all streams for the DMAX stream temperature. For reference reach DMAX stream temperatures, significant positive residual autocorrelation was observed in all of the study reaches (Lag 1 for 7 sites, Lag 2 for 17 sites, Lag 3 for 6 sites). Fitted residual values corrected for autocorrelation were assessed for goodness of fit and heteroscedasticity through diagnostic plots, indicating that the linear models were satisfactory to apply to post-harvest data. Diagnostic plots from the Cole Creek study site are provided in Figure 3.4 to illustrate the regression model validation process used on all study reaches. Pre-harvest calibration regressions were used to predict DMAX stream temperatures for the post-harvest time period in both the reference and treatment reaches at each study site.

3.2.1.1 Background Responses

Estimates of post-harvest $\text{DMAX}_{Response}$ and random disturbances in reference reaches, referred to as background responses and background disturbances, respectively, provide information on the stream temperature trajectories where no RMZ harvest treatment has occurred. Daily background responses ranged from -1.7 °C to 2.6 °C, with over 98% of the daily values less than 1.0 °C. Reach means ranged from - 0.3 °C to 0.5 °C (Table 3.5). Site sample period mean DMAX background responses (computed as the mean of daily background responses in one study site during one sample period) ranged from -0.6°C to 0.9 °C with a mean of –0.002 °C (n = 98, s = 0.262) [Table 3.6]. Background responses varied among sample periods within individual study sites, most notably in Dry Canyon (-0.5 °C in Post_1 to 0.2 in Post_4), Tungsten (0.9 °C in Post_1 to 0.1 in Post_4), Dry Creek (-0.1 °C in Post_1 to 0.5 in Post_5), and Sylvus (0.0 °C in Post_1 to -0.6 in Post_4). A total of 26 of the 98 sample period mean background responses exceeded an absolute value of 0.2 °C, the established accuracy of the Tidbit data loggers (Table 3.6).

For the reference reaches, deviations from the calibration regression differed between the pre-harvest calibration and post-harvest test periods for many of the study sites, as did the uncorrelated random disturbances. Figure 3.5 illustrates five sites that exemplify the range in reference variability of $DMAX_{Response}$. Graphical representation of background responses ($DMAX_{Response}$ in reference reach) for all of the study site reference reaches is provided in Appendix 6. The Kolmogorov-Smirnov (KS) test indicated significant change in the uncorrelated random disturbances between the pre-harvest calibration and the post-harvest test periods for 37 of the 98 sample period measures in the upstream reference reach during the post-harvest period, representing 19 (9 ASR, 10 SR) of the 30 study sites (Table 3.6). Of the 37 sample periods in which the KS tests indicate significant change the random disturbance, 20 of the 37 sample period mean background responses were an absolute value of 0.2 °C or less. More than 95% of all of the 98 site sample period mean background responses were less than 0.5°C, and 2% exceeded 0.7°C (Figure 3.6). The results suggest that the pre-harvest regressions are reasonably stable and should provide a basis to identify post-harvest stream temperature treatment responses that exceed 0.5 °C.

All sites had at least two years post-harvest temperature data. Although the overall mean of temperature background responses was near 0 during the first two sample periods following harvest ($Post_1$ and $Post_2$), site sample period means ranged from -0.5 to 0.9 °C. However, most of the daily background disturbances fell within the 95% confidence interval calculated from the calibration data (Figure 3.7). These results demonstrate that the rate of stream water cooling and warming varies from year to year even without disturbance from harvest within 200 ft of the stream. The regression analysis on the reference reaches set practical bounds on the magnitude of temperature changes that can reliably indicate a treatment response in our BACI designed study.

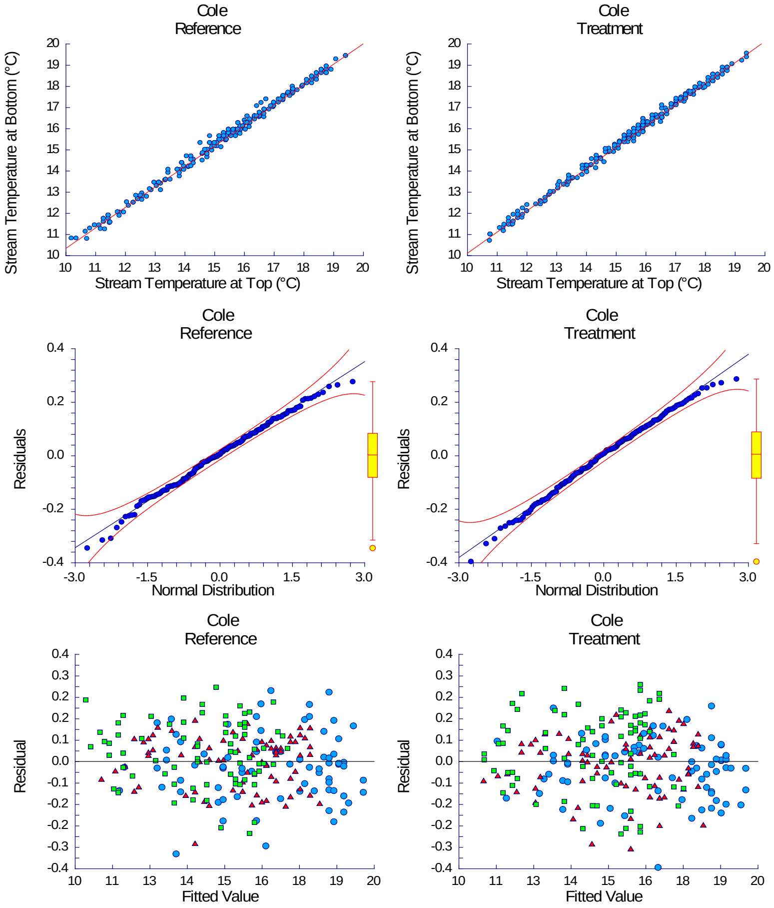


Figure 3.4 Regression diagnostics used to evaluate for (top) goodness of linear fit with regression line added, (middle) normality of residuals, and (bottom) residual heteroscedasticity. Plots include only the pre-treatment data used to calibrate the models. In the bottom graphs, the different symbols indicate year of pre-harvest sample period (green squares- Pre$_3$, red triangles-Pre$_2$, blue circles-Pre$_1$).

Table 3.5. Summary statistics of daily maximum stream temperature (°C) and $\text{DMAX}_{Response}$ in reference reaches (background response) for the All Available Shade Rule and the Standard Rule prescriptions over the course of the entire study.

	Pre-Harvest Temperature				**Post-Harvest Temperature**				$\text{DMAX}_{Response}$			
Site	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
All Available Shade Rule												
Bacon	7.6	0.7	5.7	9.3	7.2	0.7	4.9	9.1	-0.2	0.1	-0.4	0.0
Clark	12.3	1.7	8.4	15.8	11.6	1.8	8.1	15.4	0.2	0.2	-0.3	0.8
Cole	15.4	2.1	10.8	19.4	14.9	1.9	10.8	18.8	0.0	0.1	-0.3	0.2
Dry Canyon	8.4	0.5	7.2	9.4	8.3	0.5	7.2	9.4	-0.3	0.4	-1.5	0.7
Floedelle	11.3	1.8	7.1	15.3	11.6	1.7	7.5	14.8	0.4	0.2	0.0	0.8
Long Alec	11.3	1.6	7.0	14.0	10.5	1.9	6.3	14.1	0.3	0.5	-0.5	2.6
Lotze	11.1	1.1	8.3	13.1	10.3	1.2	7.8	13.2	0.0	0.1	-0.4	0.4
Mill trib	12.2	1.7	8.3	15.0	11.6	1.6	7.5	15.2	0.0	0.2	-0.6	0.6
Moses	11.0	0.9	8.8	13.1	10.8	1.0	8.5	12.9	-0.1	0.1	-0.5	0.1
NF Foundation	10.2	1.6	4.8	13.3	9.6	1.6	6.1	13.3	0.1	0.1	-0.2	0.5
Sanpoil	13.3	1.7	8.7	16.1	11.7	1.6	8.4	15.2	-0.1	0.5	-1.4	1.3
Seco	10.4	1.1	7.8	13.2	10.5	1.2	7.7	13.2	0.2	0.4	-0.7	1.3
Sema 1	8.6	0.7	7.3	9.6	8.4	0.8	6.8	9.9	0.0	0.7	-1.6	1.3
Sema 2	9.1	0.8	7.6	11.1	9.2	1.1	6.8	11.8	0.2	0.8	-1.3	2.5
SF Ahtanum	8.2	1.0	5.9	9.8	7.6	0.9	5.6	9.5	0.0	0.1	-0.3	0.3
Tungsten	12.8	0.9	10.5	15.1	12.6	1.6	8.9	16.1	0.5	0.4	-0.4	1.3
Standard Rule												
Big Goosmus	12.1	1.5	8.5	15.2	11.5	1.5	8.3	14.8	-0.1	0.3	-0.6	0.9
Byers	12.1	1.6	8.1	15.0	11.6	1.7	8.1	15.3	0.2	0.2	-0.2	0.4
Dorchester	13.2	1.4	9.5	15.3	12.8	1.6	9.3	15.9	-0.1	0.1	-0.3	0.3
Dry Creek	11.0	1.4	7.7	13.4	10.6	1.5	5.8	14.3	0.3	0.5	-1.0	1.8
EF Cedar	9.4	1.0	7.1	11.3	9.0	1.1	6.3	11.2	-0.1	0.1	-0.4	0.4
EF Cedar Trib	10.5	1.0	8.4	12.6	10.4	1.0	8.1	12.8	-0.1	0.1	-0.4	0.2
Heel	8.3	0.8	6.6	10.1	8.3	0.8	6.4	10.4	0.0	0.4	-0.9	1.0
Little Goosmus	14.5	1.7	9.2	18.1	13.3	1.8	9.2	17.0	-0.3	0.4	-1.1	0.9
Middle?	10.1	1.2	7.0	12.0	9.9	1.2	7.0	12.4	-0.1	0.1	-0.3	0.1
Prouty	10.0	1.3	7.5	12.4	9.5	1.2	6.4	11.9	0.0	0.2	-0.8	0.4
Sema 3	10.7	1.2	7.9	12.9	10.1	1.2	7.5	12.4	0.0	0.2	-0.4	0.7
Sema 4	10.8	1.4	7.9	14.0	10.4	1.5	7.3	13.8	-0.3	0.2	-0.8	0.3
SF Dairy	12.0	1.1	9.8	14.3	11.3	1.0	8.9	14.3	-0.1	0.3	-0.9	0.6
Sylvus	11.9	1.5	8.0	14.4	10.7	1.5	7.6	14.5	-0.3	0.5	-1.7	0.2

Table 3.6. Summary of mean (standard deviation in parentheses) DMAX$_{Response}$ (°C) and statistical significance of random disturbances in reference reaches. Sample period represents years before and after harvest (i.e. Pre 1 = 1 year before harvest; Post$_1$ = 1 year after). Bold values during post-harvest periods indicate significant differences (p<0.05) in distribution of disturbance based on two-sample Kolmogorov-Smirnov test between pre-harvest and post-harvest disturbances. The first column (PL) provides the 95% prediction limit [±1.96 S$_e$ (where S$_e$ is the standard error of the residuals) from the pre-harvest regression].

	Sample Period											
		PL	**Pre$_4$**	**Pre$_3$**	**Pre$_2$**	**Pre$_1$**		**Post$_1$**	**Post$_2$**	**Post$_3$**	**Post$_4$**	**Post$_5$**
	All Available Shade Rule											
Bacon		±0.3			0.0 (0.2)	0.0 (0.1)		**-0.1 (0.1)**	**-0.2 (0.1)**	**-0.2 (0.1)**	**-0.2 (0.1)**	**-0.2 (0.1)**
Clark		±0.4	-0.2 (0.1)	0.0 (0.1)	0.2 (0.2)	0.1 (0.2)		0.2 (0.1)	**0.2 (0.2)**			
Cole		±0.4		-0.1 (0.1)	-0.1 (0.1)	0.2 (0.2)		0.0 (0.1)	0.0 (0.1)			
Dry Canyon		±0.7			-0.2 (0.1)	0.3 (0.3)		**-0.5 (0.1)**	-0.3 (0.2)	-0.6 (0.2)	0.2 (0.2)	
Floedelle		±0.8	0.0 (0.3)	-0.2 (0.5)	-0.1 (0.4)	0.3 (0.2)		**0.3 (0.2)**	**0.4 (0.2)**			
Long Alec		±1.1		-0.4 (0.6)	0.5 (0.3)	0.0 (0.4)		0.4 (0.6)	0.4 (0.3)	0.2 (0.4)		
Lotze		±0.3			0.0 (0.1)	0.0 (0.1)		**-0.1 (0.1)**	0.0 (0.1)	0.1 (0.1)		
Mill		±0.4			0.2 (0.2)	-0.1 (0.1)		**-0.2 (0.2)**	0.1 (0.1)	0.1 (0.1)	0.0 (0.1)	-0.1 (0.1)
Moses		±0.4	0.2 (0.2)	0.1 (0.1)	-0.1 (0.1)	-0.1 (0.1)		-0.1 (0.1)	-0.2 (0.1)			
NF Foundation		±0.3	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)	-0.1 (0.1)		0.0 (0.1)	**0.1 (0.1)**	**0.2 (0.1)**		
Sanpoil		±0.7			-0.2 (0.2)	0.2 (0.3)		-0.1 (0.5)	0.1 (0.2)	**-0.3 (0.6)**		
Seco		±1.3			0.5 (0.6)	-0.5 (0.3)		0.1 (0.3)	0.2 (0.4)	0.3 (0.4)	0.1 (0.4)	
Sema 1		±1.1			0.2 (0.7)	-0.2 (0.4)		-0.2 (0.9)	0.1 (0.6)			
Sema 2		±1.0			0.1 (0.5)	-0.2 (0.3)		0.4 (0.8)	0.2 (0.8)			
SF Ahtanum		±0.3		0.0 (0.1)	0.1 (0.1)	-0.1 (0.1)		0.0 (0.1)	0.1 (0.1)	0.0 (0.1)		
Tungsten		±0.4				0.0 (0.2)		**0.9 (0.2)**	**0.4 (0.2)**	**0.8 (0.3)**	0.1 (0.2)	
		Standard Rule										
Big Goosmus		±0.5			-0.1 (0.3)	0.1 (0.3)		0.0 (0.2)	**-0.2 (0.2)**	0.1 (0.3)	-0.2 (0.2)	
Byers		±0.4	0.0 (0.2)	0.1 (0.2)	-0.1 (0.2)	0.0 (0.2)		**0.2 (0.2)**	**0.2 (0.1)**			
Dorchester		±0.3			0.0 (0.2)	0.0 (0.1)		**-0.2 (0.1)**	**-0.1 (0.1)**	-0.1 (0.1)	-0.1 (0.1)	
Dry Creek		±1.0			-0.1 (0.4)	0.1 (0.6)		-0.1 (0.4)	0.1 (0.4)	**0.4 (0.5)**	**0.5 (0.5)**	**0.5 (0.7)**
EF Cedar		±0.2			-0.1 (0.1)	0.1 (0.1)		0.0 (0.1)	-0.1 (0.2)	0.0 (0.2)	-0.1 (0.1)	
EF Cedar Trib		±0.3			0.1 (0.2)	-0.1 (0.1)		0.0 (0.1)	-0.1 (0.1)	-0.1 (0.1)	-0.2 (0.1)	
Heel		±0.7			0.1 (0.4)	-0.1 (0.3)		0.1 (0.3)	0.3 (0.4)	-0.3 (0.3)		
Little Goosmus		±1.2	-0.4 (0.3)	0.0 (0.7)	-0.1 (0.5)	0.4 (0.7)		**-0.5 (0.3)**	**-0.5 (0.3)**	-0.1 (0.4)		
Middle		±0.3			-0.1 (0.1)	0.1 (0.1)		0.0 (0.1)	**-0.1 (0.1)**			
Prouty		±0.2			0.0 (0.1)	0.0 (0.1)		0.0 (0.2)	**0.1 (0.2)**	-0.1 (0.2)	**-0.1 (0.3)**	
Sema 3		±0.4			0.0 (0.2)	0.0 (0.2)		0.1 (0.3)	0.0 (0.2)			
Sema 4		±0.4			0.1 (0.2)	-0.1 (0.2)		**-0.2 (0.2)**	**-0.3 (0.2)**	-0.2 (0.1)	**-0.3 (0.2)**	
SF Dairy		±0.7			0.3 (0.3)	-0.2 (0.2)		-0.3 (0.2)	0.1 (0.2)	**-0.3 (0.2)**	-0.1 (0.3)	
Sylvus		±0.2			0.0 (0.1)	0.0 (0.1)		0.0 (0.1)	**-0.1 (0.1)**	**-0.4 (0.4)**	**-0.6 (0.7)**	

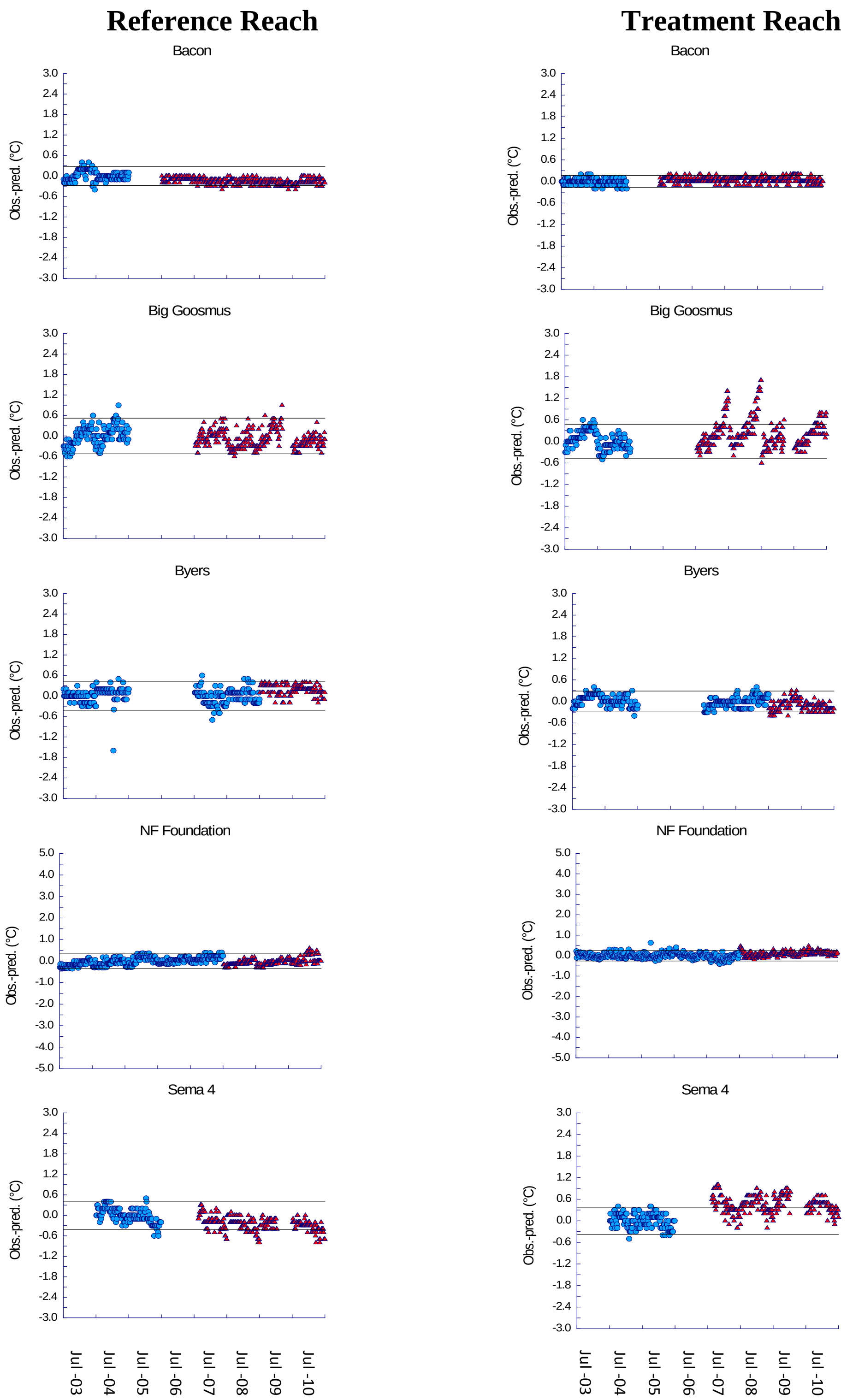


Figure 3.5. Difference between observed and predicted DMAX stream temperatures ($DMAX_{Response}$) in the treatment and reference reaches of five study sites. Data portrayed as blue diamond's were used to calibrate the regression model, while data portrayed in red triangles were used to test changes in distribution of responses during each post-harvest sample period at each study site. Dashed horizontal lines in the plots indicate 95% confidence intervals estimated as ±1.96 S_e (where S_e is the standard error of the residuals from the regression).

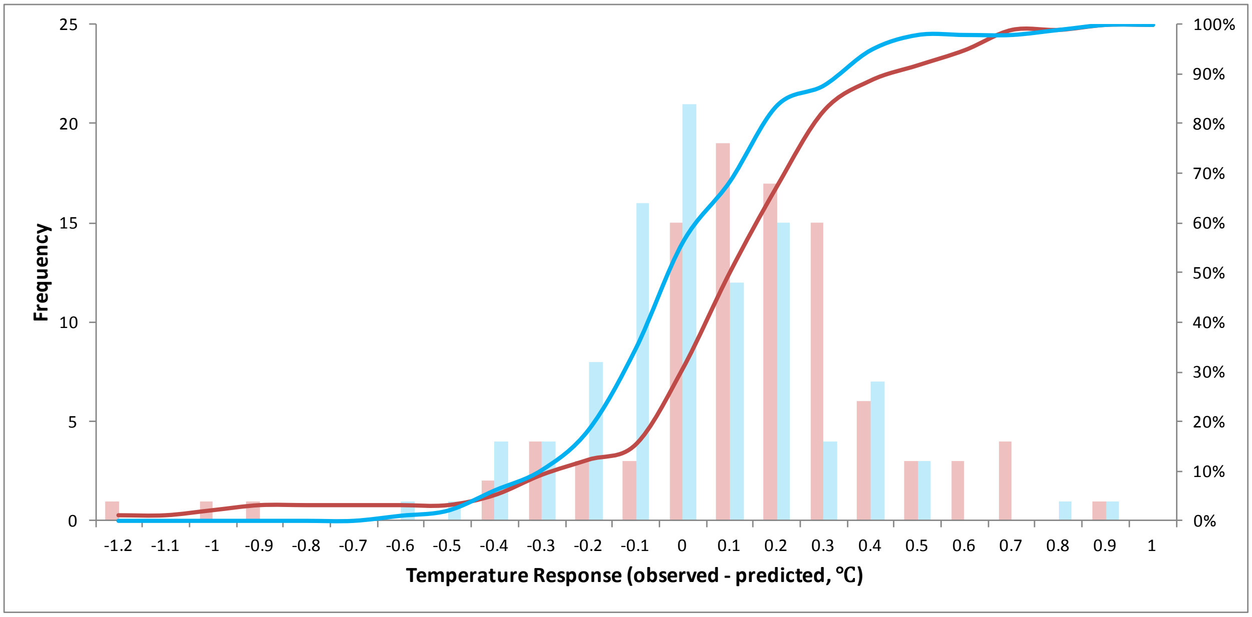


Figure 3.6. Frequency distribution of individual site sample period means of DMAX*Response* **across all post-harvest sampling years. Red and blue columns represent counts of site sample period mean** DMAX*Response* **observed in treatment and reference reaches, respectively. Red and blue lines represent cumulative frequency distribution for treatment and reference** DMAX*Response***, respectively. Sample size equals 98 for both treatment and reference reaches.**

3.2.1.2 Magnitude and Significance of Treatment Responses

DMAX*Response* in treatment reaches referred to as treatment response, ranged from -2.3 °C to 2.0°C, with study site means ranging from -0.7 °C at Seco to 0.5 °C for Sema 4 (Table 3.7). Site sample period mean treatment responses ranged from -1.2 °C (Seco, Post_4) to 0.8 °C (Dry, Post_2) [Table 3.8]. Treatment responses varied among sample periods within individual study sites, most notably in Dry (0.8 °C in Post_2 to -0.4 in Post_5), Sanpoil (0.7 °C in Post_1 to 0.2 in Post_2), Seco (-1.1 °C in Post_1 to -0.2 in Post_2), and Sylvus (0.2 °C in Post_1 to 0.6 in Post_3). A total of 29 of the 98 sample period mean treatment responses exceeded an absolute value of 0.2 °C, occurring in a least one sample period in 15 of the 30 study sites (Table 3.8).

The KS test indicated significant change in the uncorrelated random disturbances between the pre-harvest calibration and the post-harvest test periods for 46 of the 98 sample periods in the downstream treatment reach after timber harvest, representing 19 (9 ASR, 10 SR) of the 30 study sites (Table 3.8). Changes in the stream temperatures are not necessarily evident in the mean, but can be expressed by a change in variance following treatment (Table 3.8 and Appendix 6). Sample period mean treatment responses (observed minus predicted uncorrected for autocorrelation) were 0.2 °C or less in 27 of the 46 sample periods that the KS tests indicated significant changes in random disturbances. Approximately 89% of site sample period mean treatment responses were less than 0.5°C (Figure 3.6).

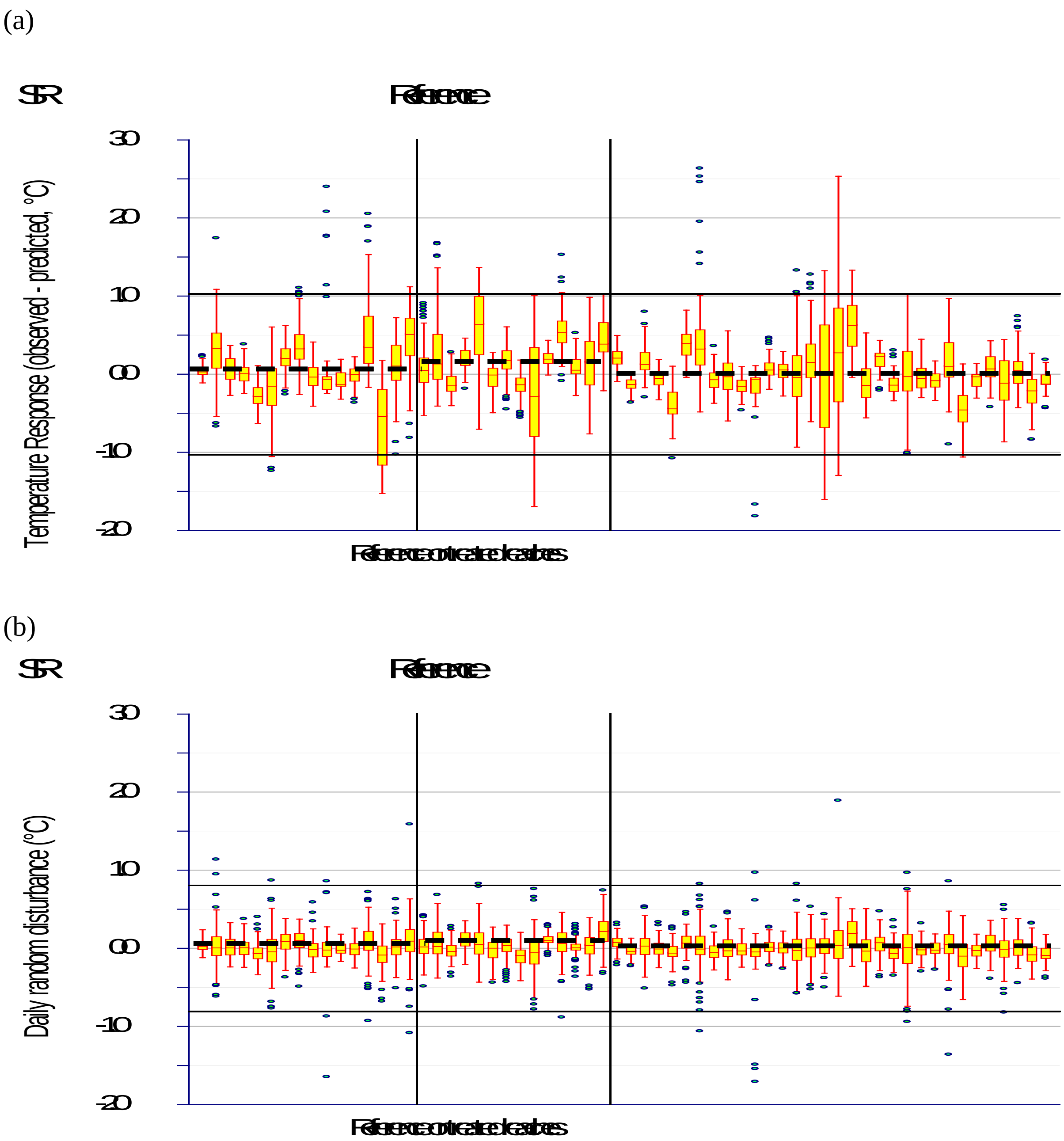


Figure 3.7. Changes in the maximum daily temperature between July 1 – September 15 during the first two post-calibration periods in the reference and treated reaches. (a) DMAX*Response* **(observed minus predicted maximum daily temperature) and (b) random disturbance (daily response corrected for residual autocorrelation). Box plots and whisker plots denote the median, quartiles, and 10 and 90 percentiles. Points represent more extreme values. The 95% confidence intervals (light dashed lines) were calculated as 0.0 ± pooled SD of (a) temperature responses and (b) uncorrelated random disturbances across all reference reaches in the calibration periods. The mean value for the reference and each treatment is indicated by the bold dashed lines on each plot.**

Table 3.7. Summary statistics of daily maximum temperature (°C) and DMAX$_{Response}$ for All Available Shade Rule and Standard Rule Prescriptions in treatment reaches over the course of the entire study.

Site	Pre-Harvest Temperature				Post-Harvest Temperature				DMAX$_{Response}$			
	Mean	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
All Available Shade Rule												
Bacon	7.9	0.7	5.9	9.8	7.4	0.7	5.0	9.5	0.0	0.1	-0.1	0.2
Clark	11.7	1.5	7.8	15.5	11.3	1.6	7.8	14.5	0.3	0.3	-0.7	1.7
Cole	15.5	2.1	10.7	19.5	15.1	1.9	10.8	19.1	0.1	0.1	-0.3	0.4
Dry Canyon	9.0	0.7	7.5	10.5	8.9	0.7	7.6	10.5	0.1	0.1	-0.3	0.4
Floedelle	11.5	1.9	7.1	15.3	11.5	1.8	7.4	14.8	-0.3	0.2	-0.6	0.1
Long Alec	11.6	1.7	7.3	14.7	10.6	1.8	6.5	14.3	-0.2	0.3	-1.2	0.6
Lotze	11.5	1.2	8.2	13.6	10.8	1.4	8.0	14.0	0.2	0.2	-0.3	0.6
Mill trib	12.5	1.6	8.6	14.9	12.2	1.5	8.7	15.4	0.2	0.4	-1.5	1.1
Moses	11.3	1.0	8.9	13.9	11.1	1.0	8.8	13.2	0.0	0.2	-0.4	0.4
NF Foundation	10.4	1.6	4.8	13.4	9.8	1.6	6.1	13.4	0.0	0.2	-0.3	0.6
Sanpoil	13.1	1.8	8.4	16.2	12.1	1.6	8.2	15.4	0.4	0.4	-0.3	2.0
Seco	10.7	1.4	7.4	13.3	10.0	1.3	7.1	13.1	-0.7	0.6	-2.3	0.2
Sema 1	8.6	0.5	7.6	9.7	8.6	0.7	7.1	9.8	0.1	0.3	-1.0	0.7
Sema 2	9.3	0.9	6.9	11.1	9.6	1.2	7.1	11.7	0.4	0.4	-0.8	1.1
SF Ahtanum	8.3	0.9	6.1	9.9	7.8	0.9	5.8	9.7	0.0	0.2	-0.4	0.7
Tungsten	13.7	1.2	10.6	17.0	13.5	1.9	8.9	17.7	0.1	0.3	-0.5	0.9
Standard Rule												
Big Goosmus	12.4	1.6	8.9	15.4	12.1	1.4	8.8	15.4	0.2	0.4	-0.6	1.7
Byers	12.2	1.6	8.6	15.3	11.7	1.7	8.2	15.2	-0.1	0.1	-0.4	0.3
Dorchester	13.3	1.4	9.5	15.3	13.1	1.6	9.5	16.4	0.2	0.1	-0.2	0.5
Dry Creek	11.7	1.3	7.8	14.3	11.4	1.5	6.8	14.8	0.1	0.7	-1.6	1.4
EF Cedar	9.6	1.0	7.2	11.7	9.3	1.1	6.4	11.5	0.0	0.1	-0.5	0.3
EF Cedar Trib	11.2	1.2	8.7	13.6	11.2	1.3	8.4	14.1	0.0	0.2	-0.6	0.6
Heel	8.8	0.9	6.7	10.7	8.8	0.9	6.7	10.9	-0.1	0.2	-0.6	0.3
Little Goosmus	13.7	1.6	8.5	17.4	12.5	1.8	8.7	16.0	-0.1	0.7	-1.7	1.3
Middle	9.9	1.1	7.0	11.7	10.0	1.2	7.1	12.4	0.2	0.1	0.0	0.4
Prouty	9.3	0.8	7.8	10.7	9.3	1.1	6.5	12.3	0.4	0.3	-0.5	1.6
Sema 3	10.4	1.1	7.9	12.1	10.1	1.2	7.4	12.6	0.2	0.4	-0.8	1.0
Sema 4	10.7	1.4	7.8	13.4	10.7	1.6	7.5	14.4	0.5	0.2	-0.2	1.0
SF Dairy	12.1	1.1	9.7	14.6	11.6	1.1	9.1	14.8	0.1	0.2	-0.3	0.6
Sylvus	11.9	1.5	7.8	14.1	11.1	1.7	7.5	14.8	0.4	0.4	-0.6	1.8

Table 3.8. Summary of mean (standard deviation in parentheses) DMAX$_{Response}$ (°C) and statistical significance of random disturbances in treatment reaches. Sample period represents years before or after harvest (i.e. Pre$_1$ = 1 year before harvest; Post$_1$ = 1 year after). Bold values during periods post-harvest periods indicate significant differences ($p<0.05$) in distribution of disturbance based on two-sample Kolmogorov-Smirnov test between pre-harvest and post-harvest disturbances. The first column (PL) provides the 95% prediction limits [±1.96 S$_e$ (where S$_e$ is the standard error of the residuals] from the pre-harvest regression.

	Sample Period									
	PL	**Pre$_4$**	**Pre$_3$**	**Pre$_2$**	**Pre$_1$**	**Post$_1$**	**Post$_2$**	**Post$_3$**	**Post$_4$**	**Post$_5$**
	All Available Shade Rule									
Bacon	0.2			0.0 (0.1)	0.0 (0.1)	**0.0 (0.1)**	**0.0 (0.1)**	**0.1 (0.1)**	0.0 (0.1)	0.0 (0.1)
Clark	1.3	-0.2 (0.3)	0.7 (0.3)	-0.6 (0.6)	0.2 (0.4)	0.2 (0.4)	0.4 (0.3)			
Cole	0.3		-0.1 (0.1)	-0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.0 (0.1)			
Dry Canyon	0.2			0.0 (0.1)	0.0 (0.1)	**-0.1 (0.1)**	**0.1 (0.1)**	**0.2 (0.1)**	**0.1 (0.1)**	
Floedelle	0.7	0.0 (0.2)	0.0 (0.5)	0.2 (0.4)	-0.2 (0.2)	-0.2 (0.2)	**-0.3 (0.1)**			
Long Alec	0.9		0.0 (0.4)	0.2 (0.4)	-0.2 (0.5)	-0.1 (0.3)	-0.3 (0.4)	**-0.1 (0.3)**		
Lotze	0.3			0.0 (0.2)	0.0 (0.2)	**0.2 (0.2)**	**0.2 (0.2)**	0.0 (0.1)		
Mill	0.5			0.0 (0.3)	0.0 (0.2)	**0.5 (0.3)**	0.2 (0.2)	0.1 (0.3)	0.0 (0.5)	**0.4 (0.3)**
Moses	0.6	-0.4 (0.2)	0.2 (0.2)	0.1 (0.1)	0.1 (0.1)	**-0.1 (0.2)**	0.0 (0.1)			
NF Foundation	0.3	-0.1 (0.1)	0.1 (0.2)	0.0 (0.1)	0.1 (0.1)	-0.1 (0.1)	-0.1 (0.1)	0.1 (0.2)		
Sanpoil	0.6			-0.2 (0.3)	0.2 (0.1)	**0.7 (0.5)**	0.2 (0.2)	0.3 (0.3)		
Seco	1.4			0.2 (0.7)	-0.1 (0.7)	**-1.1 (0.3)**	**-0.2 (0.2)**	**-0.4 (0.4)**	**-1.2 (0.5)**	
Sema 1	0.6			0.0 (0.3)	0.0 (0.3)	0.0 (0.3)	0.2 (0.3)			
Sema 2	1.2			0.0 (0.6)	0.8 (0.2)	0.6 (0.2)	0.3 (0.4)			
SF Ahtanum	0.4		0.1 (0.1)	-0.1 (0.2)	0.0 (0.1)	0.0 (0.1)	0.0 (0.1)	0.1 (0.2)		
Tungsten	0.7				0.0 (0.4)	-0.1 (0.2)	**0.2 (0.3)**	0.1 (0.3)	0.2 (0.3)	
	Standard Rule									
Big Goosmus	0.5			0.2 (0.2)	-0.1 (0.2)	0.2 (0.4)	**0.4 (0.5)**	0.0 (0.2)	0.2 (0.3)	
Byers	0.3	0.1 (0.1)	0.0 (0.1)	-0.1 (0.1)	0.0 (0.1)	-0.1 (0.2)	-0.2 (0.1)			
Dorchester	0.2			0.0 (0.1)	0.0 (0.1)	**0.2 (0.1)**	**0.2 (0.1)**	**0.3 (0.1)**	**0.1 (0.1)**	
Dry Creek	1.1			0.0 (0.5)	0.2 (0.6)	0.2 (0.4)	**0.8 (0.4)**	-0.4 (0.4)	0.2 (0.5)	-0.4 (0.4)
EF Cedar	0.2			0.0 (0.1)	0.0 (0.1)	**0.1 (0.1)**	**-0.1 (0.1)**	**0.1 (0.1)**	**0.1 (0.1)**	
EF Cedar Trib	0.3			-0.1 (0.1)	-0.1 (0.2)	**0.2 (0.2)**	0.1 (0.2)	-0.2 (0.2)	0.0 (0.1)	0.1 (0.1)
Heel	0.2			0.0 (0.1)	0.0 (0.1)	**-0.1 (0.1)**	**-0.2 (0.2)**	0.0 (0.1)		
Little Goosmus	1.6	-0.4 (0.5)	0.0 (0.8)	-0.2 (0.9)	0.4 (0.8)	-0.5 (0.6)	-0.1 (0.6)	0.2 (0.6)		
Middle	0.2			0.0 (0.1)	0.0 (0.1)	**0.2 (0.1)**	**0.2 (0.1)**			
Prouty	0.6			0.2 (0.1)	-0.1 (0.3)	**0.6 (0.3)**	**0.6 (0.2)**	**0.5 (0.3)**	0.3 (0.2)	
Sema 3	0.8			-0.2 (0.3)	0.2 (0.4)	0.3 (0.4)	0.0 (0.4)			
Sema 4	0.4			0.0 (0.2)	0.0 (0.2)	**0.4 (0.3)**	**0.5 (0.2)**	**0.6 (0.2)**	**0.4 (0.2)**	
SF Dairy	0.6			-0.2 (0.2)	0.2 (0.2)	0.1 (0.1)	0.2 (0.1)	0.2 (0.2)	0.1 (0.1)	
Sylvus	0.3			-0.1 (0.1)	0.1 (0.1)	**0.2 (0.1)**	**0.2 (0.1)**	**0.6 (0.5)**	**0.4 (0.5)**	

In the first two sample periods following harvest, uncorrelated random disturbances were statistically significant during at least one sample period for 9 ASR and 10 SR sites (Table 3.8), indicating a change in stream temperatures had occurred. Site sample period means of stream temperature response ranged from -1.1 to 0.8 °C. The sample period means of treatment response were 0.02 °C and 0.16 °C for the ASR and SR sites during the first two sample periods following harvest, respectively. Similar to the results observed in the reference reaches, most of the daily random disturbances fell within the 95% confidence interval calculated from the calibration data (Figure 3.7). The results suggest that even with the detection of significant differences in the distribution of treatment disturbances, the daily treatment responses ($DMAX_{Response}$ in treatment reaches) were within the range of background responses ($DMAX_{Response}$ in references reaches) that occurred in the absence of riparian harvest.

Significant treatment responses were observed beyond the 2-yr period and the timing of these responses varied among sites. Beyond the first two post-harvest periods, disturbances were statistically significant during at least one year for 5 of the 11 SR sites sampled for 3 or more seasons and 5 of 10 ASR sites sampled for 3 or more seasons (Table 3.8). Significant changes in disturbances were detected throughout four consecutive post-harvest periods for four SR sites (Dorchester, EF Cedar, Sema 4, and Sylvus) and two ASR sites (Seco and Dry Canyon). The timing of the significant changes was not always consistent with what was expected. Although we anticipated that significant treatment responses would be most evident during the first two years following timber harvest, none were observed for two ASR sites (Long Alec and Mill) until sample periods $Post_3$ and $Post_4$. Mean treatment responses at the Sylvus site more than doubled between sampling period $Post_2$ and $Post_3$.

3.2.1.3 Relationship of Air and Stream Temperature Responses

Post-harvest air temperature responses were estimated as deviations between observed air temperature in the treatment reach and predictions made from reference reach air temperatures using a GLS linear model fit during the pre-harvest period. DMAX air temperature responses ranged from -8.2 °C to 15.3°C (Table 3.9). The maximum response of DMAX air temperature varied from 2.8°C for Long Alec to 15.3°C for Sylvus. The mean response of DMAX air temperature ranged from -1.2 °C for Clark Creek to 7.0 °C for Sylvus. Post-harvest mean DMAX air temperature response varied between the ASR (0.7 °C) and the SR (2.4 °C) study sites

DMAX stream temperature treatment responses were correlated with DMAX air temperature responses. In the regression model, the effect of daily air temperature responses was significant in 21 of the 30 study sites (Table 3.10). DMAX air temperature response on average accounted for 3 to 38% of the variation observed in DMAX stream temperature treatment effect as indicated by r^2 values. Most notable relationships were observed in Middle ($r^2 = 0.38$) and NF Foundation ($r^2 = 0.22$) study sites. Air temperature accounted for less than 15% of the variability in stream temperature treatment effects in the remaining 28 sites. Interpretation of significance is complicated by the presence of residual autocorrelation in the regressions and heteroscedasticity for some of the sites. Consequently, we consider the relationship of air temperature response to stream temperature responses as an exploration of factors that may influence stream temperature response effects, rather than as a definitive test.

Table 3.9. Summary statistics of maximum daily air temperature (°C) and air temperature response for All Available Shade Rule and Standard Rule Prescriptions in treatment reaches during the two sample periods prior to and two sample periods following harvest.

	Pre-Harvest Temperature				Post-Harvest Temperature				Temperature Response			
Site	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
All Available Shade Rule												
Bacon	23.8	5.8	9.6	35.7	23.8	4.1	8.1	32.6	1.0	1.3	-1.5	4.0
Clark	24.6	5.2	12.9	36.8	23.2	5.3	10.9	32.6	-1.2	2.7	-7.3	7.4
Cole	25.2	4.5	13.4	33.5	28.1	5.8	13.8	38.2	2.4	3.5	-3.3	10.0
Dry Canyon	24.8	6.0	10.2	34.5	26.5	4.9	14.9	36.3	1.3	1.0	-0.4	4.6
Floedelle	20.3	5.4	11.7	33.3	19.1	4.2	10.9	29.1	-0.3	2.2	-3.6	5.6
Long Alec	22.8	5.9	8.1	35.5	21.9	5.1	10.0	31.6	0.0	0.9	-3.3	2.8
Lotze	19.1	4.7	8.3	27.1	21.9	4.5	10.8	31.1	3.4	1.5	-0.1	7.2
Mill trib	23.0	6.0	8.3	33.5	24.8	4.3	8.9	33.8	0.3	1.1	-2.9	3.9
Moses	23.1	4.9	11.7	32.7	23.0	5.1	11.5	33.1	1.9	1.1	-0.8	5.1
NF Foundation	22.9	5.2	4.8	33.9	24.2	5.4	8.8	34.5	0.5	3.0	-7.4	6.3
Sanpoil	26.0	7.1	9.7	38.2	22.5	4.5	11.6	31.3	-1.7	1.0	-4.6	0.9
Seco	21.2	6.1	7.9	32.6	24.0	6.0	12.0	34.9	1.3	1.8	-2.8	7.5
Sema 1	22.9	4.2	11.7	30.0	22.1	5.3	10.7	31.7	1.0	0.9	-1.4	3.9
Sema 2	24.0	5.8	7.7	33.7	22.9	5.8	10.7	32.3	1.7	1.2	-1.0	5.3
SF Ahtanum	20.3	4.4	9.3	28.5	21.3	4.1	8.3	30.6	0.3	2.5	-6.6	5.7
Tungsten	27.9	5.5	9.8	38.1	26.0	5.4	14.5	37.5	-0.8	2.8	-8.2	5.6
Standard Rule												
Big Goosmus	23.0	5.8	8.6	32.5	25.6	5.1	13.8	36.8	2.4	2.8	-6.4	11.2
Byers	22.7	4.4	12.6	33.8	22.9	5.0	11.3	31.7	2.0	2.5	-5.1	7.1
Dorchester	21.8	4.4	10.6	30.3	27.7	6.1	14.5	38.1	6.4	3.4	-0.7	13.3
Dry Creek	23.6	5.4	9.9	33.6	24.5	4.6	8.3	32.7	-1.8	1.9	-5.5	2.9
EF Cedar	21.0	5.4	8.1	31.0	22.2	4.3	11.5	30.8	1.5	1.1	-1.2	4.1
EF Cedar Trib	20.3	5.9	8.5	29.7	24.8	5.0	12.3	35.3	1.9	0.9	-0.3	4.2
Heel	17.3	4.3	7.3	25.8	20.3	4.1	10.3	27.7	2.0	1.3	-1.3	4.8
Little Goosmus	23.1	4.0	6.2	30.5	24.8	4.8	12.7	34.6	1.7	2.3	-6.9	7.9
Middle	18.2	4.7	7.3	27.3	20.0	4.7	10.2	28.9	1.8	2.0	-3.5	5.9
Prouty	22.3	4.2	12.4	29.3	24.1	4.6	11.6	35.0	2.5	1.6	0.0	9.2
Sema 3	25.3	6.5	8.5	35.4	27.5	7.1	11.8	38.2	2.6	2.8	-4.0	11.4
Sema 4	20.9	5.9	7.6	29.9	27.6	6.0	12.4	38.3	4.3	3.1	-0.8	12.1
SF Dairy	29.4	6.4	11.6	38.3	29.0	4.7	14.9	38.3	-0.2	3.2	-5.9	7.2
Sylvus	22.5	6.0	8.7	31.9	29.5	5.8	13.4	37.8	7.0	3.3	0.0	15.3

Table 3.10. Summary of the correlation of maximum daily air temperature (°C) temperature response and DMAX$_{Response}$ for All Available Shade Rule and Standard Rule Prescriptions in the treatment reach during the two sample periods following harvest. The coefficient of determination describing how well the regression fits the data is shown as r^2 and its significance level is shown as p.

Site	Air Temperature Response (°C)	Stream Temperature Treatment Response (°C)	r^2	p
All Available Shade Rule				
Bacon	-0.8	0.1	0.01	0.03
Clark	0.3	0.0	0.06	0.00
Cole	1.7	0.5	0.00	0.96
Dry Canyon	1.0	0.1	0.13	0.00
Floedelle	1.3	-0.7	0.04	0.02
Long Alec	-1.8	-0.1	0.02	0.04
Lotze	0.5	-0.1	0.13	0.00
Mill	1.9	0.0	0.00	0.05
Moses	0.3	0.4	0.12	0.00
NF Foundation	3.4	0.2	0.22	0.00
Sanpoil	0.0	-0.2	0.04	0.00
Seco	-0.3	-0.3	0.04	0.00
Sema 1	1.3	0.0	0.00	0.04
Sema 2	2.4	0.1	0.01	0.19
SF Ahtanum	-1.2	0.3	0.01	0.12
Tungsten	1.0	0.0	0.03	0.00
Standard Rule				
Big Goosmus	7.0	0.2	0.12	0.00
Byers	-0.2	0.1	0.08	0.00
Dorchester	4.3	0.4	0.09	0.00
Dry Creek	2.6	0.2	0.14	0.00
EF Cedar	2.5	0.6	0.01	0.12
EF Cedar trib	1.8	0.2	0.08	0.00
Heel	1.7	-0.3	0.05	0.00
Little Goosmus	2.0	-0.2	0.00	0.40
Middle	1.9	0.2	0.38	0.00
Prouty	1.5	0.0	0.00	0.29
Sema 3	-1.6	0.5	0.13	0.11
Sema 4	6.4	0.2	0.01	0.20
SF Dairy	2.0	-0.1	0.14	0.00
Sylvus	2.4	0.3	0.00	0.40

3.2.2 Prescription / Shade Rule Effectiveness – Pooled Analysis

Stream temperature response differed slightly between the SR harvest ($\bar{X}$ = 0.16 °C; 95% CI = 0.04, 0.29), ASR harvest ($\bar{X}$ = 0.02 °C; 95% CI = -0.01, 0.14), and the no-harvest reference ($\bar{X}$ = 0.02 °C; 95% CI = -0.07, 0.10). Within each RMZ prescription level, stream temperature response varied only slightly between the first and second years following harvest (Figure 3.8). Following harvest, planned comparisons revealed $\mathrm{DMAX}_{Response}$ increased at SR sites relative to no-harvest reference sites on average by 0.15 °C (Table 3.11, 95% CI= -0.01, 0.30). Likewise, $\mathrm{DMAX}_{Response}$ increased at SR sites relative to ASR sites on average by 0.15 °C (95% CI= -0.03, 0.32). Harvest on ASR sites did not produce a temperature response that differed from the no-harvest background responses.

Table 3.11. Individual comparison of seasonal means of post-harvest DMAX stream temperature responses ($\mathrm{DMAX}_{Response}$) for RMZ prescriptions types. F-Value is based on the F approximation of Kenward and Roger (1997). Given the limited numbers of made, the probability values gives the strength of evidence for a single comparisons, unadjusted for multiple testing.

Comparison Hypothesis	Mean Difference	Standard Error	F-Value	Probability
ASR – No-Harvest = 0	0.00	0.074	0.000	0.998
SR – No-Harvest = 0	0.146	0.078	3.695	0.059
ASR - SR = 0	0.146	0.088	2.884	0.095

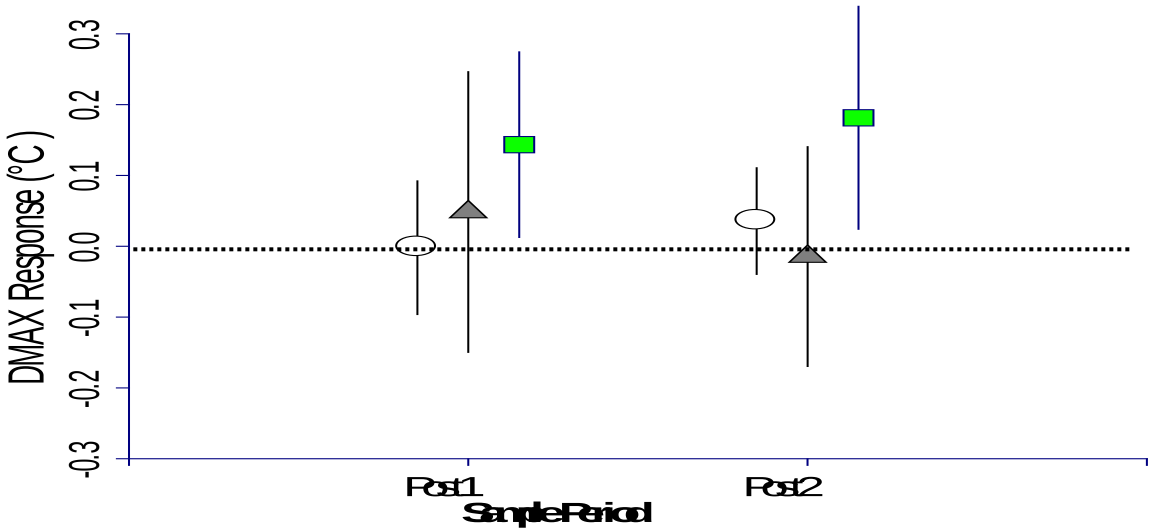


Figure 3.8. Stream temperature response for the no harvest reference (open ellipses, n=30), All Available Shade Rule (ASR, grey triangles, n=16) and Standard Rule (SR, green rectangles, n = 14) prescriptions in first and second sample periods immediately after timber harvest. Vertical bars represent 95% confidence limit of mean stream temperature response.

3.2.3 Site Descriptives, Shade, Canopy Closure, Solar Input, Climate Data and Stream Temperature Responses

In northeastern Washington (where most of the sites are located), mean summer temperatures were warmer than the other sample years (Table 3.12). In the southeast Cascades region (where the remaining sites are located), the summer of 2003 was warmest. Total hydrologic year precipitation and mean stream flow during the study period, as measured by regional climate data stations, also varied across the study years. Total 12-month precipitation was highest during 2006 across eastern Washington. Regional climate attributes as measured at three regional SNOTEL stations were not significantly correlated with mean $DMAX_{Response}$ (Table 3.12).

Site descriptive variables of channel, riparian, and basin characteristics were examined to determine if they could account for differences in $DMAX_{Response}$ between prescription types. Stream channel attributes were consistent between the SR and ASR sites in both the reference and treatment reaches (Table 3.3). Site descriptive variables describing the basin (watershed area, elevation), channel (channel gradient, bankfull channel width, degree deviation from east to west), air temperature, base flow and pre-harvest values of shade, basal area, trees per acre, and solar input were not significantly correlated with mean DMAX treatment effects in either the ASR or SR sites (Table 3.13).

Other treatment response variables that were derived from pre-harvest to post-harvest computations, including air temperature response, change in shade following harvest, change in solar radiation attenuation, reduction of trees per acre and basal area in the inner zone, and reduction of trees per acre and basal area in the outer zone, provided little additional insight to factors influencing average treatment effects in the treatment reach (Table 3.14). Although correlation between DMAX air temperature response and DMAX stream temperature responses was found to be significant under the site-specific evaluations, we found no correlation of seasonal means of $DMAX_{Response}$ with the ADMAX air temperatures in the pooled analysis.

Table 3.12. Climate data (total 12-month precipitation encompassing October from previous calendar year through September of listed year) and air temperature during the study period (July 1 – September 15) at three regional SNOTEL stations. Mean stream flow and maximum water temperature recorded for July 1 – September 15. Pearson's correlation coefficient with treatment reach annual mean DMAX$_{Response}$ is shown as *r* and its significance level is shown a *p*.

	2003	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	***r***	***p***
Southeast Cascades										
P, inches	30.8	30.6	29.8	48.1	28.1	36.2	36.5	42.1	***0.29***	***0.21***
Air T_{max} °C	31.6	27.1	27.1	29.5	28.6	28.3	28.5	26.1	***0.22***	***0.36***
Air T_{mean} °C	13.5	12.5	12.4	13.6	13.1	12.1	13.4	11.5	***-0.27***	***0.25***
Ahtanum Q_{mean} ft^3 s^{-1}	19.0	22.3	15.5	23.8	22.8	31.2	25.9	40.0	***-0.34***	***0.15***
Northeast Highlands – Kettle Range										
P, inches		22.0	24.2	25.8	17.3	22.7	23.2	25.6	***-0.02***	***0.91***
Air T_{max} °C		30.0	28.1	32.8	30.7	30.6	29.9	28.7	***0.13***	***0.48***
Air T_{mean} °C		15.6	14.9	17.0	16.7	14.9	15.8	14.1	***-0.20***	***0.26***
Kettle River Q_{mean} ft^3 s^{-1}	533.5	1330.1	1068.1	898.9	702.0	787.4	711.5	1067.9	***0.07***	***0.71***
Northeast Highlands – Pend Oreille										
P, inches	50.3	49.6	42.9	61.8	49.7	46.2	46.7	58.4	***0.02***	***0.84***
Air T_{max} °C	31.2	30.8	27.7	33.7	32.1	30.6	28.8	26.3	***0.00***	***0.96***
Air T_{mean} °C	13.5	13.1	12.7	14.4	14.6	12.0	12.8	11.2	***0.00***	***0.98***
Chamokane Q_{mean} ft^3 s^{-1}	28.0	26.2	20.8	29.6	27.8	28.0	26.3	27.6	***0.06***	***0.48***

Table 3.13. Means of channel descriptives in treatment reaches of the eastern Washington Riparian Shade and Temperature Study. Pearson's correlation coefficient with mean $\text{DMAX}_{Response}$ in the treatment reaches during the first two post-harvest sample periods is shown as *r* and its significance level is shown a *p*.

Site	**Basin Size (acres)**	**Elevation (feet)**	**Channel Gradient (%)**	**Base flow discharge (ft^3 / sec)**	**Bankfull Width**	**Azimuth**	**%Gravel**
All Available Shade Rule							
Bacon	2614	3163	11	1.5	12.7	1	58
Clark	705	3275	3	<0.1	5.8	86	65
Cole	11814	1852	4	1.6	14.5	81	50
Dry Canon	1641	2132	4	0.5	6.5	37	54
Floedelle	2855	3344	3	0.2	9.8	8	62
Long Alec	2199	4108	6	0.1	8.6	23	50
Lotze	1809	3379	7	0.9	14.4	90	73
Mill trib	273	3430	12	0.0	5.8	44	54
Moses	880	2985	7	0.5	7.6	78	85
NF Foundation	1619	4691	10	0.5	12.7	40	42
Sanpoil	2387	3307	5	0.0	6.1	20	54
Seco	1318	3444	5	0.4	7.9	80	65
Sema 1	234	3441	7	0.0	5.2	9	58
Sema 2	333	3450	9	0.0	6.7	55	58
SF Ahtanum	2478	4426	9	3.7	20.8	2	54
Tungsten	213	3233	8	0.0	3.9	35	50
r	**-0.09**	**-0.09**	**0.24**	**-0.05**	**-0.08**	**0.09**	**-0.01**
p	**0.63**	**0.63**	**0.19**	**0.78**	**0.68**	**0.62**	**0.95**
Standard Rule							
Big Goosmus	1129	3105	9	0.2	9.5	10	75
Byers	1337	3353	5	0.1	13.5	13	83
Dorchester	2082	2145	6	0.6	10.2	9	46
Dry	2426	3518	16	0.2	22.5	88	8
EF Cedar	3686	3164	7	2.4	16.7	5	0
EF Cedar trib	757	3123	11	0.3	8.8	4	0
Heel	298	3796	9	0.2	5.5	60	42
Little Goosmus	933	3221	11	0.0	6.0	36	65
Middle	2251	3682	10	1.9	12.8	48	25
Prouty	349	3962	16	<0.1	9.7	4	58
Sema 3	922	3443	2	0.4	8.0	63	42
Sema 4	429	3418	7	0.1	5.0	75	65
SF Dairy	2009	2270	6	0.4	12.2	13	50
Sylvus	1789	3279	5	0.6	8.7	57	88
r	**-0.04**	**0.13**	**0.36**	**-0.12**	**0.22**	**0.15**	**-0.08**
p	**0.84**	**0.51**	**0.06**	**0.53**	**0.27**	**0.44**	**0.67**

Table 3.14. Means of pre-harvest to post-harvest changes in riparian attributes, shade, incoming solar radiation, and air temperature in treatment reaches of the Eastern Washington Stream Shade and Temperature Study. Pearson's correlation coefficient with mean $\mathrm{DMAX}_{Response}$ in the treatment reaches during the first two post-harvest sample periods is shown as *r* and its significance level is shown a *p*.

Site	Air Temperature Response (C°)	Shade Reduction (%)	*t* Solar Attenuation Reduction (%)	Increase of Post-harvest Solar Radiation (W/m^2)	Reduction Basal Area (ft^2/acre)	Reduction Trees per Acres
All Available Shade Rule						
Bacon	1.1	1.2	-0.3	1.1	8	10
Clark	-1.2	0.8	-1.0	14.6	7	19
Cole	2.4	1.1	3.7	-2.6	7	34
Dry Canyon	1.4	-3.7	-3.4	15.9	27	53
Floedelle	-0.3	1.5	1.9	2.5	23	24
Long Alec	0.2	0.0	7.2	-53.0	3	19
Lotze	3.2	5.0	2.5	-9.4	21	34
Mill trib	1.3	0.2	-0.7	3.0	13	51
Moses	1.9	2.6	0.6	-6.6	28	63
NF Foundation	-0.4	2.9	-0.1	9.5	39	53
Sanpoil	-0.8	2.3	2.5	-28.4	-1	5
Seco	1.3	1.0	-2.0	40.5	6	24
Sema 1	1.0	3.1	0.5	-3.6	-11	-15
Sema 2	1.7	0.9	-1.3	2.6	-9	0
SF Ahtanum	0.1	1.3	-4.3	32.3	17	39
Tungsten	0.4	3.5	1.0	-11.2	6	24
r	**0.11**	**0.02**	**-0.09**	**-0.08**	**0.07**	**-0.02**
p	**0.54**	**0.91**	**0.63**	**0.64**	**0.69**	**0.91**
Standard Rule						
Big Goosmus	2.4	2.8			96	126
Byers	2.0	1.6			60	58
Dorchester	5.9	5.5			79	97
Dry	-0.3	10.1			13	10
EF Cedar	0.6	3.2			35	58
EF Cedar trib	1.9	-0.6			33	106
Heel	2.0	5.0			28	73
Little Goosmus	1.6	4.3			55	102
Middle	1.8	2.2			103	111
Prouty	3.2	3.0			112	208
Sema 3	2.6	1.1			35	155
Sema 4	5.1	8.5			37	116
SF Dairy	-1.3	4.1			13	68
Sylvus	7.3	8.1			172	184
r	**0.03**	**0.32**			**-0.13**	**-0.18**
p	**0.89**	**0.10**			**0.50**	**0.37**

4 Discussion

We quantified and compared the response of canopy closure, shade, solar radiation, and stream temperature for two riparian timber harvest prescriptions by examining differences between pre- and post-harvest summer daily maximum stream temperatures. No harvest was allowed within 30 ft of the stream banks in either prescription. In the ASR prescriptions, requirements included retention of all available shade within 75 ft of the stream bank, whereas the SR prescriptions required leaving sufficient shade, trees per acre, and basal area per acre based on elevation and forest type as defined in the Washington Forest Practice Rules and Practices Board Manual. On average, changes in canopy closure, shade, solar radiation, air temperature and stream temperature following harvest were small.

4.1 Prescription Effectiveness at Maintaining Shade

Reduction in canopy closure and shade was small under both the SR and ASR prescriptions. Mean change in pre-harvest to post-harvest shade measurement was greater in the SR sites (-5%) than in the ASR sites (-1%). Although the all available shade rules are designed to prevent removal of trees that provide shade to the stream within 75 ft of the stream bank, measured post-harvest shade values decreased in 13 of the 16 ASR sites as much as 5%. Shade reductions of this magnitude may be caused by three factors, 1) harvest of trees outside of the 75-ft wide band resulted in reduction of stream shade, 2) field crews misjudged which trees actually provided shade to the channel, or 3) measurement error. However, an analysis of retained upland trees' contribution to shade indicated that trees further than 75 feet contributed less than 0.7% to effective shading at all stations investigated. All of the trees situated beyond 75 feet from the stream were very low in the sky and often masked by retained trees and other vegetation closer to the channel. Four of the five RMZ-only harvest sites had a reduction in post-harvest shade values, so it is unlikely that the shade reduction was a result of trees harvested outside of 75 feet. Field crews can have difficulty in discerning which trees do not contribute shade to the stream. Errors in judgment may be inevitable, especially considering that nearly every tree designated for harvest was situated behind another that was designated for retention. At times the core zone trees and other trees designated for retention in the inner zone appear to completely mask the designated take tree, but once the take tree is harvested, a small reduction in shade may result. The reductions in shade and canopy closure within the ASR sites may also be a result of measurement error. The ability of field crews to consistently measure canopy closure and shade within a 3-5% margin of error may be limited. In previous studies examining forest canopy closure measurement techniques, (Cook et al. 1995, Jennings et al. 1999, Lemmon 1956), the percent of variation attributable to crew measurement for canopy closure as measured with a spherical densiometer were reported to be from 3% to 7%.

Change in shade following harvest in SR sites was as much as -10%, with a mean of - 4%. Washington Forest Practice Rules require retention of at least 50 trees per acre and adherence to an established minimum basal area, depending upon site index in the area 30 to 75 feet away from the stream bank. If necessary, the rules further require tree retention to ensure post-harvest shade remains above elevation-specific minimum canopy closure levels. None of the 14 SR sites required retention of any additional trees beyond the minimum leave tree requirement to achieve minimum shade levels. That is, the units were first laid out in accordance with leave tree densities and basal area requirements. No additional tree retention was needed to meet the minimum shade requirements. Due to the range in site elevations, post-harvest canopy closure requirements in the sites harvested under the SR prescriptions ranged from 1% to 84%, based on nomographs in Section 1 of the Forest Practices Board Manual (Table 2.4). However, canopy closure at one site (Dorchester) was reduced below the minimum requirement by 2%; the minimum requirement was 84% whereas the post-harvest canopy as measured by the handheld densiometer was 82%.

The measured shade values within treatment reaches were greater during the post-harvest period in two sites (one in each prescription). Increased shade following harvest may be due to tree or shrub growth (especially hardwoods) or the repositioning of vegetation that existed prior to the harvest (for example, individual trees or branches leaning over measurement locations).

The pre- to post-harvest changes in measured shade and canopy closure values may be within the measurement accuracy and precision of both the hemispherical photograph and hand-held densiometer readings. In the treatment reaches, reduction in measured shade values (hemispherical photography) was equal to or exceeded 5% in one ASR and 6 SR sites. Changes in measured change in canopy closure values exceeded 5% in 3 ASR sites and 8 SR sites.

Shade reductions between SR and ASR study sites were similar (3 % and < 1% respectively). Such small difference is not surprising given that both prescriptions require retention of a 30 foot wide core zone where no trees are harvested. In addition, the SR rule requires tree retention of at least 50 of the largest trees per acre in the inner zone (between 30 to 75 feet). It appears that in these study sites, the tree retention rules provide for more shading in most cases than would be specified by shade rules alone.

In our study, the basic riparian harvest prescriptions for basal area and stem density restrictions were similar within 75 ft of the channel for both treatment types; however the requirement for shade retention was different between the two prescriptions. Within the SR sites, the allowable basal area and stem density was not restricted by the shade restrictions. Within the ASR sites, the allowable basal area and stem densities were often overridden by the all available shade restrictions. Considering how the two shade rule restrictions differentially affect the allowable harvest within the riparian management zone, it was notable that the difference in pre-harvest to post-harvest shade between the SR and ASR sites was as small as it was. Canopy closure was reduced by more than 10% in only 2 sites within the SR prescription group.

4.2 Relationships Among Shade and Riparian Characteristics

Although overall changes in shade were small, variability in post-harvest changes in shade measured with hemispherical software ranged from +3% to -10%, whereas canopy closure values measured with a hand-held densiometer ranged from +7% to a decrease of -17%. We examined if the ranges in response could be accounted for by differences in harvest level, natural tree mortality due to windthrow or disease, channel widths, stream aspect, or level of pre-harvest shading. We expected that wider channels and streams oriented in a more east-west direction would be more susceptible to shade reduction following harvest. However, channel azimuth or bankfull channel width of treatment reaches were not related to post-harvest shade values or to pre-harvest to post-harvest change in shade values. The lack of correlation between channel width and change in shade is likely influenced by the limitation on the size of channel that was included in the study. Note that under the SR sites, the widest channel had the largest decrease in shade following harvest (Dry, channel width = 22 ft, -10% pre- to post-harvest change in shade). However, the second widest channel among the SR sites demonstrated one of the smallest changes in shade following harvest (EF Cedar, channel width =16 ft, -3% pre- to post-harvest change in shade).

Unlike other studies on the relationships between shade and stand attributes, changes in shade values following timber harvest in this study cannot be accounted for by the changes in any of the riparian stand characteristics, including tree density, mean tree height, and mean tree diameter. In a study located in the Oregon Coast Range, where post-harvest shade values ranged between 50% - 90%, Groom et al. (2011) found that up to 75% of variability in post-harvest shade values could be accounted for by tree height and basal area within approximately 100 ft of the stream bank. DeWalle (2010) found in a modeling study that buffer height and density were as important as buffer width in providing shade. Modeling tools developed by Beschta and Weathered (1984) and Chen et al. (1998) indicate that shade is more closely correlated with tree height and canopy closure. We found no correlation among basal area, tree height, tree density, shade, and incoming radiation in either the pre-harvest or post-harvest period.

Similarly, metrics describing the pre-harvest to post-harvest changes in stand attributes did not account for variability in changes in shade following harvest. We had anticipated that the allowable harvest in SR sites would result in a greater reduction in shade value, where post-harvest canopy closure requirements were typically well below the existing pre-harvest canopy closure. However, even in sites where more than 50% of the basal area was harvested within the inner zone (30 – 75 ft from the stream bank), we observed on average less than 5% reduction in shade. These findings suggest that stream shading in these small channels was controlled largely by complete retention of trees within 30 ft of the stream banks and the requirement of leaving 21 of the largest trees and 29 other codominant trees per acre in the inner zone (between 30 and 75 ft of the stream bank). In most situations, the codominant trees were retained within 50 ft of the stream bank due to felling and harvest logistics. The largest leave trees were scattered throughout the inner zone, as the largest 21 trees per acre had to be retained regardless of their position.

Sites in this study were consistently well-shaded with high levels of canopy cover both prior to and after harvest. Such conditions limited the usefulness of stand attributes as a predictor of shade in both pre-harvest and post-harvest periods. Pre-harvest shade values in both the reference and treatment reach of all 30 study sites exceeded 89%. Following harvest, treatment reach shade values all exceeded 79%, with only 3 of 30 sites attaining post-harvest shade values of 85% or lower. These findings further illustrate the effectiveness of the two prescriptions in maintaining shade levels of forested streams similar to the study sites.

4.3 Stream Temperature Response to Harvest

Small increases in stream temperature occurred in specific streams after harvest under both the ASR and SR prescriptions. Site level evaluations demonstrate that both the mean and/or variance in temperature responses changed in at least one season in 10 of 14 SR and 9 of 16 ASR sites following timber harvest. Yet temperatures also changed in 19 of 30 no-harvest reference reaches during at least one season during the post-harvest sampling period. Although the KS test indicated significant differences in 19 treatment reaches in some years, the results were inconsistent across years and the mean response was 0.2 °C or less in 27 of the 46 sample period means in which significant differences were determined.

Statistical tests conducted under the pooled analysis revealed that temperature changes following harvest were not significantly different in the no-harvest, ASR harvest, and SR harvest reaches at a probability level of $\alpha = 0.05$. However, the marginal test results of $p = 0.059$ for the difference in sample period mean $\mathrm{DMAX}_{Response}$ between the no-harvest and SR harvest reaches and $p = 0.095$ for sample period mean $\mathrm{DMAX}_{Response}$ between the SR and ASR harvest suggest that small increases in stream temperatures may be more likely under the SR harvests. The mean difference in post harvest $\mathrm{DMAX}_{Response}$ between the SR harvest and no-harvest reaches, as well as the differences between the SR harvest and ASR harvest reaches, was very small (estimated as 0.15 °C in both cases).

Over the course of the study, we observed sample period mean $\mathrm{DMAX}_{Response}$ ranging from -1.2 to 0.9 °C across the reference and treatment reaches. The range in temperature responses could be due to a number of factors, including harvest effect, management conducted further upstream in the basin, or natural influences. We examined several factors that could possibly explain the variability in temperature responses, including the harvest intensity, changes in shade following harvest, riparian stand attributes both before and after harvest, channel characteristics, including gradient, azimuth, size, flow, and bed conditions, and other disturbance factors. None of these factors accounted for variability in temperature responses. This lack of correlation is likely due to the fact that there was very little change in stream temperature following harvest throughout most of the reference and treatment reaches.

Solar radiation is a key driver of midday high stream temperatures (Beschta and Taylor 1988), and several studies have established the importance of shade for maintaining stream temperature (Brown 1970, Beschta et al., 1987). Because direct solar radiation has been shown to be the primary contributor to maximum summer stream temperatures at the site level (Ice 2000, Johnson 2004, Moore et al. 2005a), differences in temperature responses should, in part, be reflected by stream shading. However, the five sites with the greatest post-harvest shade levels and the least shade reduction observed in the study (Dry Canyon, Bacon, Mill, EF Cedar trib, Sema 2) exhibited stream temperature responses ranging from -0.1°C to 0.6 °C. Daily maximum stream temperatures were not significantly correlated to shade or the change in shade following harvest. Higher or lower levels of shade, or change in shade in the treatment reaches, did not appear to affect temperature response. For instance, the site with the highest DMAX stream temperature response (Sema 3) had the 2nd smallest decrease in shade following harvest. The Dry Creek site that had the lowest shade value (79%) following harvest and greatest reduction in shade (-10%), yet ranked at the bottom 40% in temperature response. No relationships among shade or change in shade were apparent. Within the ASR sites, we also examined the influence of incoming solar radiation, as measured in the companion Solar Study (McGreer et al. 2011). Similar to our canopy closure and shade measures, the solar study also found only a very small increase in thermal energy input in the ASR sites. The mean increase in solar radiation of +3.0 $\mathrm{W\ m^{-2}}$ was not statistically significant and within the range of the instrument measurement error. Likewise, the mean canopy attenuation decrease of 0.43% was not statistically significant.

These small changes in shade and incoming solar radiation are consistent with the small changes in stream temperature. The Solar Study (McGreer et al. 2011) predicted the small change in energy would not cause a significant temperature change, which is consistent with our results. Incoming solar radiation, or changes to incoming solar radiation, did not account for variation in stream temperature responses. We found no correlation between changes in solar radiation and solar attenuation with stream temperature treatment responses. However, as previously mentioned, sites in this study were consistently well-shaded with high levels of canopy closure both prior to and after harvest. Such conditions limited the usefulness of shade and incoming solar radiation as a predictor of stream temperature pre-harvest or stream temperature response post-harvest. The results from the ASR sites indicate that removing trees that don't qualify as "all available shade" does not significantly affect attenuation of solar radiation, stream shading, or stream temperature. In other words, the ASR requirement when implemented carefully can be effective at preserving all available shade.

We initially expected that climate, channel and stand attributes would influence stream temperatures and their response to timber harvest. For example, we expected that temperature responses may be higher at sites or during periods with higher ambient air temperatures (as measured by reference reach air temperature), lower baseflow discharges, wider bankfull channels, and east/west trending streams. We examined how these factors accounted for variation in stream temperature background and responses to timber harvest. None of these factors helped explain the variability in mean stream temperature responses observed across the study sites. However, site-specific evaluations indicated that the post-harvest $DMAX_{Response}$ was related to post-harvest daily air temperature response in some sites. Most notable was the relationship exhibited between air and stream temperature in Middle Creek and NF Foundation. Both of these channels had only about a 2% reduction in shade. While we did find significant relationships among daily stream and air temperature response at the site level, the mean air and stream temperature response for all sites was not related. There was no apparent relationship among pre-harvest to post-harvest changes in shade, stream temperature, or air temperature. But given the fact that 21 of the 30 sites exhibited mean post-harvest stream temperature response of between -0.2 and 0.2 °C, it is not surprising that we found no strong associations with other contributing factors.

4.4 Magnitude of Harvest Effects

Post-harvest $DMAX_{Response}$ varied from -2.3 °C to 2.0 °C under the ASR harvest and from -1.6 °C to 1.8 °C under the SR harvest over the course of the entire study. $DMAX_{Response}$ varied between -1.7 °C to 2.6 °C in the no-harvest reference reaches. Sample period means of $DMAX_{Response}$ in treatment reaches during the first two years following harvest averaged 0.02 °C (range -1.1 °C to 0.7 °C) in the ASR harvest reaches and 0.16 ° (range -0.5 °C to 0.8 °C) in the SR harvest reaches. In reference reaches, sample period means of $DMAX_{Response}$ during the first two post harvest years averaged 0.02 °C and ranged from -0.5 °C to 0.9 °C. Seasonal mean $DMAX_{Response}$ equal or exceeding 0.3 °C were observed at 10 treatment sites during at least one season. $DMAX_{Response}$ equal or exceeding 0.3°C was observed in 7 reference reaches during at least one season.

The magnitudes of both daily and sample period mean stream temperature responses reported for this study are smaller than effects found in many previous studies evaluating timber harvest practices with riparian buffers. The effects are substantially lower than values associated with harvesting without buffers. In the Needle Branch Watershed, DMAX water temperature increased 10 °C following clear-cut harvest to the stream (Brown 1970). Gomi et al. (2006) found that for four headwater streams subject to clear-cut harvesting with no buffer retention, DMAX temperatures increased between 1.9 °C and 8.8 °C with seasonal mean values between 0.4 °C and 3.9 °C, while a stream with a 33 ft buffer exhibited a maximum daily increase of 4.1 °C and a seasonal mean increase of 1.0 °C. Gomi et al. (2006) reported temperature effects more consistent with this study under treatments that included a 100 ft no harvest buffer; maximum daily temperature increases ranged between 0.7 °C to 2.2 °C with seasonal means ranging from -0.2 °C to 0.4°C . They also observed control reach temperature changes in the post-harvest period, with daily maximums from -0.3 °C to 0.8 °C and seasonal means between -0.6 °C and 0.1 °C

Other research on stream temperatures indicate that stream buffer effectiveness is variable. In the Oregon Coast Range, the mean of the summer monthly maximum temperatures increased by only 2°C at buffered Deer Creek, compared to the 5.5°C increase observed at unbuffered Needle Branch (Harris, 1977). In the Washington Coast Range, post-harvest changes in DMAX temperature ranged from 0.5°C to 2.6°C for three streams with no harvest buffers (45 to 65 ft wide), while streams with buffers of non-merchantable species warmed by 2.8 to 4.9°C (Jackson et al. 2001). In another western Washington study, Janisch et al. (2012) found daily maximum temperatures during July and August increased in clearcut catchments by an average of 1.5 °C (range 0.2 to 3.6 °C), in patch-buffered catchments by 0.6 °C (range -0.1 to 1.2 °C) and in continuously buffered catchments by 1.1 °C (range 0.0 to 2.8 °C). Groom et al. (2011) studied response to harvesting in the Oregon Coast Range with different buffer requirements. Groom et al. (2011) found that on private land streams with 50 and 70 ft buffers, no harvest allowed within 20 ft to the stream bank, and partial harvest down to a minimum basal area, experienced the largest temperature increases (mean increases of 0.7 °C with a range of -0.9 to 2.5 °C). Groom et al. (2011) also found stream temperature changes were smallest (mean increases of 0.0 °C with a range of -0.9 to 2.3 °C) on state land streams with 170-ft buffers, a 25-ft no cut zone, and limited harvest in the remaining buffer. Gravelle and Link (2007) reported temperature changes ranging from 0.2 ° to 0.6 °C during the first year following partial harvest in Idaho, whereas streams flowing through clear cuts increased as much as 3.6 °C. Wilkerson et al. (2006) reported that streams without a buffer showed the greatest increase in mean weekly maximum stream temperatures following harvesting (1.4 to 4.4°C) in forested lands of Maine, whereas streams with a 33 ft buffer showed minor, but not significant, increases (1.0 to 1.4°C). Wilkerson et al. (2006) found that streams with a 70 ft buffer, partial-harvest treatment, and control streams showed no changes in mean weekly maximum temperatures following harvest.

The results from these studies and our findings for both the SR and ASR prescriptions indicate that some buffer retention practices appear to reduce the magnitude of change but do not necessarily completely eliminate the risk of harvest effects on stream temperature at all sites. This study indicates that both the SR and ASR prescriptions, applied to streams approximately 22 ft in width or less with pre-harvest canopy closure exceeding 85%, prevent temperature changes greater than those changes observed in unharvested streams in similar settings.

4.5 Variability in Longitudinal Stream Temperature Patterns

Longitudinal stream temperature patterns at reference and treatment reach scales were not consistent across the study area as demonstrated by the longitudinal profiles displayed in Appendix 4. In general, mean stream temperature increased in a downstream direction through the entire study site. However, longitudinal patterns displayed alternating warming and cooling trends at the reach scales; the rate of warming and cooling changed between sample years, and patterns of warming and cooling changed from one year to the next in some situations. These trends were especially apparent when investigating the practicality of using a BACI paired design, where the assumption of parallel temperature response trajectories is implicit in the analysis. These findings suggest that a simple model of consistently increasing temperature in a downstream direction does not adequately characterize temperature patterns for many of these small streams. Similar variability in stream temperature patterns is cited by Poole and Berman (2001) and Dent et al. (2008).

Four of the sites with the highest and lowest post-harvest temperature responses serve to portray the variability in longitudinal patterns. Treatment reaches in Seco and Floedelle consistently showed a decrease in stream temperature during the post-harvest period. Both of these sites were typified by cohesive and fine-grained, moist banks in both the treatment and reference reach. This condition was not uncommon in the study areas (Tables 2.2 and 2.3), yet these two sites showed the highest decreases in treatment reach temperature during the post-harvest period. Both sites were accompanied by post-harvest stream temperature increases in the reference reaches. While no harvest was conducted upstream of the study sites within 200 ft of the channel for at least 2,000 ft upstream, both basins had large harvest units situated along the flanks of the upper basin, possibly influencing snowpack and water availability for run-off and groundwater recharge. Sylvus and Sema 4 were both well shaded and densely forested prior to harvest. Following harvest, shade levels remained high, but each of these sites had mean temperature responses exceeding 0.4° C. These increases in temperatures were not correlated with the warmest climatic air temperatures as indicated by the regional SNOTEL stations. Both were moderate gradient channels with sustained flows throughout the summer. Shade levels and near stream stand density remained high following harvest. However, the reference reach stream temperature decreased on average nearly as much as the treatment reach increased. The last two sample periods monitored in Sylvus Creek were especially notable for the opposite patterns in the two reaches.

Increases in treatment reach stream temperature responses were commonly associated with decreases in reference reach temperature response during the same year. Sample period means of background responses (difference between observed and predicted in the reference reach in the post-harvest period) exhibited a significant, negative correlation with post-harvest treatment reach temperature response (treatment responses) across all study sites ($r = -0.24$, $p = 0.016$). This negative relationship between the two reaches was similar to observations of Dent et al. (2008) and Groom et al. (2011). They found that an abrupt temperature increase in the control reach was generally accompanied by an opposite change in the pre-harvest treatment reach. Minor changes in hydrological conditions at or near the site center, resulting in locally warmer or cooler water temperature, could have produced this temperature pattern. The temperature of the downstream station did not reflect this condition and appeared to reverse the increase or decrease in temperature observed in the reference.

4.6 Applicability across Eastern Washington Forested Streams

Site selection criteria were applied in an effort to account for confounding variables that might mask a treatment effect on stream temperature. However, these criteria greatly reduced the availability of potential sites. On private- and state-owned forest lands, it is uncommon to encounter streams with over 2,000 feet of channel that meet all of the established criteria. Much of the land had been previously managed, had considerable stream-adjacent road networks, contained extensive wetland or beaver pond complexes, or was intersected by one or more nearly equal size tributary channels. In addition, it was sometimes difficult to find land managers intent on harvesting timber along suitable areas within the study's time constraints. Sites in the central and north Cascade regions were particularly difficult to find.

Because of BACI-related design constraints, a random sample was not practical. We asked all industrial, private and state forest managers in eastern Washington to provide a list of stream reaches that would be harvested within a specific time frame and also met other criteria or constraints. An initial list of 116 study sites was reduced to the final 30, and includes all stream reaches that generally met design constraints. Disturbances from beaver activities, influences of wetlands and tributary input, and past roading disturbances, although common in eastern Washington, were generally avoided because such disturbances overwhelm temperature patterns that otherwise could be influenced by harvesting in the post-treatment stage of this project. While generally avoided, many sites did include some degree of groundwater influence, side slope seeps, tributary input, and road influences, which are common along streams in state and private industry lands in eastern Washington.

Results from this study are most applicable to streams in the mixed conifer zone ranging from 5 to 22 feet bankfull width in mid-successional forests, which also make up the majority of Washington State and private forests available for timber harvest. A comparison with the results of an assessment of Eastern Washington riparian conditions along fish bearing channels (Bonoff et al. 2008) indicate that the forest stands included in this study had greater basal area and higher tree densities than those typically observed on state and private forestlands. However, Bonoff et al (2008) reported that 60% of the randomly selected riparian sites included in their study were classified as non-harvestable, based on basal area and trees per acre in the inner zone (band extending 30 to 75 ft away from stream bank). Sites for this stream temperature study were required to meet the basal area and density thresholds for timber harvest in the inner zone in order to meet the site selection criteria for inclusion within the study. Sites in the Bonoff et al. (2008) study also had a higher proportion of sites within the Site Class IV category (as defined by WADNR State Soil Survey) versus the higher proportion of Site Class II and III category sites inclusive in the current study. The similarities between the two studies include the fact that both observed higher basal area and tree densities within the core zone (0 – 30 ft from stream bank), as compared to the inner zone. The sites in this study do not represent, nor are they intended to represent, unmanaged, old growth, or late-successional forest conditions and associated stream temperature patterns. In addition, the resulting sample had no sites from the east side of the north and central Cascade Mountains.

4.7 Potential Confounding by Broadened Selection Criteria

As mentioned earlier, study site selection criteria were established to minimize the anticipated influence of other environmental or anthropological factors on stream temperature responses to timber harvest. As the search for potential study areas ensued, identification of potential sites that strictly adhered to the criteria became very challenging. Because of the difficulty in finding sites exceptions to selection criteria were made, including requirements of maximum channel widths, presence of tributary inflows and stream adjacent seeps, roads situated within the RMZ, presence of disconnected flows during some periods, and failure to harvest the entire stand along both sides of the stream.

The influence of each of the broadened criteria on treatment effects assessment was evaluated through post hoc analysis of shading and stream temperature responses to harvest. Four sites were included with streams exceeding 15 feet bankfull width (which exceeded an initial requirement in the study plan). The riparian prescriptions for streams less than or equal to 15 feet wide were applied. Results indicated that bankfull channel widths did not influence canopy closure, shade, solar radiation, and stream temperature response to harvest.

Seven sites with at least seasonal tributaries were included in the study. Tributary confluences were within the reference reach upstream of the site center in four of the seven cases (EF Cedar, Heel, Sema 1, and Sema 4). Although the tributaries joined the treatment reaches in Bacon and

Big Goosmus, no tributary surface flow was ever detected entering the study reaches. The tributary inflow in SF Ahtanum joined the upper end of the treatment reach near the site center. In all cases, tributary surface flow contributed to less than 10% of the total discharge as measured at the bottom of the reach, but may have contributed to groundwater inputs and bank seepage. Small, stream-adjacent seeps and small wetland pockets were situated within the treatment areas of ten sites (Big Goosmus, Dorchester, EF Cedar, Heel, Middle, Mill, NF Foundation, Sema 2, Sema 4, SF Ahtanum). Many of these features were located at or near the confluence with the seasonal tributaries. These small wetlands are typically very shallow with puddles or saturated soils that may maximize the opportunity for warming. However, the seeps, wetlands, and tributary channels were all small and densely covered with understory vegetation, so direct solar radiation was minimized. Conversely, groundwater inflow potentially occurring at or near the seep areas and tributary confluences would tend to counteract solar heating during the daytime (Story et al., 2003; Moore et al., 2005b). No significant differences in treatment effects were observed between the ten sites that contained tributary and streamside seeps and the remaining sites with the absence of such features (two tailed, two-sample $t = -1.323$. $p = 0.19$). Stream temperature profiles of the study sites with tributaries and seeps were similar to sites lacking such features. In other words, the tributary and seep features did not appear to cause anomalous stream warming or cooling rates as compared to sites without such features.

Two sites included culvert road crossings at the site center of the study site (EF Cedar Trib, Tungsten). The two road crossings both included culvert crossings of approximately 40 feet in length. The roads right of way at and near the crossings were narrow (30-50 ft) with mature forest immediately adjacent. Pre-harvest canopy and shade measurements within 25 feet upstream and downstream of the crossings exceeded 90%. Canopy measurements taken atop the road surface exceeded 85%. Road-related gaps in stream canopy were not apparent at any of the nine sites with roads within the riparian zone. New stream crossings, installed for timber harvest purposes, were situated downstream of the site center in two study sites (Sema 2, Sema 4) as part of the standard operations. Data logger stations were not affected by the new road crossings and no anomalous reading of stream temperatures attributable directly to the road were apparent.

Four sites contained discontinuous flows during some years. During low flow periods in some years, these sites break up into a series of poorly connected or disconnected pools and riffles, which may promote anomalous warming. Although data screening procedures ensured that only data from fully submerged data loggers were used, there was still some uncertainty behind the timing and extent of intermittent flow status. Even in years or during periods when flows were continuous throughout the site, there were stretches where discharge became quite small and there was a high likelihood of subsurface flows emerging in downstream areas. Under the limited canopy reductions observed in this study, treatment effects in the four sites with discontinuous flows were similar to sites where flows persisted throughout the season (two tailed, two-sample $t = -1.215$, $p = 0.23$). Stream temperatures in streams with discontinuous surface flows may respond differently to major canopy reductions, but with limited impact on shading and solar attenuation observed in this study, the confounding of treatment effects appears to be minor.

Five of the ASR sites and two of the SR sites were treated with timber harvest only in the RMZ, potentially confounding the treatment effects. However, the errors associated with this situation are likely to be minor. Re-analysis of hemispherical photographs revealed that retained upland trees within the RMZ-only harvest sites contributed very little to effective shading. The retained upland tree shade contribution did not differ between the RMZ-only harvest sites and the standard upland harvest operation sites as reported. A post hoc analysis of $\mathrm{DMAX}_{Response}$ between the RMZ-only harvest sites and the standard sites suggest no differences between the two upland harvest strategies (two tailed, two-sample t = 1.350. p= 0.19).

Six sites had a four-year lag time between the time the first shade, temperature, and riparian stand measurements were made and the stand was harvested. The delay had little influence on the stream temperature measurements, as their data loggers were deployed for several years prior to harvest. In addition, canopy closure was measured twice at four sites during the pre-harvest period (Clark, Cole, Floedelle, Moses) due to a four-year lag between the first measurement and RMZ harvest at these sites. Therefore, all canopy measurements and stream temperatures were made within, at the most, two years preceding timber harvest. However, McGreer et al. (2011) reported as much as six years elapsed between pre- and post-harvest solar measurements due to delayed harvest of private lands and state timber sales, increasing the likelihood of non-treatment effects in the solar analysis. The repeated shade and canopy closure measurements prior to harvest revealed a range of -2 to +6% differences in reach mean canopy closure. All of the changes occurred in the reference reaches. No changes in canopy closure were detected in the treatment reaches during the four year span prior to harvest. Across all of the study sites, the change in shade from pre- to post-harvest ranged from -2 to 6% in the no-harvest reference reaches, whereas as much as 4 years elapsed in some situations. As described earlier, these values are considered to be within the error calibration of the instruments. Thus, the long delay in harvest and the lag between pre- and post-harvest measurement periods had little influence in detecting changes to stream shading and solar radiation input. Moreover, the stream temperature treatment effects were unaffected by the lag, as the data loggers were deployed in the two sample periods immediately prior to harvest at all sites.

4.8 Experimental Design and Data Analysis

In this study, the basic BACI study design was enhanced by including more replication of treatments than has been the norm in previous studies. For example, Gomi et al. (2006) had at most four streams in a given treatment class, Wilkerson et al. (2006) had three streams in each treatment class, and Janisch et al. (2012) had at most six streams in a given treatment class. In this study, the ASR and SR treatments included 16 and 14 sites, respectively, with 30 no-harvest references. This level of replication, similar to that of Groom et al (2011), provides useful information on the variability of response within treatments and also increases the statistical power of the study, i.e., the ability to detect significant differences in responses among treatments.

This study was not plagued by inconsistencies in the interpretation and implementation of prescription rules that may be associated with operational studies. In order to ensure standard and consistent implementation of RMZ prescriptions, one field crew was assigned the responsibility of laying out the RMZ prescriptions according to the original study design plans. Post-harvest QA/QC and subsequent follow-up felling operations further ensured consistent treatment application. In this manner, riparian prescriptions could be interpreted consistently and sites could be laid out to the fullest extent of the forest practice rules.

The GLS regression for fitting pre-harvest relationships using daily time series uses all of the information available in a relatively short pre-harvest period. It also is an effective tool for examining site-specific post-harvest temperature responses on a daily and seasonal basis. The replication of harvest treatments highlighted the variability of temperature response among streams. The use of multiple control (reference) reaches in this study provided a basis for assessing the background variability among seasons and locations. We observed a moderate degree of variability in stream temperature responses and patterns in the reference reaches. Sample period mean $\mathrm{DMAX}_{\mathrm{Response}}$ in the reference reaches varied between - 0.5 °C to 0.9 °C. Daily $\mathrm{DMAX}_{Response}$ in reference reaches ranged from -1.7 to 2.6 °C. Although the mean in the background responses observed in the reference reaches was very near 0, the variability was comparatively, although not absolutely, large, and similar to the variability observed in the treatment reaches.

Observed reach-to-reach variability was likely a result of spatially variable instream processes that influence temperature patterns at small reach scales. Similar variability in stream temperature patterns is cited by Dent et al. (2008), Ebersole et al. (2003), and Janisch et al. (2012). Given that channel attributes did not appear to provide much explanation, the variability of temperature response is likely due to differences in stream-subsurface exchanges of heat and water both over time and space, a factor not addressed in this study. Possible explanations for observed longitudinal patterns and temporal variability include possible shifts with influx of ground water (Beschta et al. 1987, Ebersole et al. 2003, Moore et al. 2005a). This variability can be problematic for BACI-paired designed studies, which assume that both control and impact reaches would have similar trends with no treatment applied. Initial data exploration revealed that many of the sites investigated under this study were not consistent with such an assumption. Stream temperature profiles varied among reaches from year to year before harvest treatments were applied. For this reason, we did not use a direct paired analysis as originally proposed (Light et al. 2002). Rather, we analyzed differences in post-harvest temperature changes between the ASR harvest, SR harvest, and no-harvest reference reaches.

5 Conclusions

Our study results suggest that the ASR limited the mean decrease in shade to 1%, with a maximum decrease of 4%. Under the SR, shade was reduced by a mean of 4%, with a maximum decrease of 10%. We found no relationship among pre-harvest to post-harvest change in shade and incoming solar radiation in the ASR sites. Results of the site-specific evaluation on stream temperature suggested that there were post-harvest treatment reach temperature responses, albeit small, in at least one sample period following harvest in 19 of the 30 study sites. However, similar analysis on the reference reaches also indicated a significant post-harvest temperature response in 19 of the 30 study sites during at least one year. The pooled analysis of data from the first two summers following timber harvest indicated there was no difference in stream temperature response under the ASR prescription and the no-harvest reference. Stream temperature increased 0.15°C more under the SR prescription as compared to both the ASR prescription and no-harvest reference. These differences were not found to be statistically significant at a specified probability level ($\alpha = 0.05$). However, the marginal test results of $p=0.059$ for the SR harvest to no harvest comparison and $p=0.095$ for the SR to ASR comparison suggest that a small increase in stream temperature would be more likely under the SR prescription harvest. The difference observed in stream temperature responses observed under the two harvest prescriptions is indicative of the study design’s ability to detect small changes. However, the seasonal variability observed in the no-harvest reference reaches set practical bounds on the magnitude of temperature changes that can reliably indicate a treatment response in our BACI designed study. Seasonal mean stream temperature responses of up to 0.5 °C in the no-harvest references were common during the post-harvest test period.

Temperature responses were variable after harvest; sample period means of $DMAX_{Response}$ in the ASR treatment reaches the first two years following harvest varied from -1.1 °C to 0.7 °C. Sample period means of $DMAX_{Response}$ in the SR reaches during the first two years following harvest ranged from -0.5 °C to 0.8 °C. $DMAX_{Response}$ in the reference reaches varied between -0.5 °C to 0.9 °C. Changes in canopy closure, shade, and stand attributes did not account for the variations observed in stream $DMAX_{Response}$. Processes not directly related alteration of canopy closure over the stream channel may be primarily responsible for the small variations observed in stream temperature following timber harvest.

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7 Appendices (next 36 pages)

Appendix 1. Reference and treatment reach characteristics of study included in the Eastern Washington Shade and Temperature Effectiveness study. Azimuth represents a 0–90° deviation from either east or west.

	Reference Reach							Treatment Reach						
Study Site	**Bankfull Width (ft)**	**Basin Area (ac)**	**Gradient (%)**	**Base flow (ft^3/sec)**	**Elevation (ft)**	**Azimuth [a]**	**% Gravel**	**Bankfull Width (ft)**	**Basin Area (ac)**	**Gradient (%)**	**Base flow (ft^3/sec)**	**Elevation (ft)**	**Azimuth [a]**	**% Gravel**
All Available Shade														
Bacon	14.3	2499	16.4	1.7	3304	1	38	12.7	2614	10.8	1.5	3163	1	58
Clark	6.1	676	4.2	0.0	3308	86	75	5.8	705	3.3	0.0	3275	86	65
Cole	17.6	11793	3.4	1.5	1892	81	83	14.5	11814	4.1	1.6	1852	81	50
Dry Canyon	5.6	1622	4.5	0.4	2159	37	67	6.5	1641	3.6	0.5	2132	37	54
Floedelle	8.2	2783	5.1	0.3	3367	8	38	9.8	2855	3.4	0.2	3344	8	62
Long Alec	10.5	2111	6.8	0.1	4158	23	65	8.6	2199	5.9	0.0	4108	23	50
Lotze	11.9	1730	4.1	1.0	3449	90	96	14.4	1809	6.5	0.9	3379	90	73
Mill	4.7	212	14.3	0.2	3511	44	67	5.8	273	12.5	0.2	3430	44	54
Moses	6.7	811	7.8	0.5	3065	78	88	7.6	880	7.2	0.5	2985	78	85
NF Foundation	11.8	1582	10.5	0.5	4761	40	38	12.7	1619	9.8	0.5	4691	40	42
Sanpoil	4.8	2237	5.6	0.1	3359	20	38	6.1	2387	5.2	0.1	3307	20	54
Seco	8.0	1203	6.0	0.5	3488	80	67	7.9	1318	5.3	0.4	3444	80	65
Sema 1	4.3	210	6.3	0.1	3505	9	55	5.2	234	6.7	0.1	3441	9	58
Sema 2	5.9	310	9.0	0.1	3530	55	41	6.7	333	9.0	0.1	3450	55	58
SF Ahtanum	19.7	2414	10.8	2.8	4514	2	33	20.8	2478	8.8	3.7	4426	2	54
Tungsten	3.3	208	8.2	0.1	3296	35	63	3.9	213	7.6	0.1	3233	35	50
Standard Rule														
Big Goosmus	7.0	1026	10.2	0.1	3191	10	83	9.5	1129	9.3	0.1	3105	10	75
Byers	9.7	1296	5.4	0.1	3443	13	75	13.5	1337	5.4	0.1	3353	13	83
Dorchester	9.7	2056	4.3	0.6	2201	9	54	10.2	2082	5.6	0.6	2145	9	46
Dry Creek	22.5	2413	12.0	0.9	3678	88	8	22.5	2426	15.6	0.2	3518	88	8
EF Cedar	19.9	3611	9.0	2.1	3236	5	0	16.7	3686	7.4	2.4	3164	5	0
EF Cedar trib	7.2	566	12.0	0.4	3247	4	0	8.8	757	11.3	0.3	3123	4	0
Heel	4.9	245	11.8	0.2	3893	60	50	5.5	298	8.8	0.2	3796	60	42
Little Goosmus	5.1	896	9.3	0.0	3339	36	50	6.0	933	10.5	0.0	3221	36	65
Middle	10.2	2152	10.8	1.0	3806	48	23	12.8	2251	9.8	1.9	3682	48	25
Prouty	7.9	275	18.7	0.1	4134	4	68	9.7	349	16.1	0.1	3962	4	58
Sema 3	7.8	890	3.2	0.4	3471	63	38	8.0	922	1.7	0.4	3443	63	42
Sema 4	5.5	410	8.3	0.1	3471	75	83	5.0	429	6.8	0.1	3418	75	65
SF Dairy	14.9	1973	7.7	0.4	2340	13	27	12.2	2009	6.0	0.4	2270	13	50
Sylvus	8.5	1759	5.6	0.7	3344	57	79	8.7	1789	5.2	0.6	3279	57	88

Appendix 2. Reference and treatment reach riparian characteristics before and after timber harvest in study sites of the Eastern Washington Shade and Temperature Effectiveness study (1 of 2 pages)

	Reference Reach Pre-Harvest								Reference Reach Post-Harvest							
Study Site	**Basal Area per Acre**	**Trees per Acre**	**Mean Height (ft)**	**Crown Ratio**	**Effective Shade (%)**	**Canopy Closure (%)**	**Solar Energy (W / m^2)**	**Solar Attenuation (%)**	**Basal Area per Acre**	**Trees per Acre**	**Mean Height (ft)**	**Crown Ratio**	**Effective Shade**	**Canopy Closure**	**Solar Energy (W / m^2)**	**Solar Attenuation (%)**
All Available Shade Rule																
Bacon	141	101	76	45	94	93	35	96	142	101	76	45	93	87	33	95
Clark	154	237	76	60	93	87	134	82	148	229	75	60	92	83	149	82
Cole	125	121	69	62	92	79	115	83	126	124	66	61	92	80	65	92
Dry Canyon	155	212	65	67	91	94	38	95	161	207	66	67	91	89	30	95
Floedelle	94	165	66	48	94	88	28	94	101	176	65	48	92	90	31	95
Long Alec	133	290	70	56	92	84	85	89	133	290	70	57	90	81	67	91
Lotze	342	288	73	47	95	93	49	94	356	282	73	48	92	90	26	97
Mill	145	118	92	51	95	95	20	94	152	119	91	51	94	94	22	97
Moses	194	229	75	68	92	93	63	92	193	226	75	67	92	95	64	92
NF Foundation	238	194	77	58	94	88	134	83	232	182	78	60	91	78	121	87
Sanpoil	120	137	77	46	91	88	76	91	123	137	77	46	91	90	59	91
Seco	186	397	64	56	95	79	91	86	186	394	65	56	95	81	71	91
Sema 1	130	332	61	50	95	86	31	96	115	288	62	49	89	88	42	93
Sema 2	131	290	63	59	94	91	55	88	126	276	64	59	94	90	39	93
SF Ahtanum	131	162	63	56	90	72	35	96	132	156	63	56	88	71	136	82
Tungsten	92	120	65	59	91	90	114	87	92	117	66	62	89	90	108	87
Standard Rule																
Big Goosmus	91	125	67	57	94	91			86	111	66	57	91	87		
Byers	137	131	77	56	94	93			139	131	77	56	91	94		
Dorchester	175	209	67	64	90	71			174	204	68	64	92	79		
Dry Creek	166	76	84	52	89	71			164	74	84	52	84	65		
EF Cedar	209	198	75	62	95	81			209	198	75	62	93	83		
EF Cedar trib	170	187	74	58	93	95			165	179	75	60	92	95		
Heel	191	260	69	54	94	91			204	260	69	54	95	92		
Little Goosmus	79	82	79	55	92	90			74	67	80	55	89	84		
Middle	168	251	66	41	93	93			172	254	65	41	92	91		
Prouty	223	288	72	56	94	96			223	282	71	56	92	94		
Sema 3	166	299	62	53	91	84			163	288	62	52	93	86		
Sema 4	210	402	60	65	94	86			179	363	63	67	93	87		
SF Dairy	222	135	73	49	97	95			222	138	69	48	93	93		
Sylvus	200	257	76	0	93	93			197	251	75	0	91	90		

Appendix 2. Reference and treatment reach riparian characteristics before and after timber harvest in study sites of the Eastern Washington Shade and Temperature Effectiveness study (2 of 2 pages)

	Treatment Reach Pre-Harvest								**Treatment Reach Post-Harvest**							
Study Site	**Basal Area per Acre**	**Trees per Acre**	**Mean Height (ft)**	**Crown Ratio**	**Effective Shade (%)**	**Canopy Closure (%)**	**Solar Energy (W / m^2)**	**Solar Attenuation (%)**	**Basal Area per Acre**	**Trees per Acre**	**Mean Height (ft)**	**Crown Ratio**	**Effective Shade (%)**	**Canopy Closure (%)**	**Solar Energy (W / m^2)**	**Solar Attenuation (%)**
All Available Shade Rule																
Bacon	124	92	79	59	95	93	34	96	91	75	75	61	94	87	35	95
Clark	121	170	71	60	92	89	36	94	106	142	70	60	92	91	51	93
Cole	113	147	71	59	91	86	107	83	78	85	73	66	90	82	104	87
Dry Canyon	159	235	67	62	91	94	33	96	71	98	69	63	95	89	49	92
Floedelle	140	168	74	41	94	84	31	92	108	128	76	42	92	85	34	94
Long Alec	121	291	72	52	93	78	99	87	121	280	72	54	93	79	46	95
Lotze	213	251	67	38	94	94	52	92	147	145	68	38	89	90	43	95
Mill	221	262	76	46	94	93	21	97	173	183	78	47	94	91	24	96
Moses	229	260	78	56	92	93	81	90	165	156	84	60	89	95	75	91
NF Foundation	112	121	67	52	92	88	117	85	85	85	66	52	89	75	127	85
Sanpoil	108	123	76	52	93	80	124	86	74	78	79	54	91	82	95	88
Seco	188	377	65	55	93	85	59	90	138	265	64	60	92	82	100	88
Sema 1	83	195	62	57	95	88	30	96	71	165	58	57	92	89	27	96
Sema 2	168	276	65	66	94	89	27	95	143	209	65	67	93	90	30	94
SF Ahtanum	158	131	76	46	90	74	87	90	149	109	80	46	89	71	119	86
Tungsten	260	201	84	44	93	89	72	92	194	123	91	49	89	89	61	93
Standard Rule																
Big Goosmus	257	266	74	59	94	96			146	103	78	59	91	85		
Byers	165	154	77	52	94	92			118	103	77	54	91	92		
Dorchester	195	204	74	65	95	87			105	81	87	69	89	82		
Dry Creek	204	108	89	66	89	75			145	52	97	72	79	58		
EF Cedar	223	120	73	48	95	86			182	50	82	49	92	85		
EF Cedar trib	144	232	65	50	92	96			76	95	68	54	93	92		
Heel	265	313	77	54	93	89			144	134	80	52	88	88		
Little Goosmus	120	172	69	59	93	90			49	44	79	60	88	85		
Middle	266	288	73	50	94	89			170	196	71	54	91	89		
Prouty	283	383	67	58	93	96			125	123	75	62	89	91		
Sema 3	186	405	64	46	92	84			120	201	68	47	91	77		
Sema 4	142	307	67	64	94	81			81	142	68	68	85	76		
SF Dairy	172	166	60	47	96	95			148	109	63	53	92	93		
Sylvus	254	274	76	0	93	95			95	89	73	0	85	90		

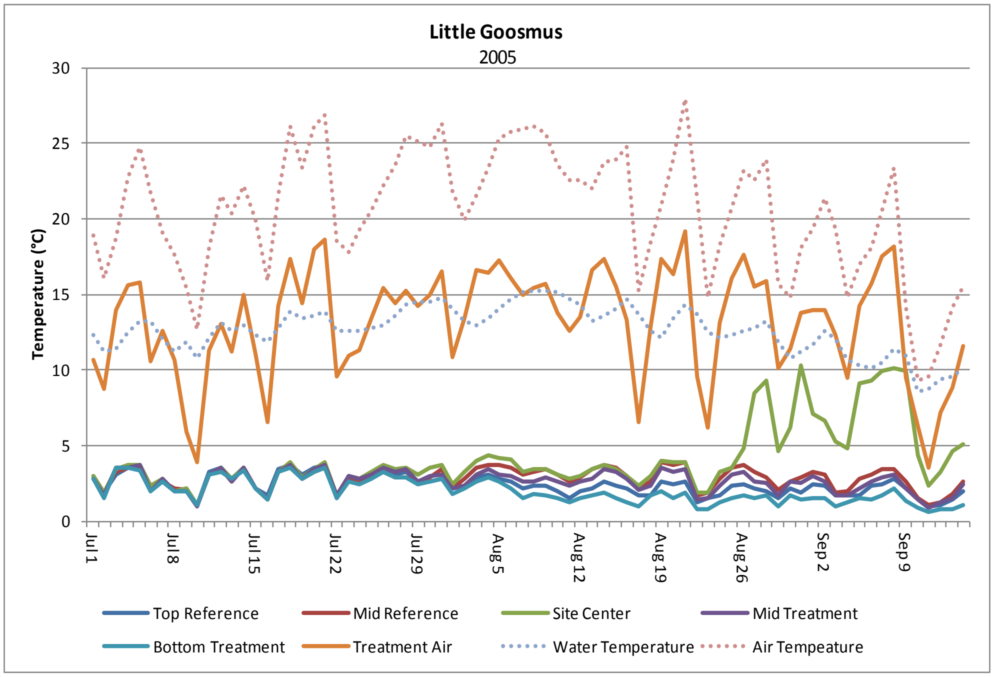
Appendix 3. (14 pages)

Temperature Data Quality Control and Quality Assessment

During the course of the study, four sites (Little Goosmus, Prouty, Sema 1 and Sema 2) were suspected to contain stretches of discontinuous flows beginning in mid to late summer at least during some years. Disconnected flows were first detected during late September and October between 2003 and 2006 sample seasons while data loggers were being retrieved. Because the exact timing of the onset of the discontinuous flows was not observed during those years, it was unclear if the sites had contained disconnected stretches during the July 1 through September 15 sample period. Graphical exploration of stream temperature data was used to determine the timing of the dewatering. Daily temperature readings were screened to ensure that data reflected fully submerged temperature data loggers and that temperature patterns did not reflect peculiar increases or decreases associated with dewatering.

In order to identify the date at which streams may have experienced discontinuous surface flows, the diurnal flux of water temperature at the top, middle, and lower thermograph sites was plotted for each day and compared with a similar line plot of the diurnal flux of air temperature. The temperature pattern at each logger station was examined for anomalies in daily fluctuation in relationship to other stations in the site. Figure A3.1 provides graphical illustrations of the diurnal temperature flux at each water temperature data logger station and the flux of air temperature in the treatment reach. The graph also includes the DMAX stream temperature as represented by a known fully submerged data logger (in the middle of the reference reach) and the DMAX air temperature in the reference reach. Note that in the 2005 Little Goosmus data portrayed in Figure A3.1, the diurnal flux in the site center begins to diverge dramatically from the diurnal flux at other stations around August 26. Data from all stations beyond August was excluded from further analysis in the Little Goosmus site during the 2005 season. Peak water temperature occurred on August 11 and peak air temperatures occurred prior to August 26. During the 2009 and 2010 sampling, field surveys were conducted at 7- to 10-day intervals between late July and early September at the four sites to determine the temporal and spatial extent of wet and dry channel reaches.

Graphs evaluated for the screening process follow Table A3.1. The timing of apparent surface flow infiltrations in relation to seasonal peak stream temperatures was determined by comparison to other submerged loggers at the site. All data collected after the day the stream temperature patterns among loggers began to diverge were excluded from further analysis. Table A3.1 provides a summary of the data screening process.



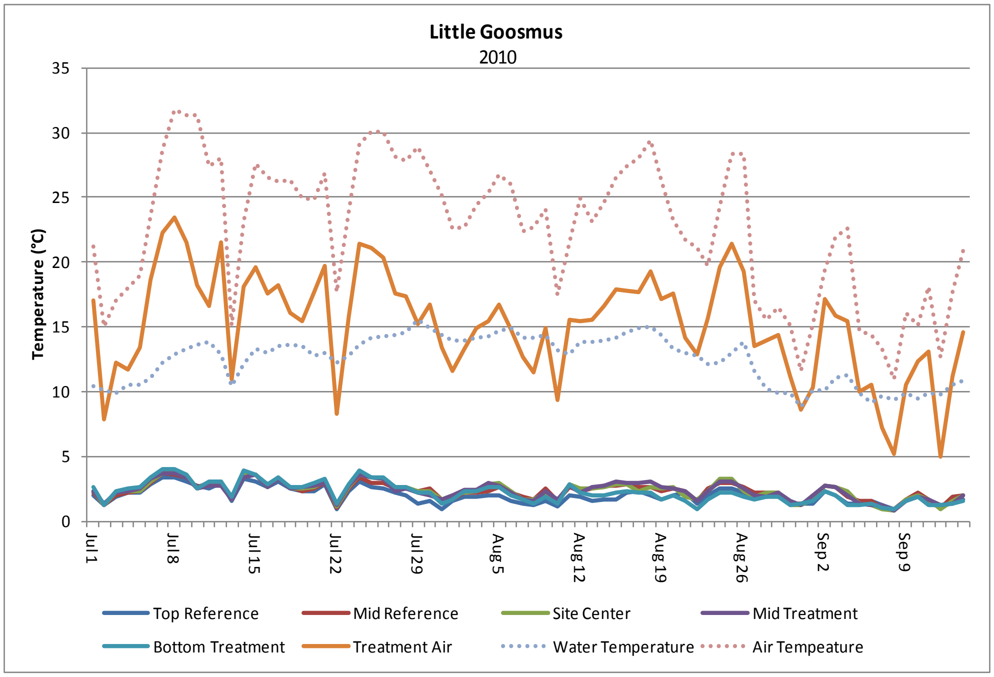
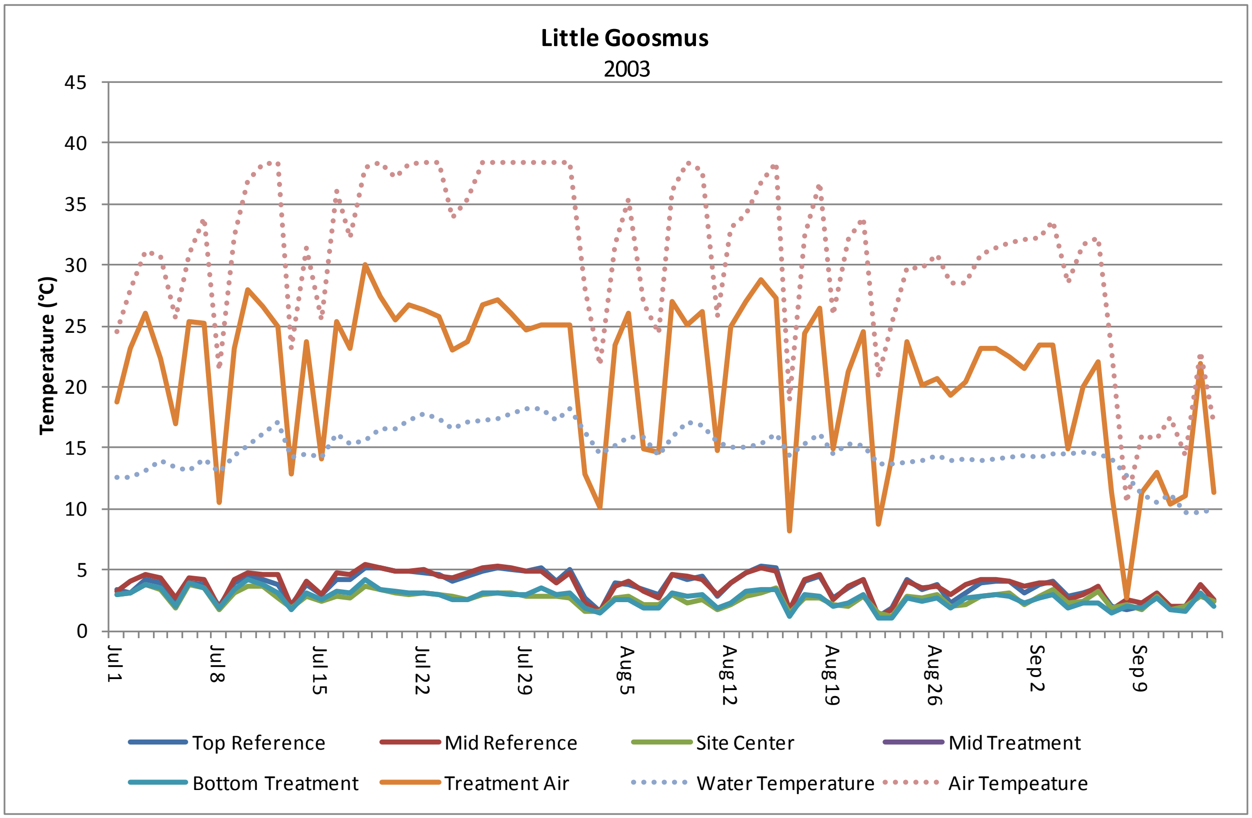
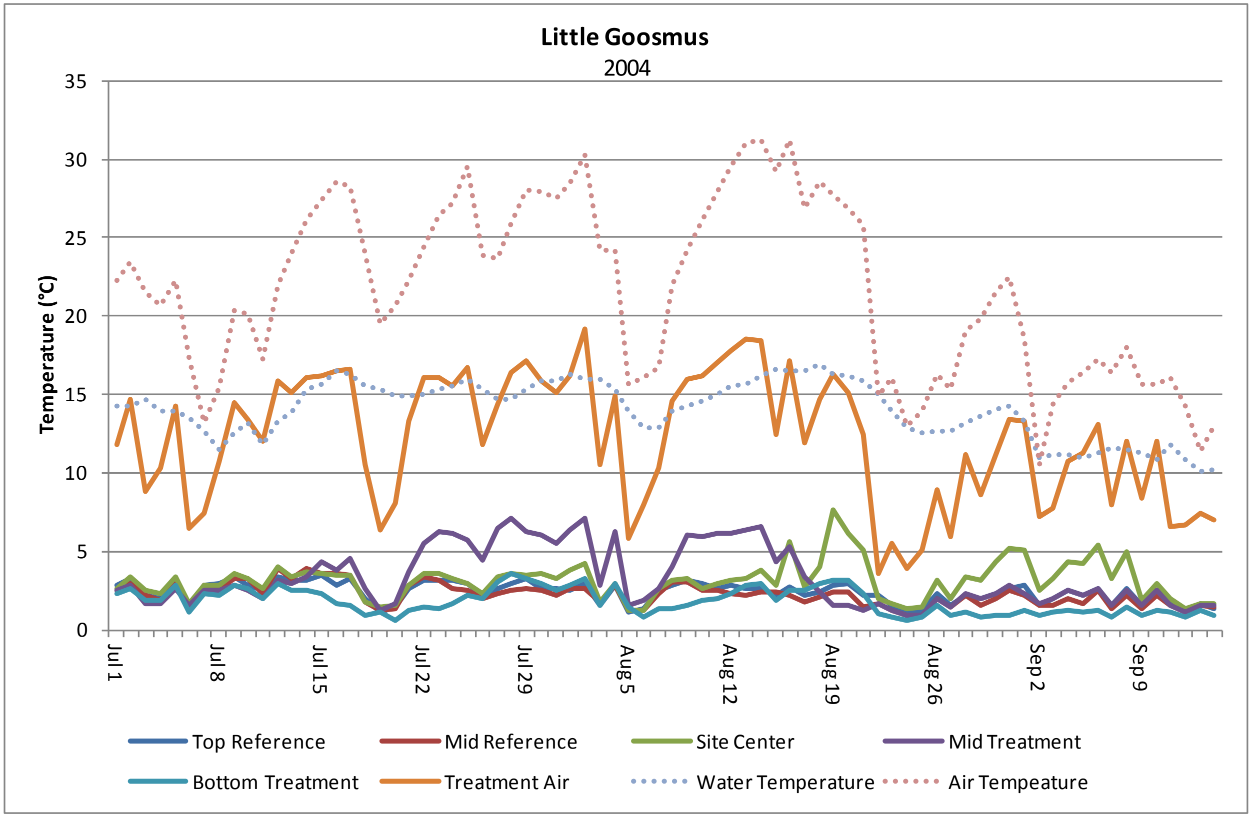


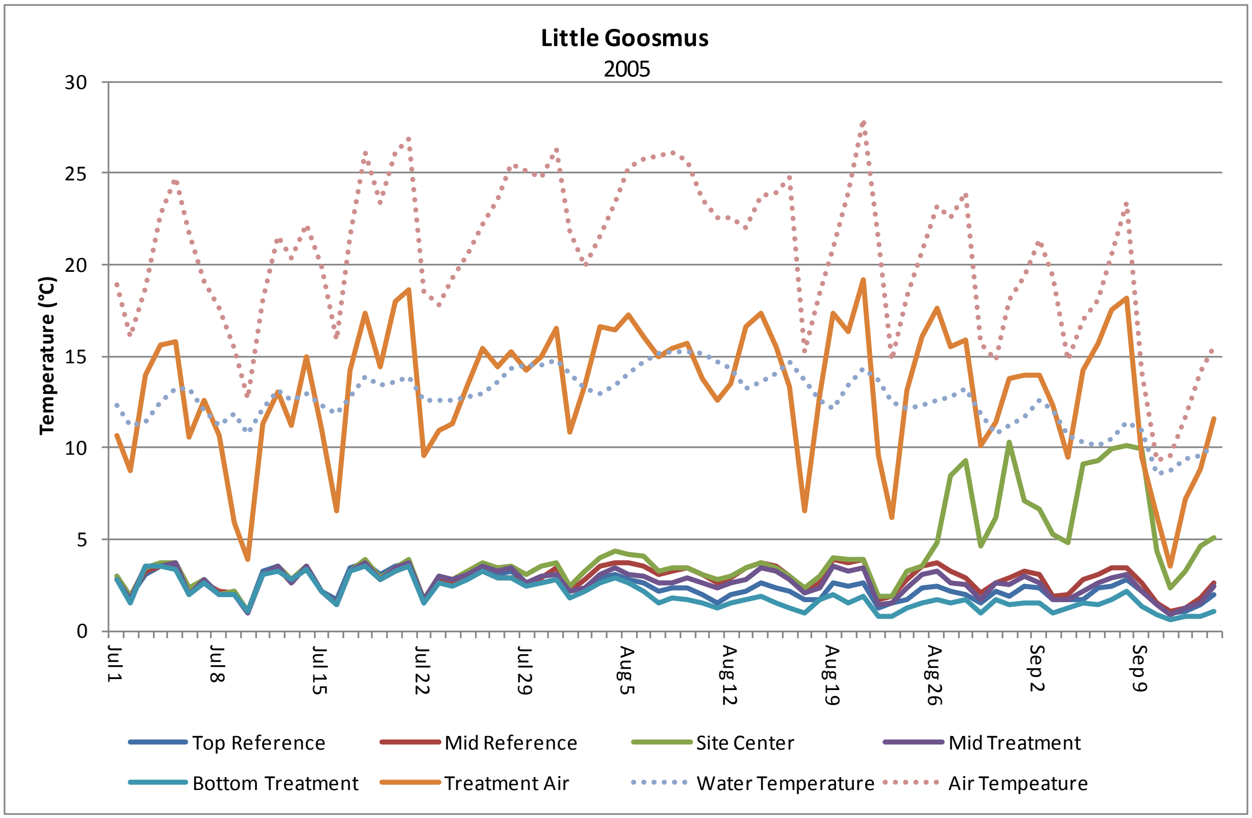
Figure A3.1. Graphical analysis used to indentify periods of discontinuous flows for data screening purposes. The dotted lines represent DMAX stream and air temperatures. The solid lines represent temperature diurnal flux at each data logger station as indicated. The 2010 graph demonstrates temperature behavior during a year when no discontinuous flows were observed during weekly site visits.

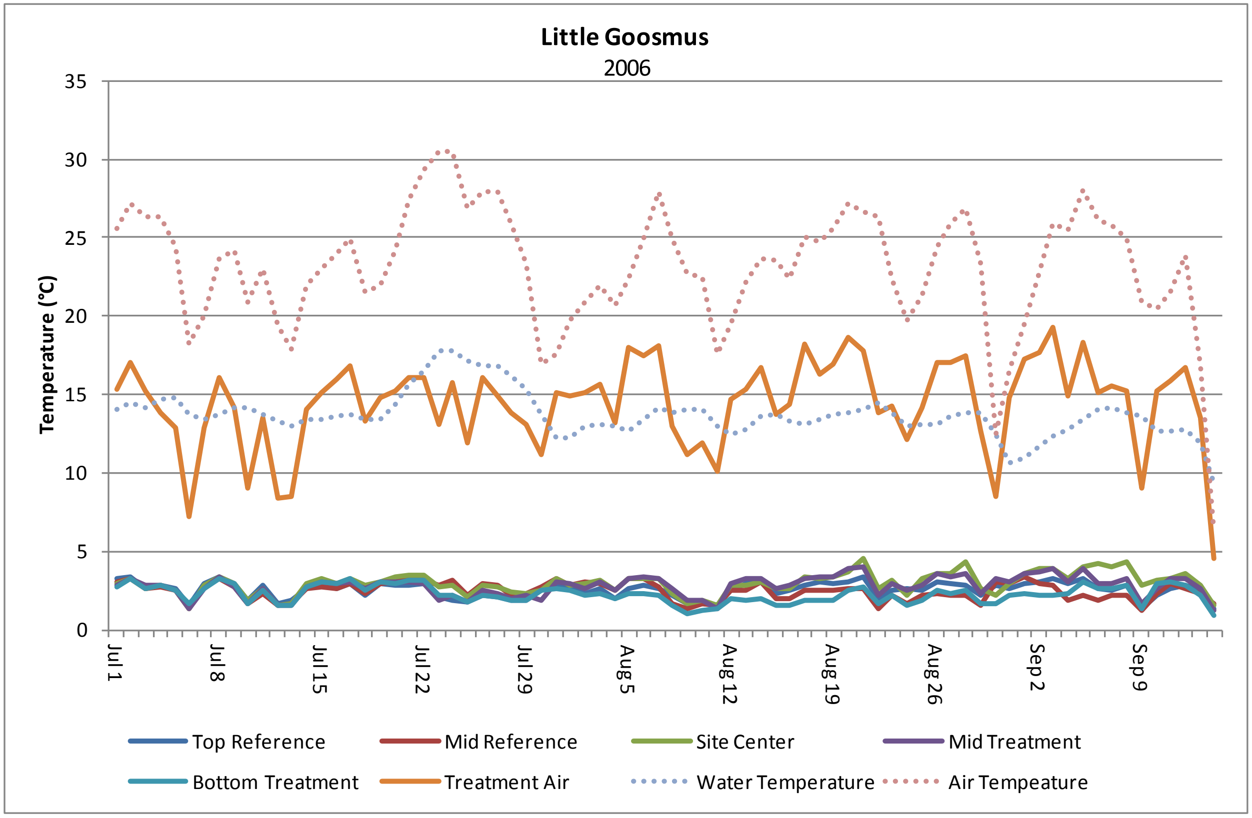
Table A3.1. Results of data screening efforts to determine if and when streams experienced discontinuous flows. The date in parentheses indicates the date of peak air and water temperatures in the site. Data beyond the date shown in the left hand column under each site was excluded from further analysis. The term All indicates that data for the entire sample year was retained in the analysis.

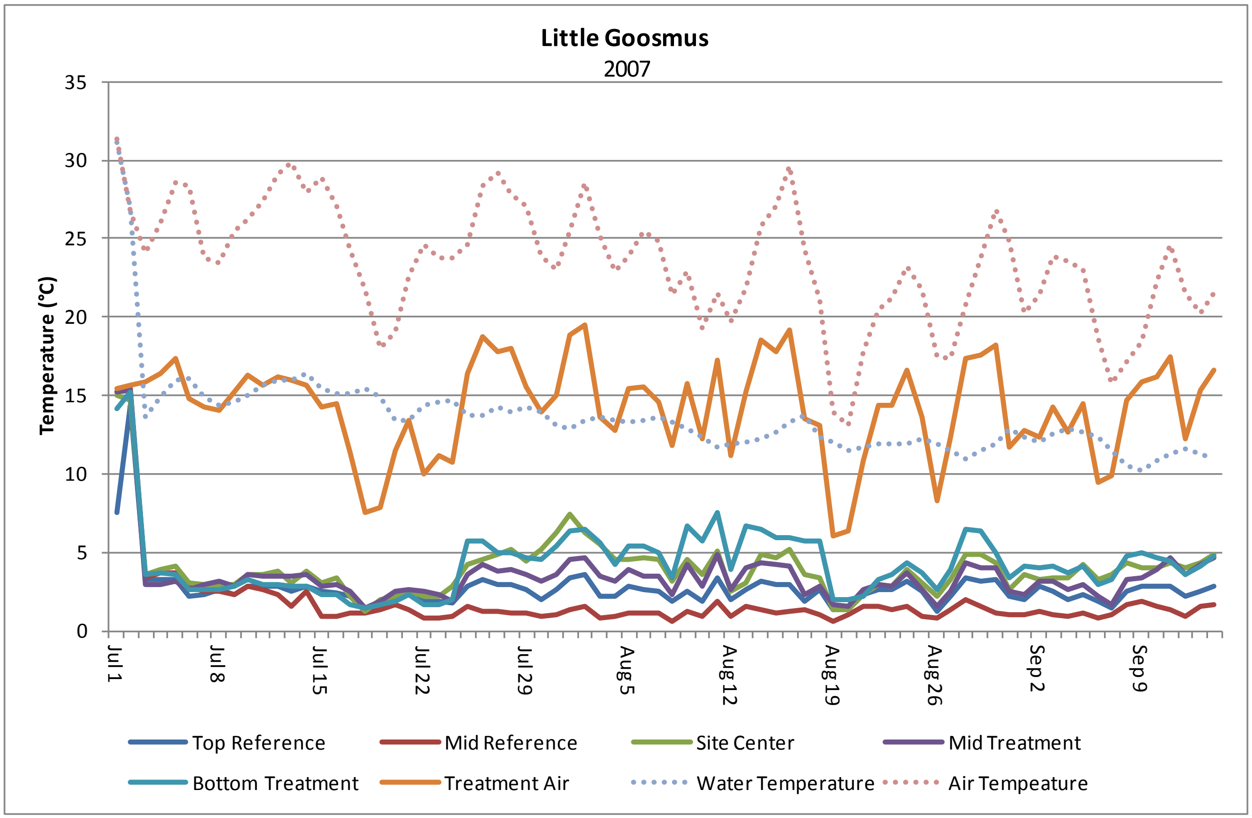
Year	Little Goosmus		Prouty		Sema 1		Sema 2	
2003			24-Jul	(5-Aug)				
2004	18-Aug	(15-Aug)	21-Aug	(19-Aug)				
2005	1-Aug	(25-Aug)			29-July	(8-Aug)	26-Aug	(25-Jul)
2006	All	(23-Jul)						
2007	23-Jul	(14-Jul)	12-Aug	(23-Jul)		(17-Jul)		
2008	All	(9-Aug)	26-Aug	(19-Aug)	2-Aug	(19-Aug)	1-Aug	(19-Aug)
2009	2-Sep	(28-Jul)	2-Aug	(6-Aug)	4-Aug	(2-Aug)	18-Aug	(6-Aug)
2010	All	(29-Jul)	All	(18-Aug)	22-Aug	(30-Jul)	20-Aug	(20-Aug)

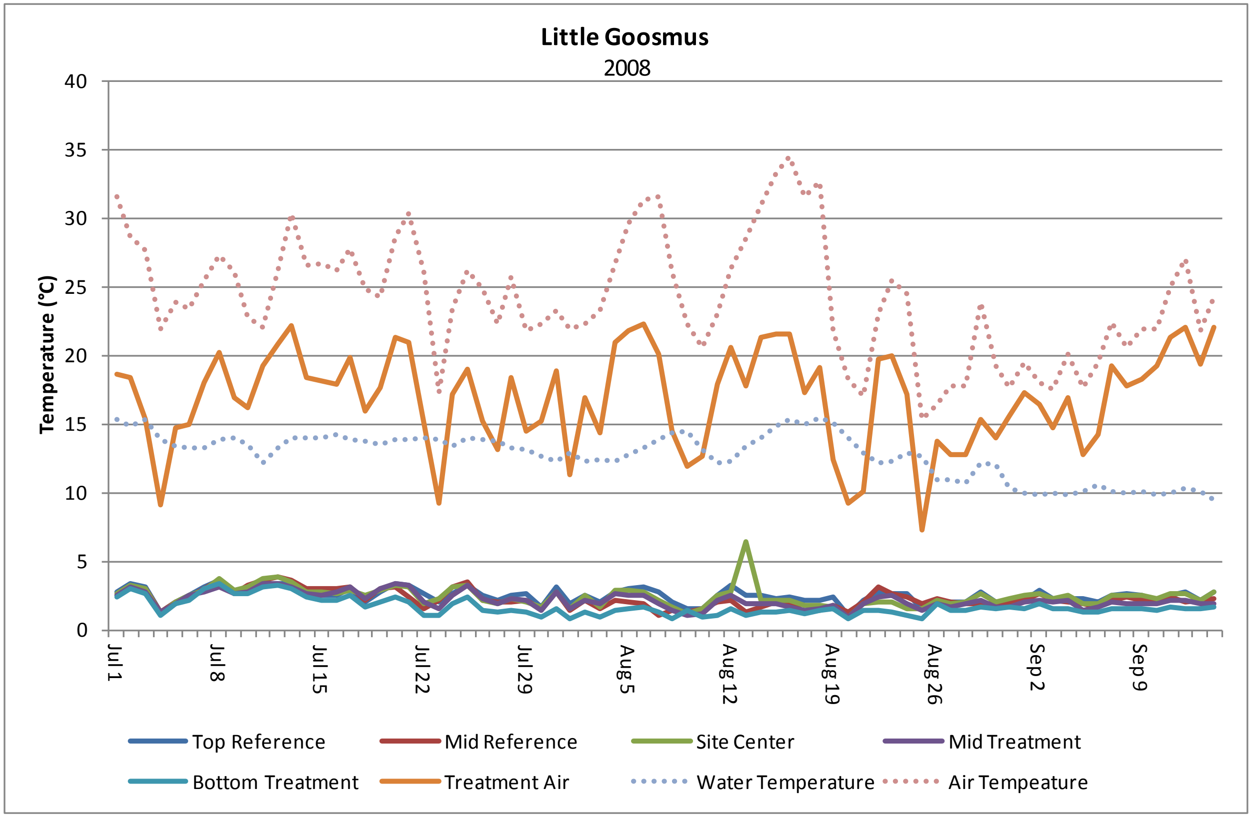

Little Goosmus
2003
Temperature (°C)
0
5
10
15
20
25
30
35
40
45
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2004
Temperature (°C)
0
5
10
15
20
25
30
35
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2005
Temperature (°C)
30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2006
Temperature (°C)
35
30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2007
Temperature (°C)
0
5
10
15
20
25
30
35
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2008
Temperature (°C)
0
5
10
15
20
25
30
35
40
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
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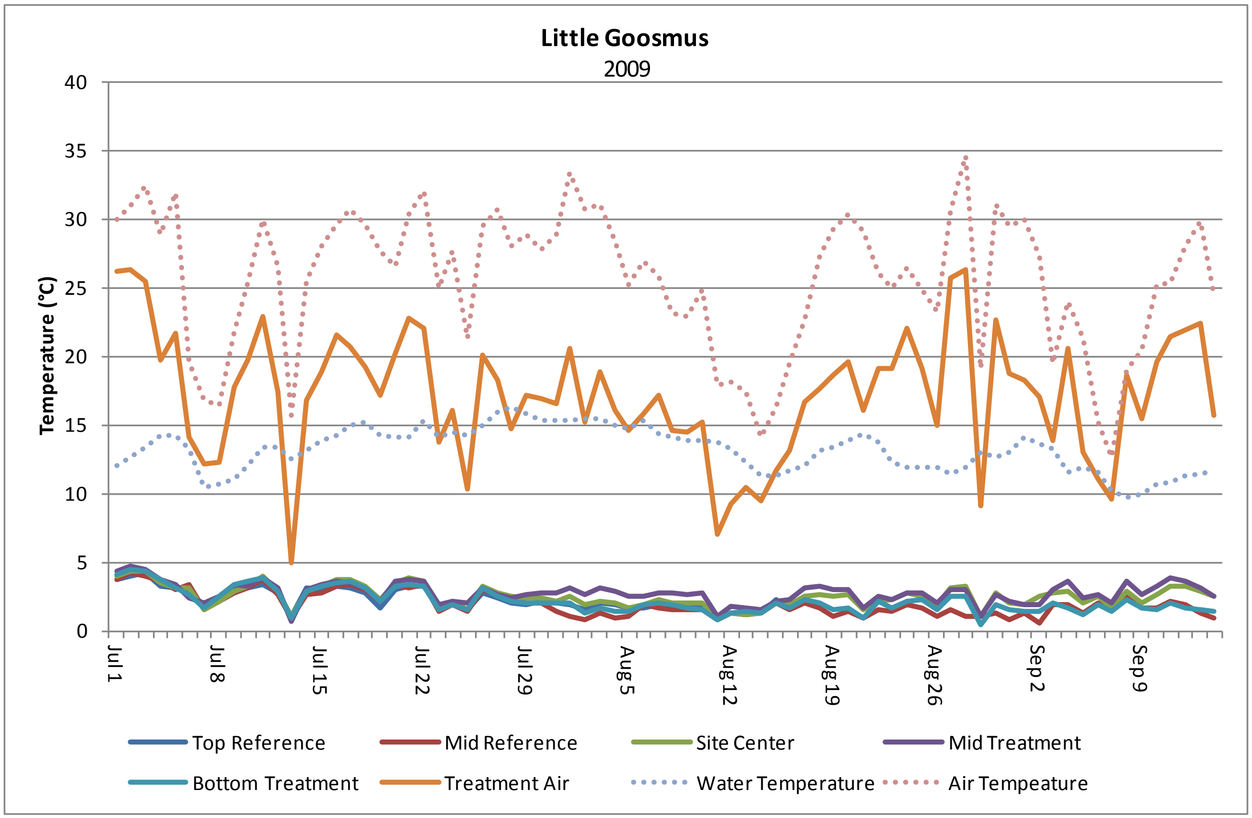
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2009
Temperature (°C)
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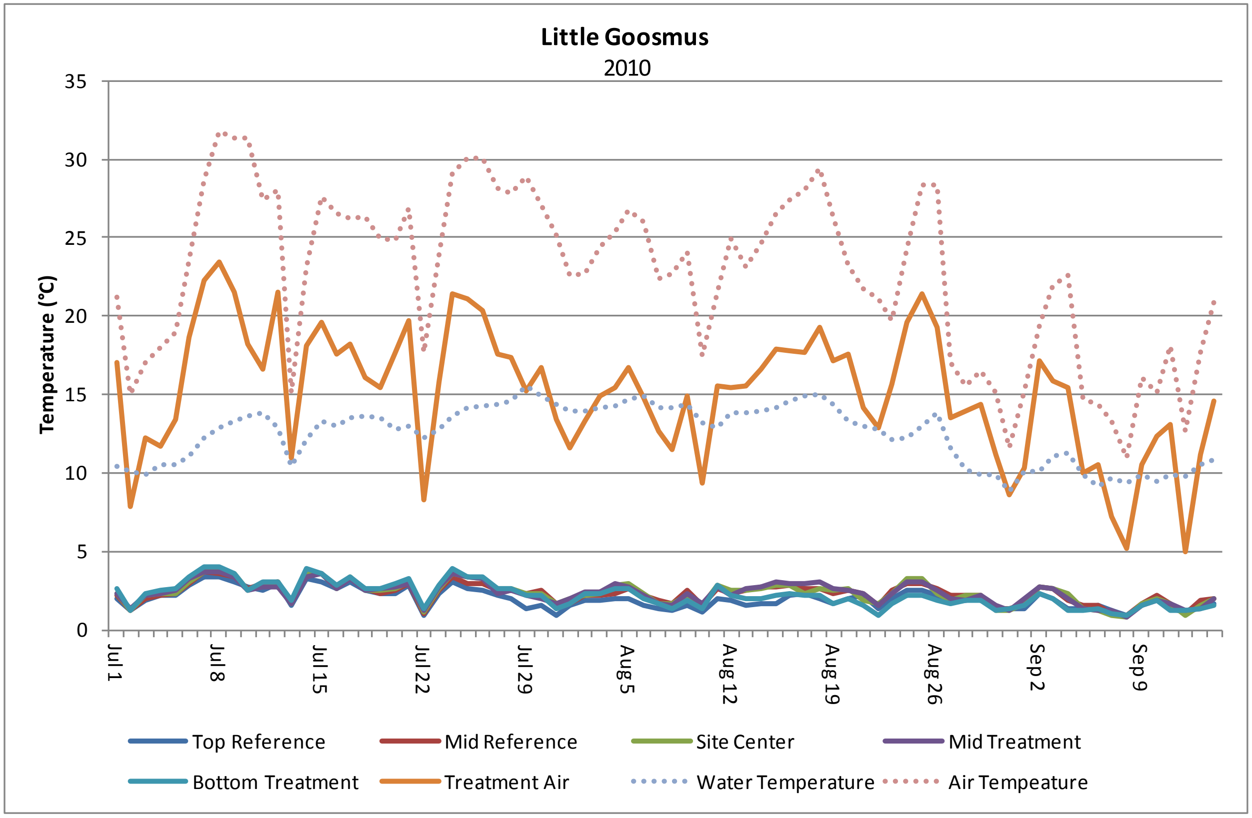
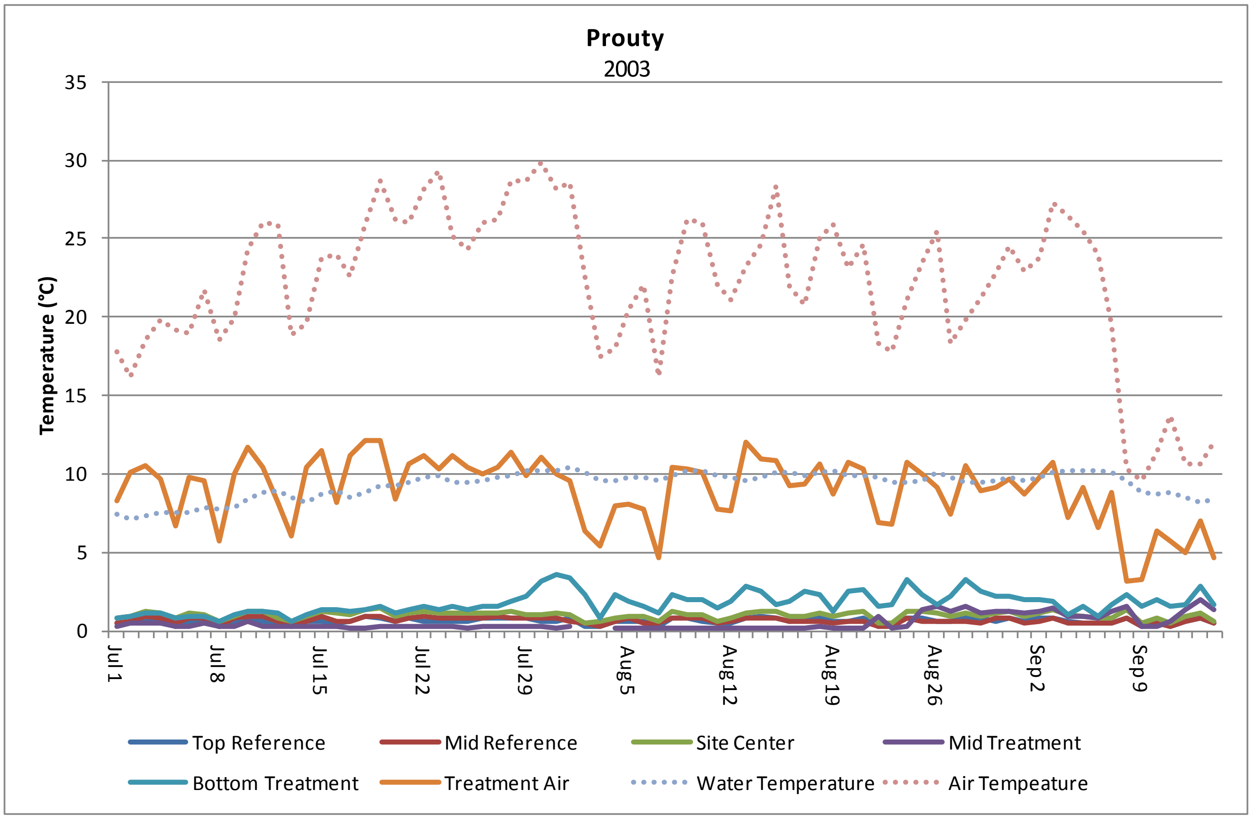
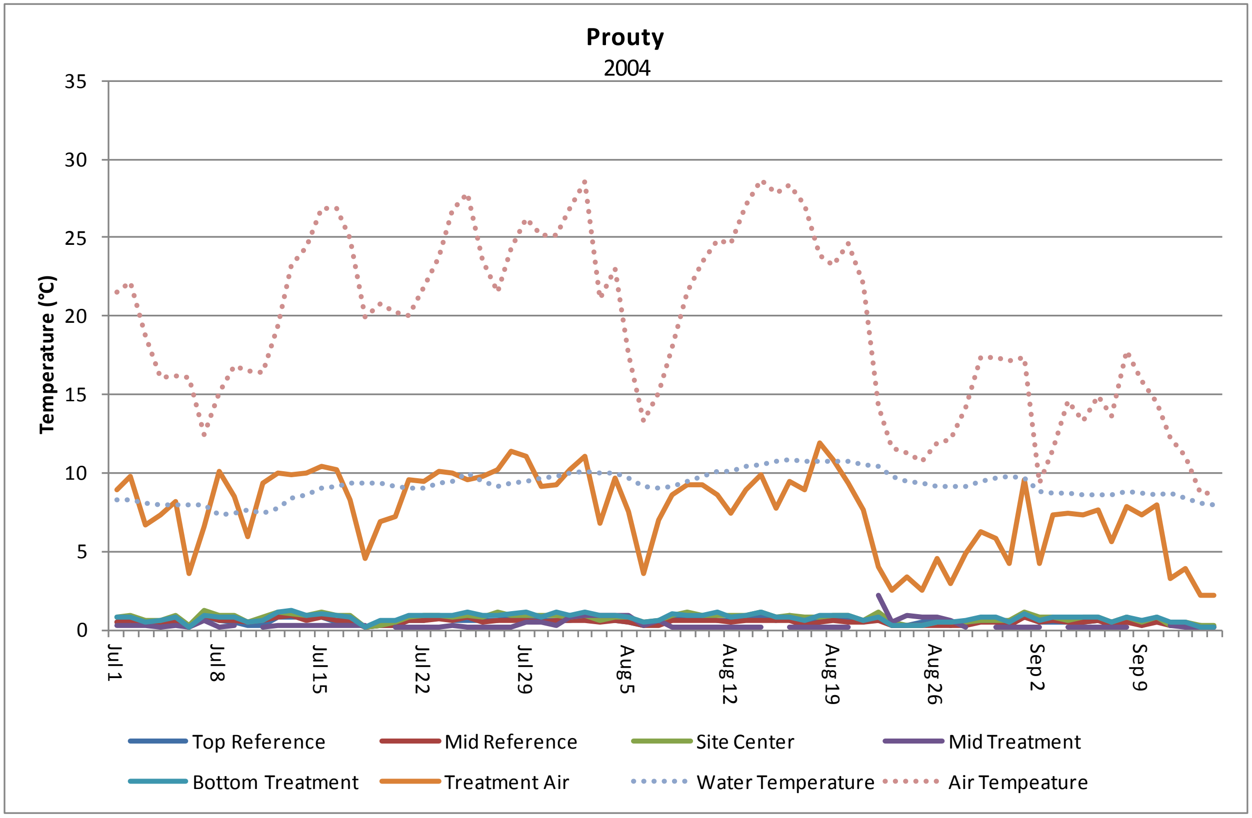
5
10
15
20
25
30
35
40
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Little Goosmus
2010
Temperature (°C)
0
5
10
15
20
25
30
35
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Prouty
2003
Temperature (°C)
35
30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Prouty
2004
Temperature (°C)
35
30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
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Aug 19
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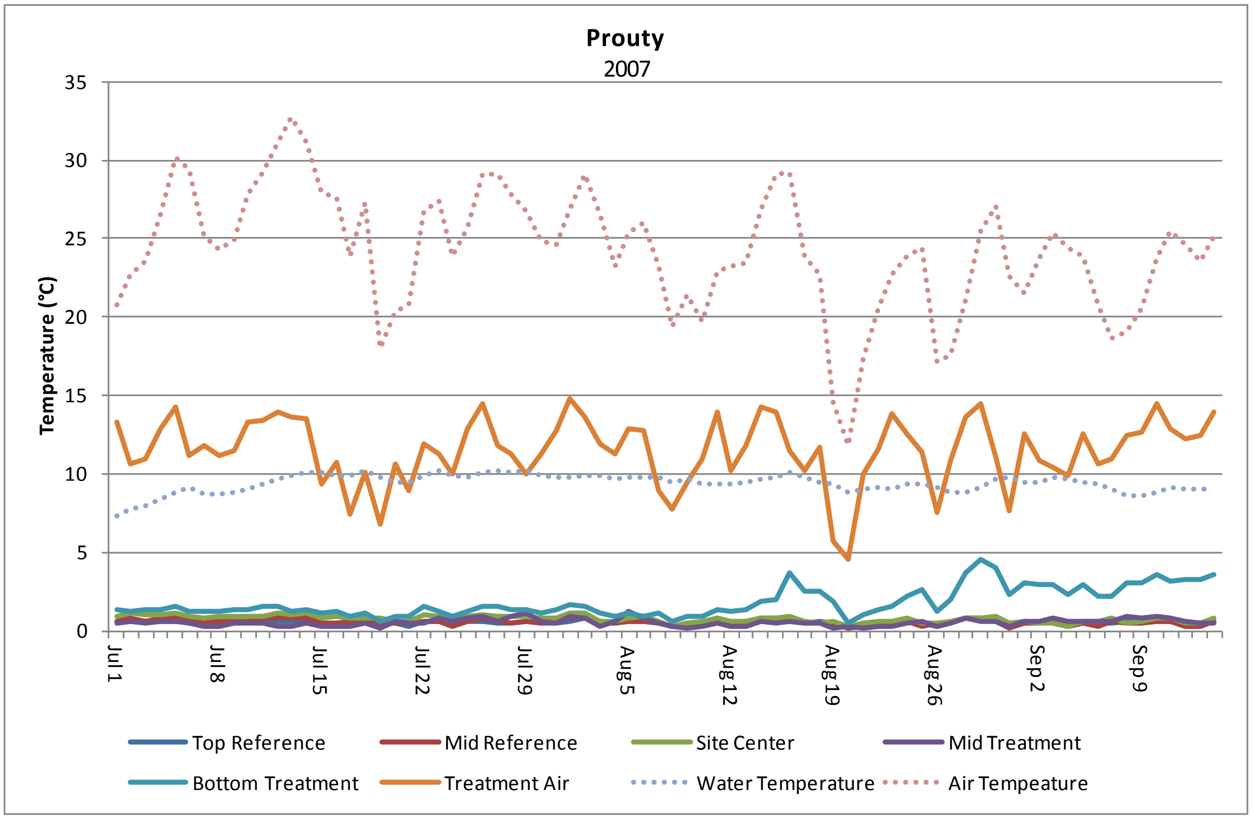
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Prouty
2007
Temperature (°C)
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30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
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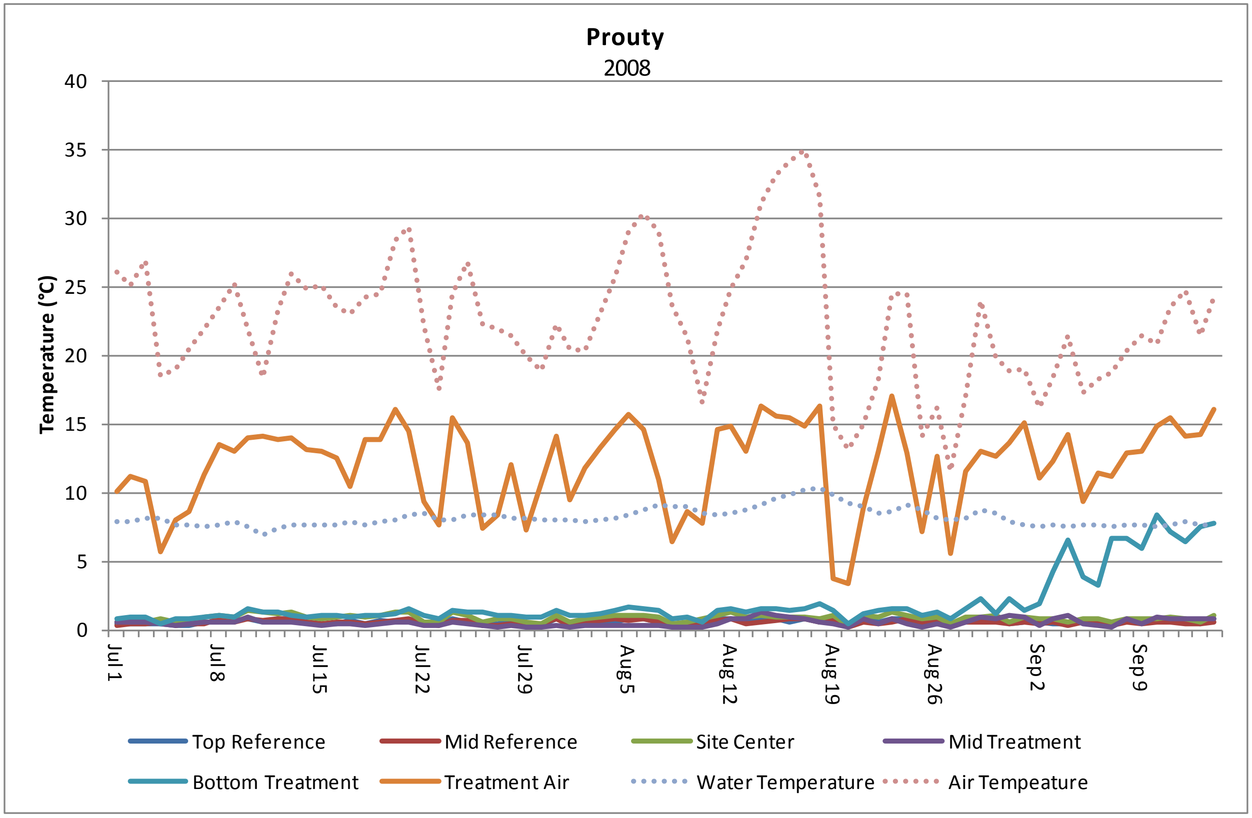
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Prouty
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Temperature (°C)
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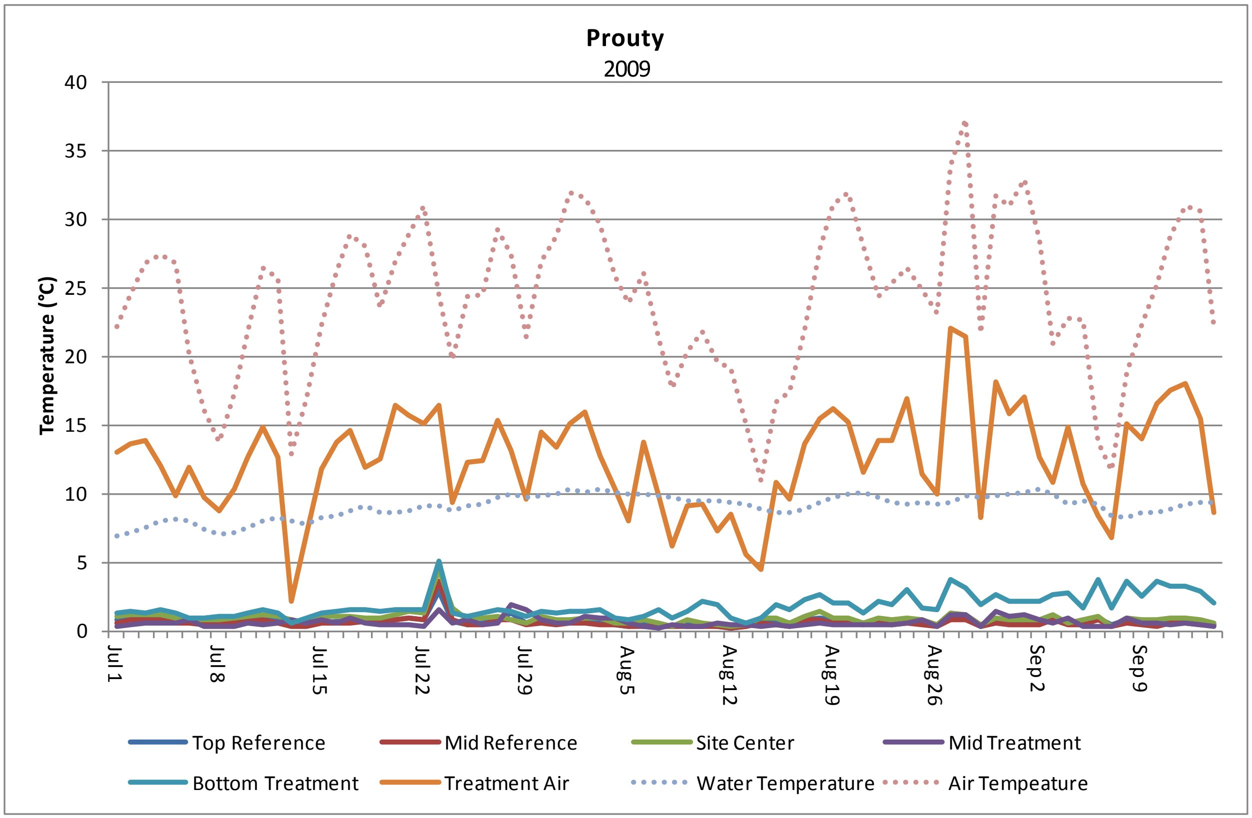
35
30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature


Prouty
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Temperature (°C)
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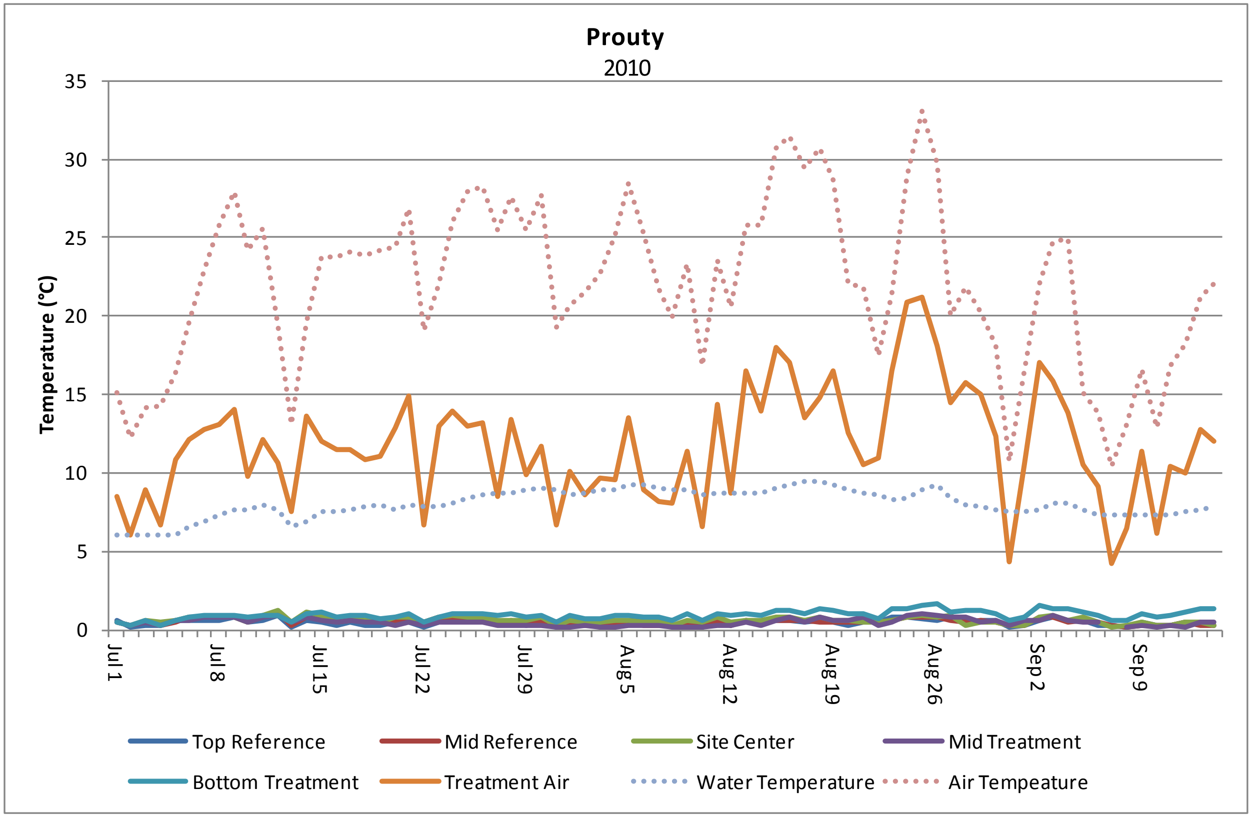
35
30
25
20
15
10
5
0
Jul 1
Jul 8
Jul 15
Jul 22
Jul 29
Aug 5
Aug 12
Aug 19
Aug 26
Sep 2
Sep 9
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature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2010
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35
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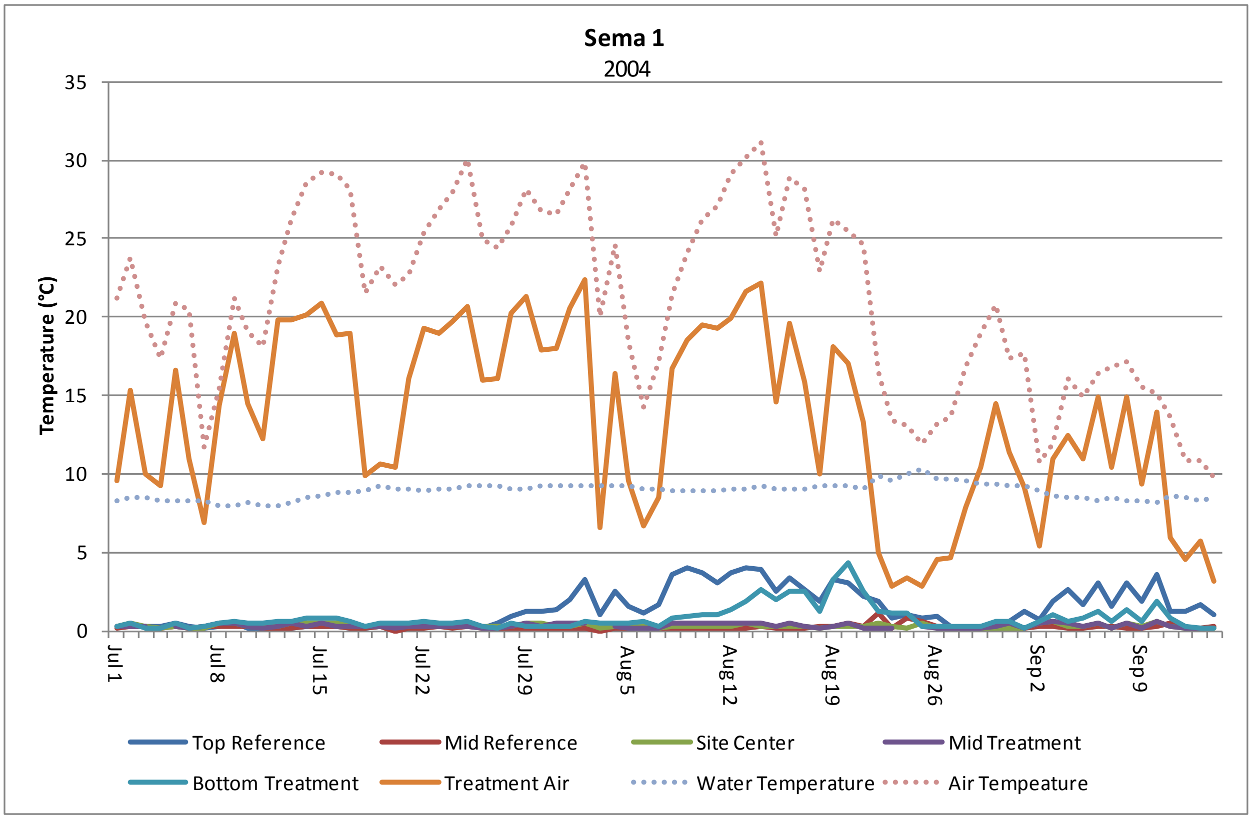
Top Reference
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature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2004
Temperature (°C)
35
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Mid Treatment
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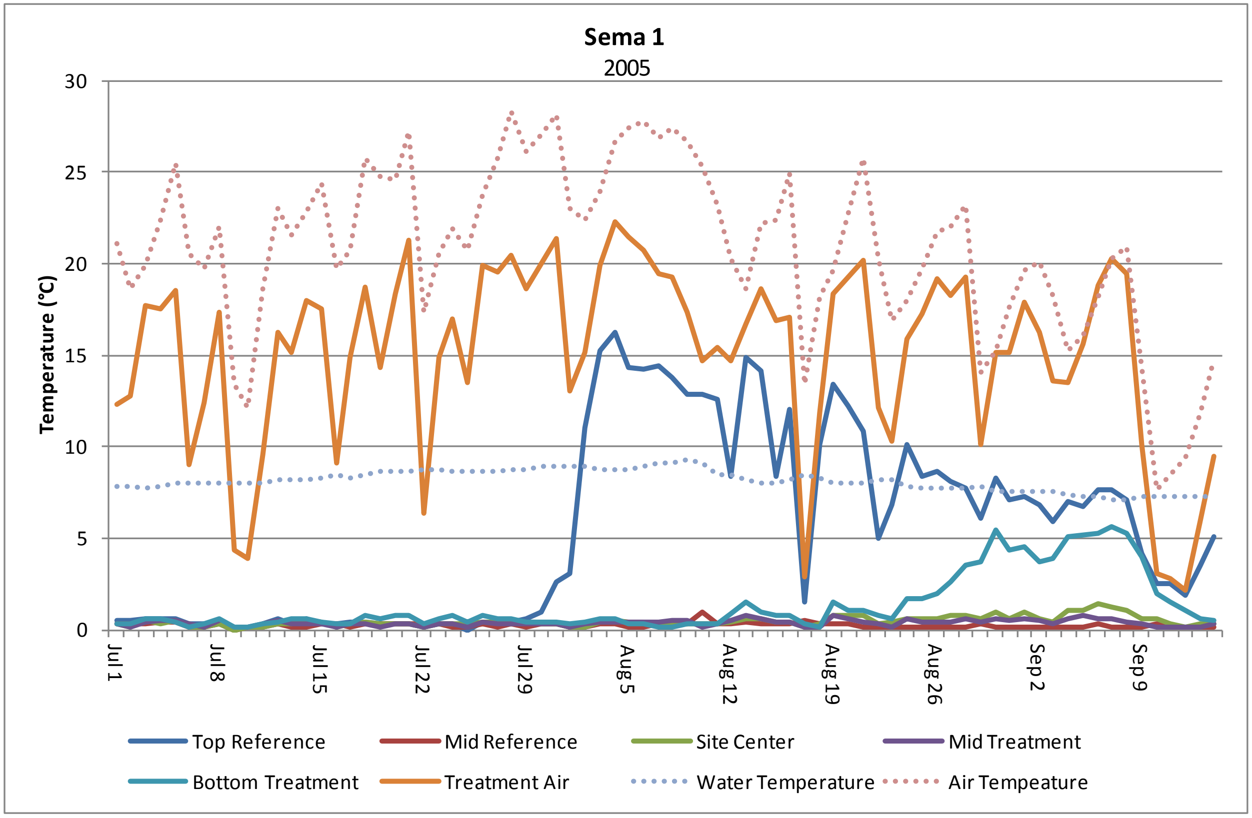
Treatment Air
Water Temperature
Air Tempeature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2005
Temperature (°C)
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Treatment Air
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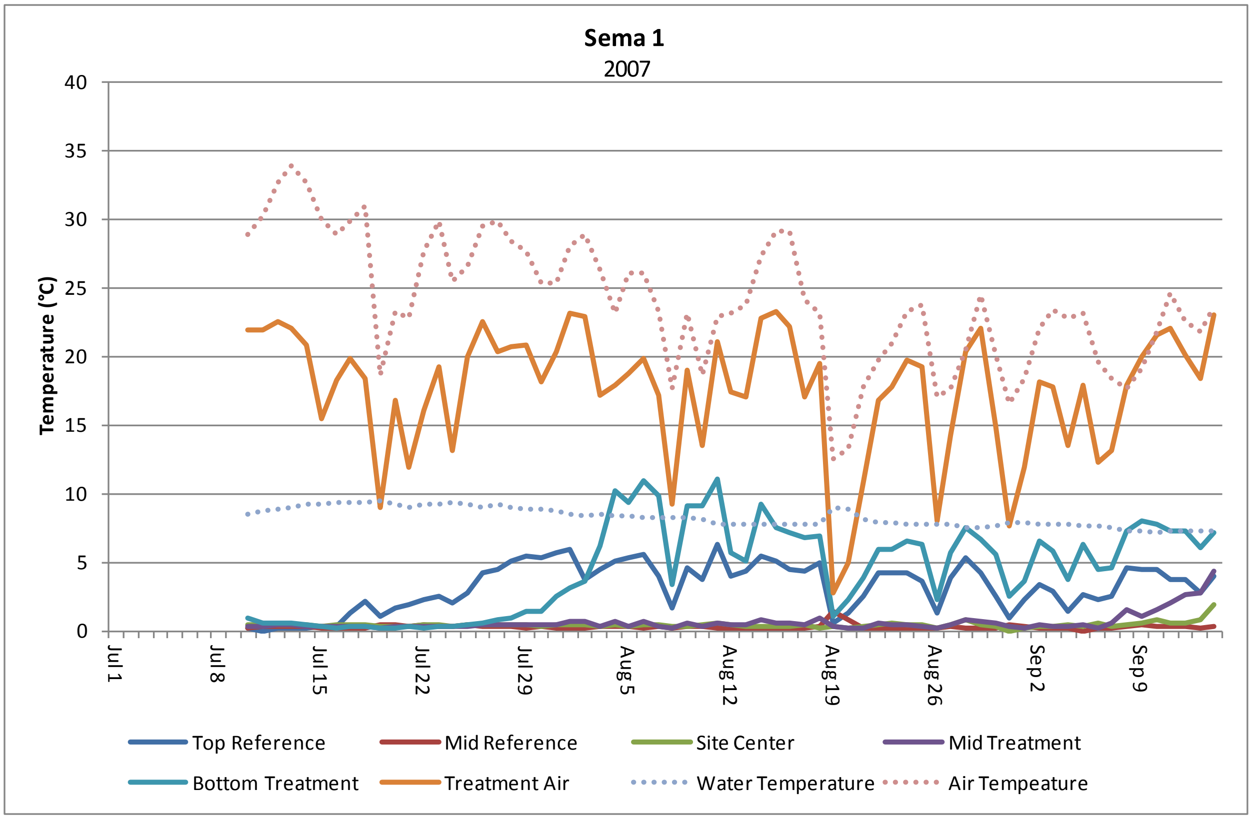
Air Tempeature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Temperature (°C)
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Top Reference
Mid Reference
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Mid Treatment
Bottom Treatment
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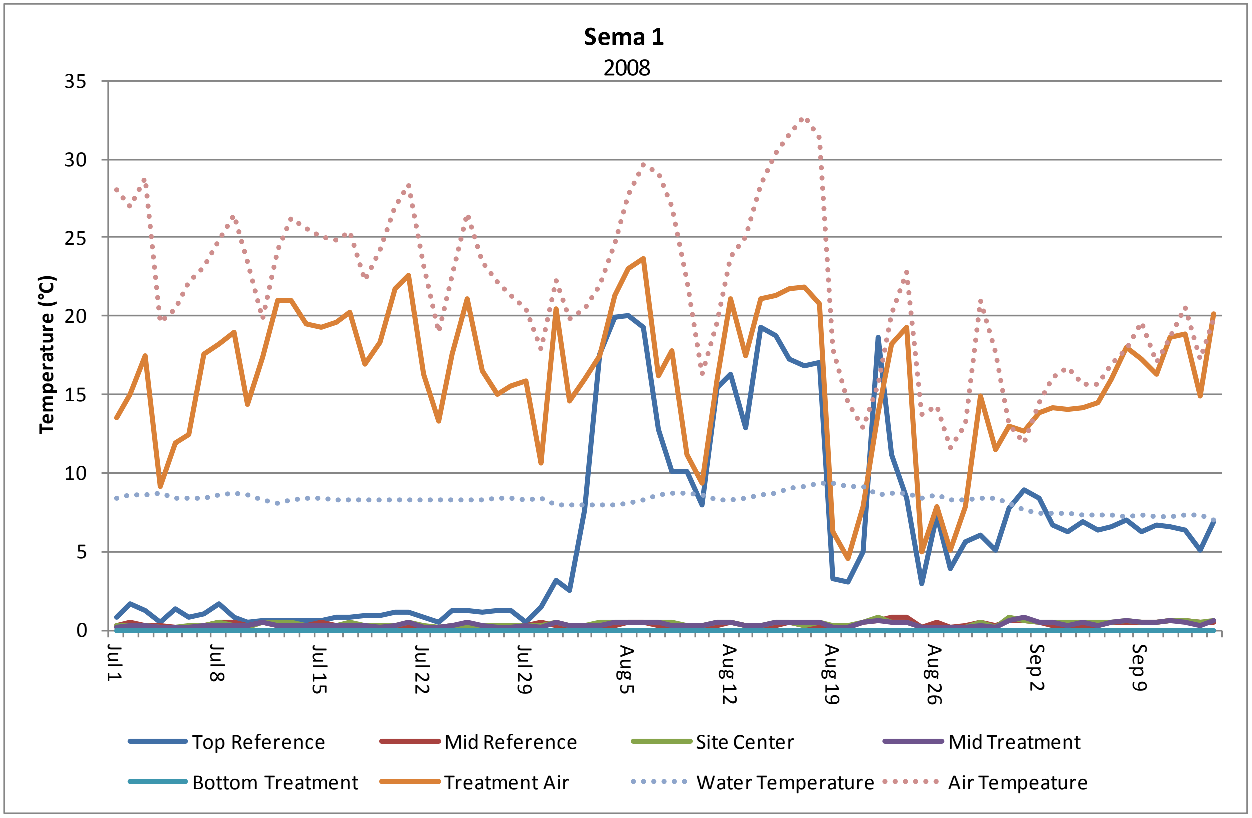
Air Tempeature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2008
Temperature (°C)
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Top Reference
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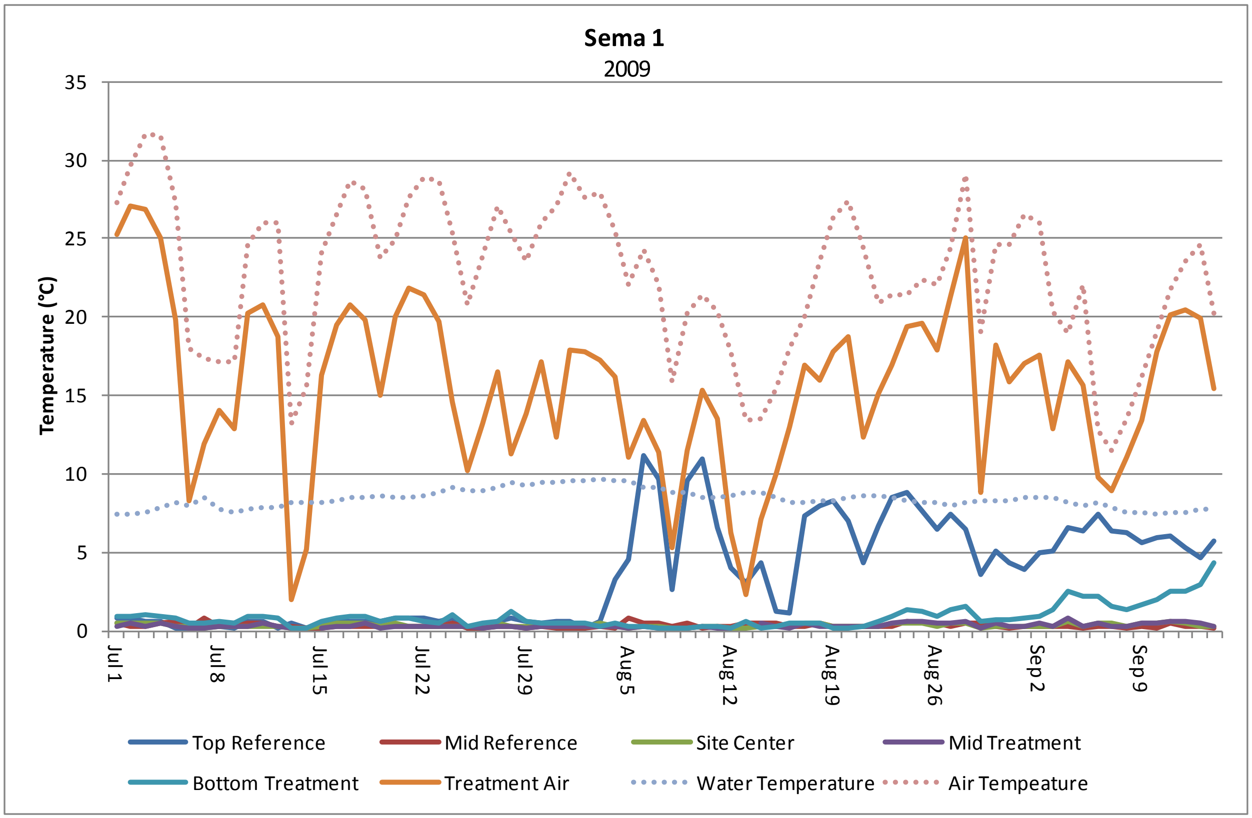
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature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2009
Temperature (°C)
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Mid Treatment
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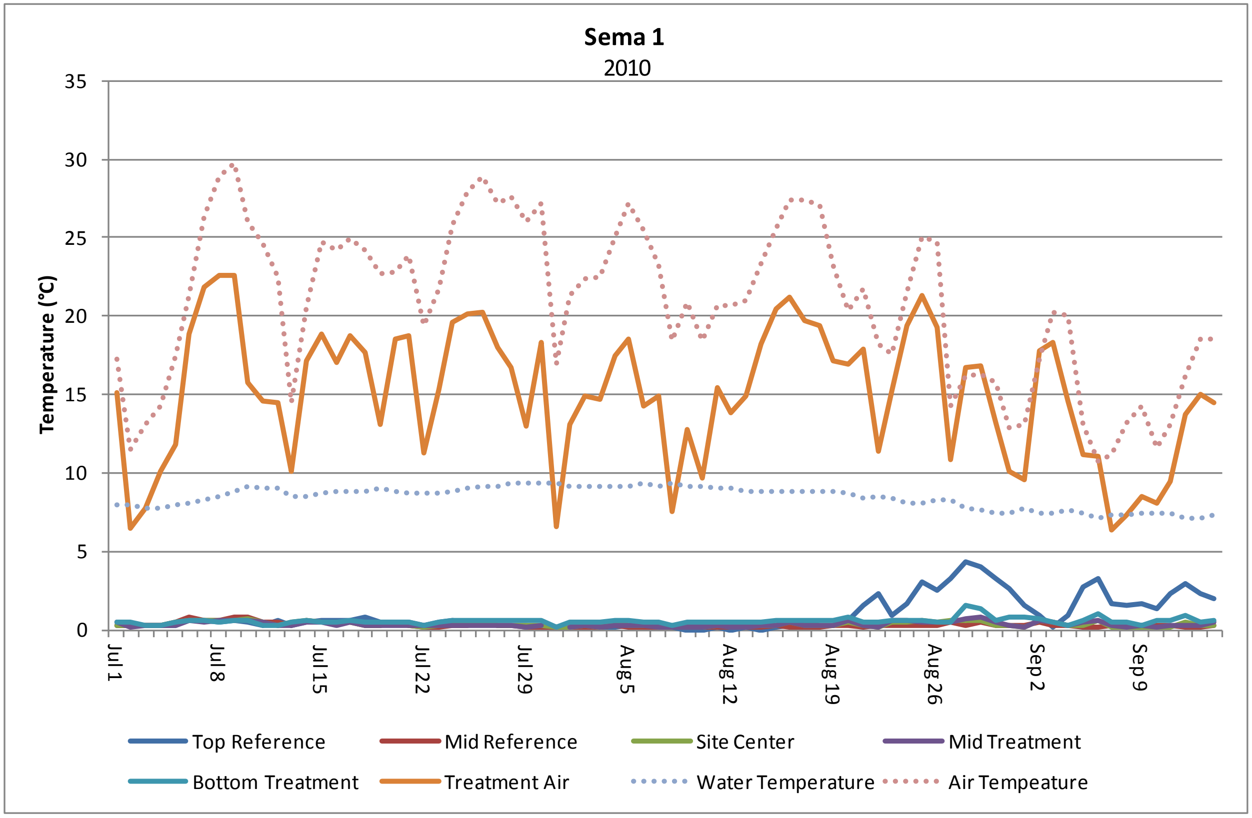
Water Temperature
Air Tempeature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Temperature (°C)
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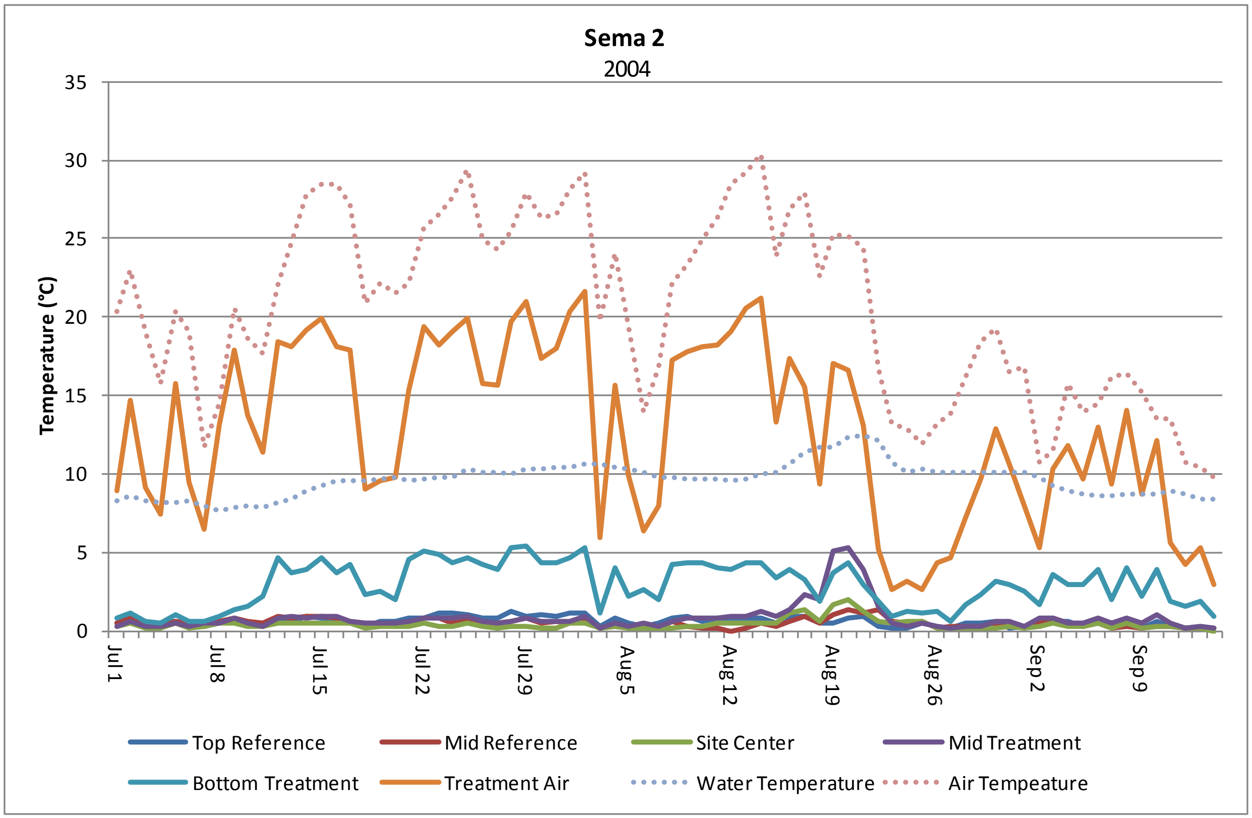
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Temperature (°C)
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Site Center
Mid Treatment
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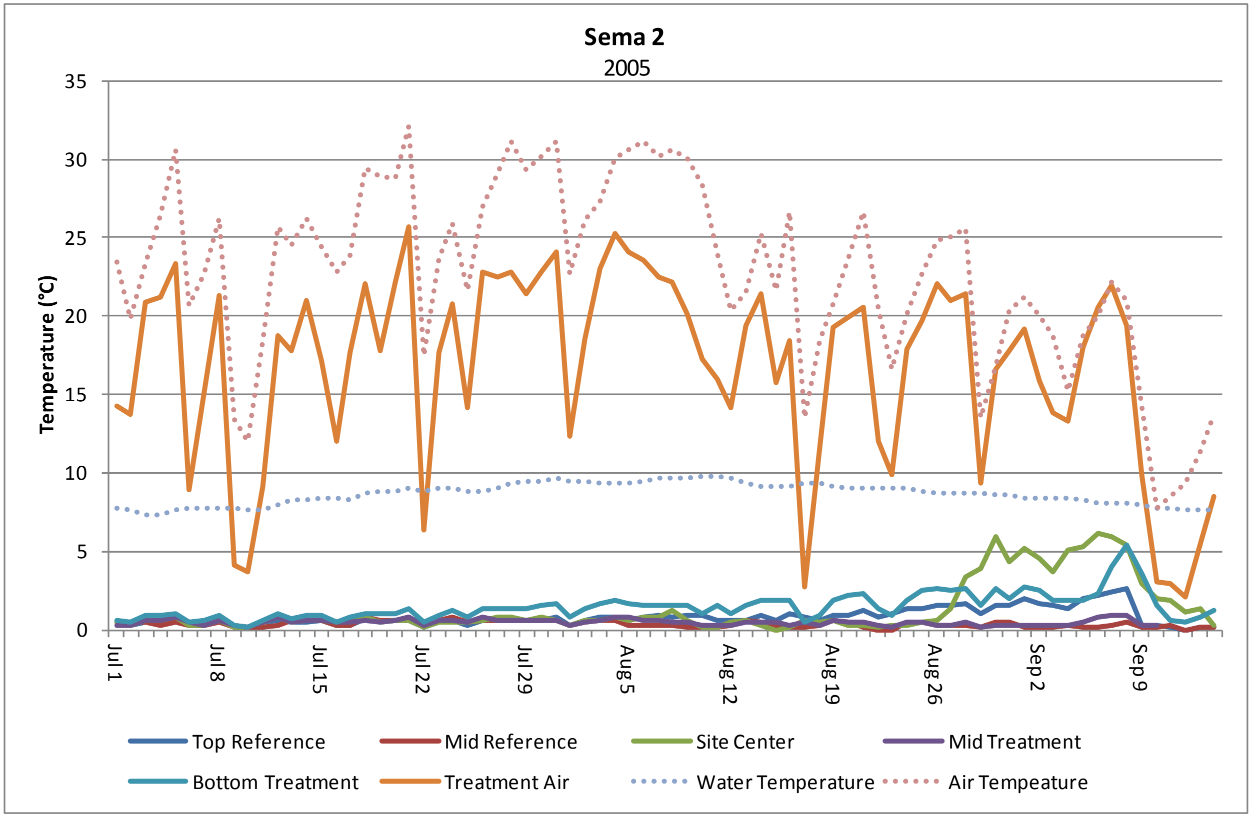
Treatment Air
Water Temperature
Air Tempeature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2005
Temperature (°C)
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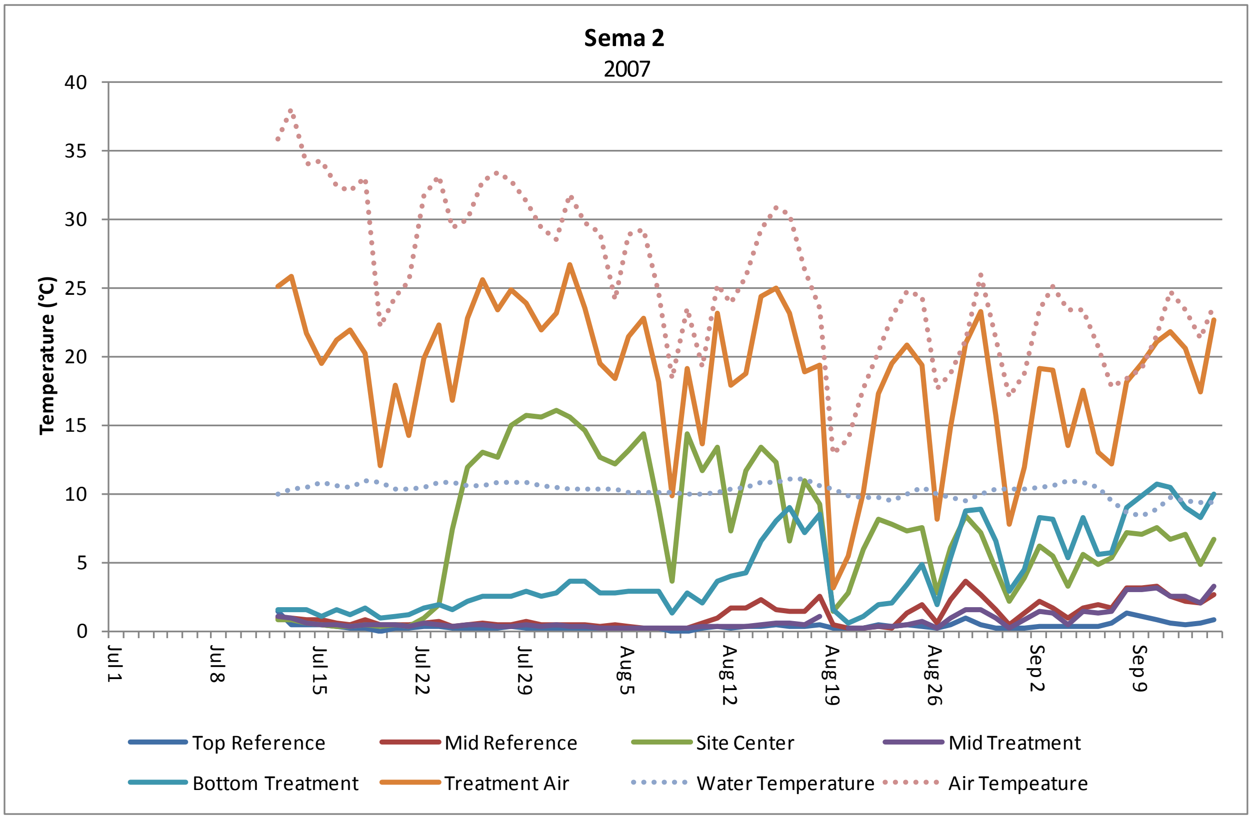
Mid Reference
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature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2007
Temperature (°C)
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Top Reference
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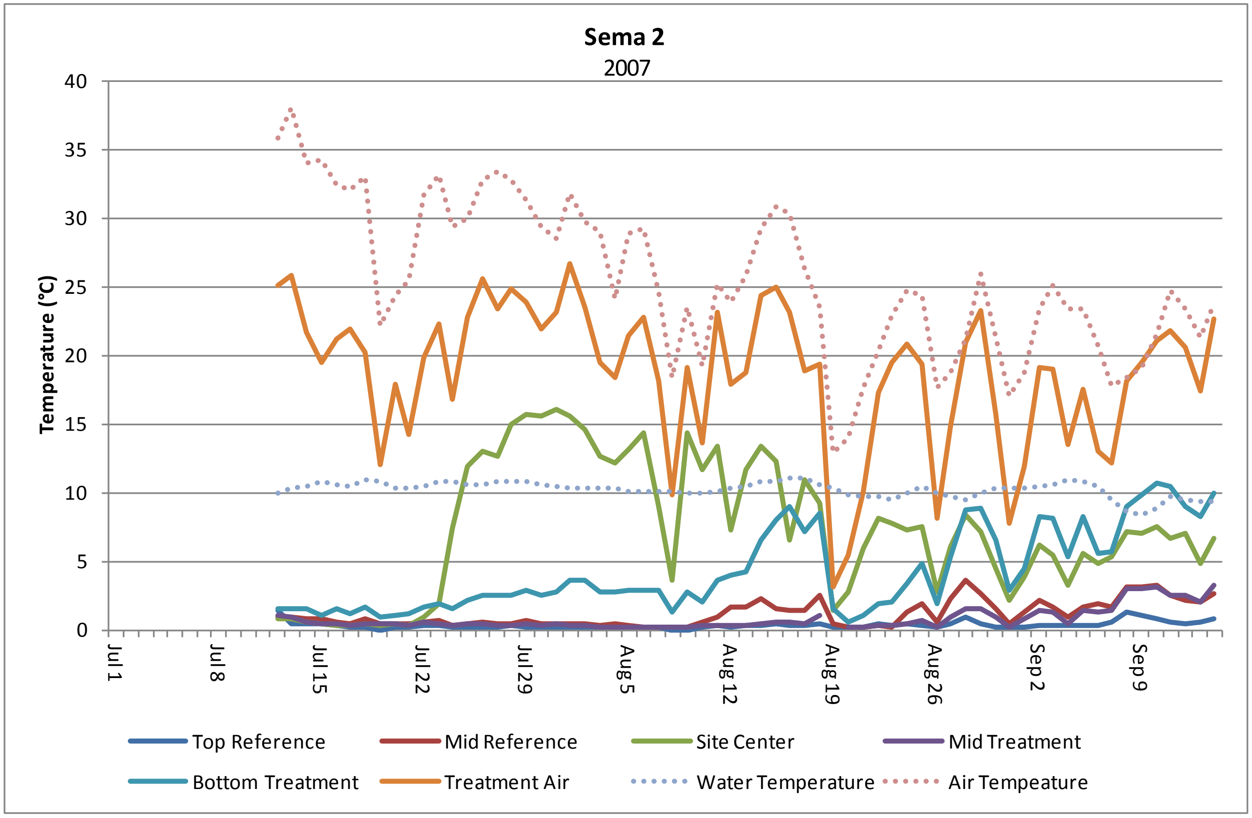
Site Center
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature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2007
Temperature (°C)
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Site Center
Mid Treatment
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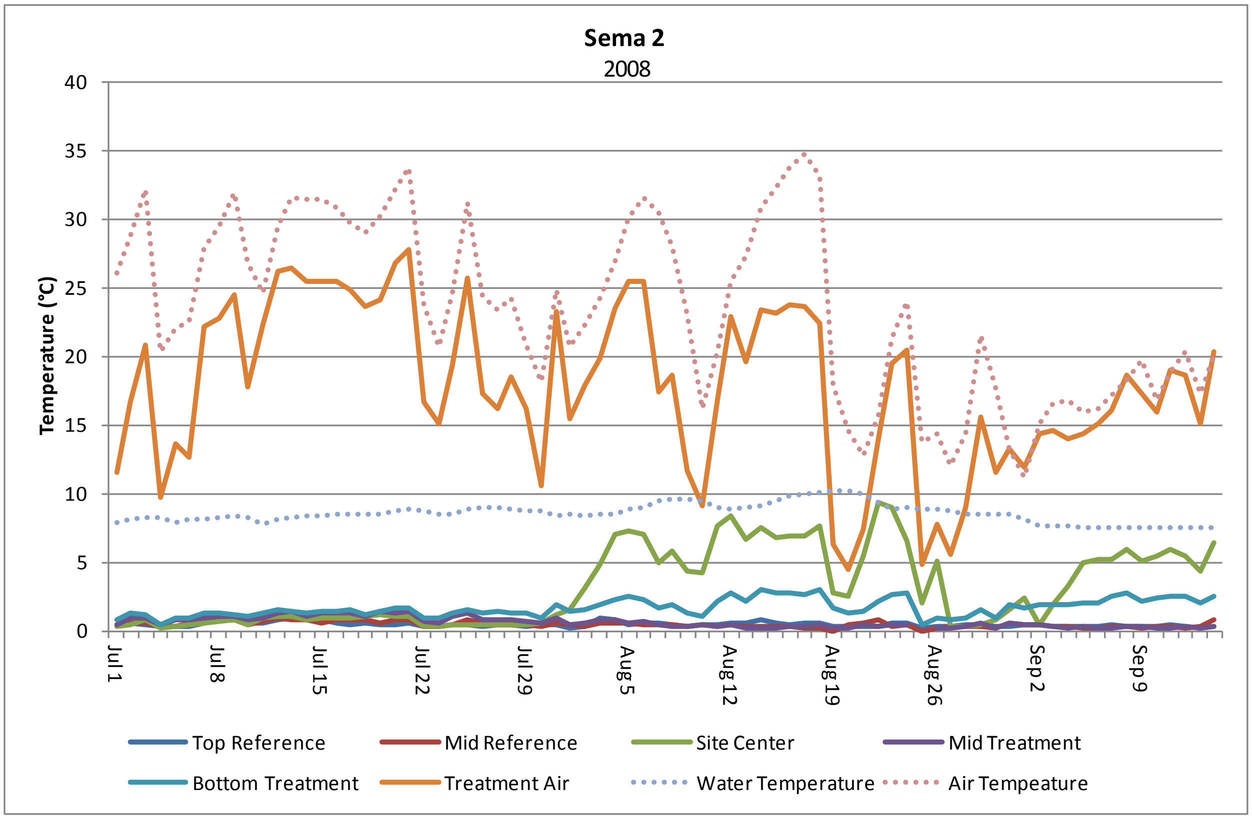
Treatment Air
Water Temperature
Air Tempeature


Sema 2
2008
Temperature (°C)
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Top Reference
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Site Center
Mid Treatment
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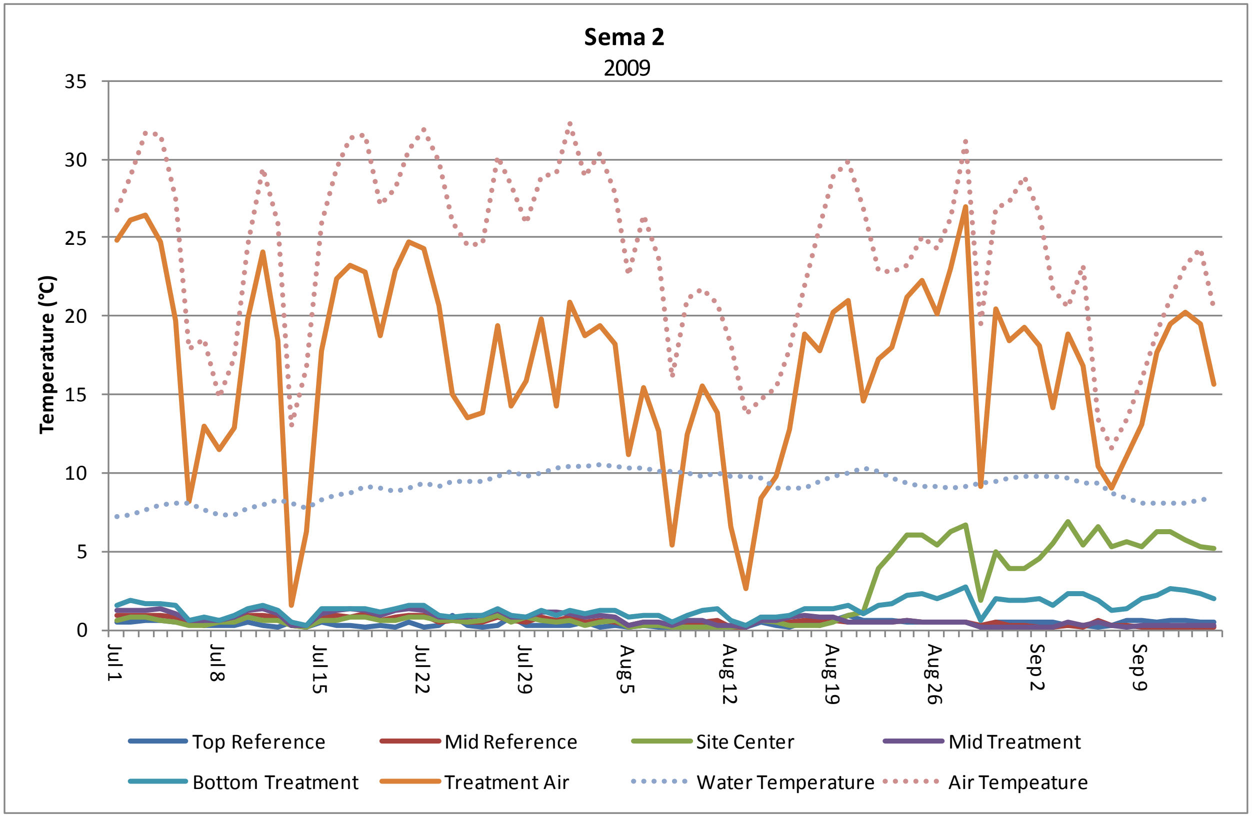
Treatment Air
Water Temperature
Air Tempeature


Sema 2
2009
Temperature (°C)
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Mid Treatment
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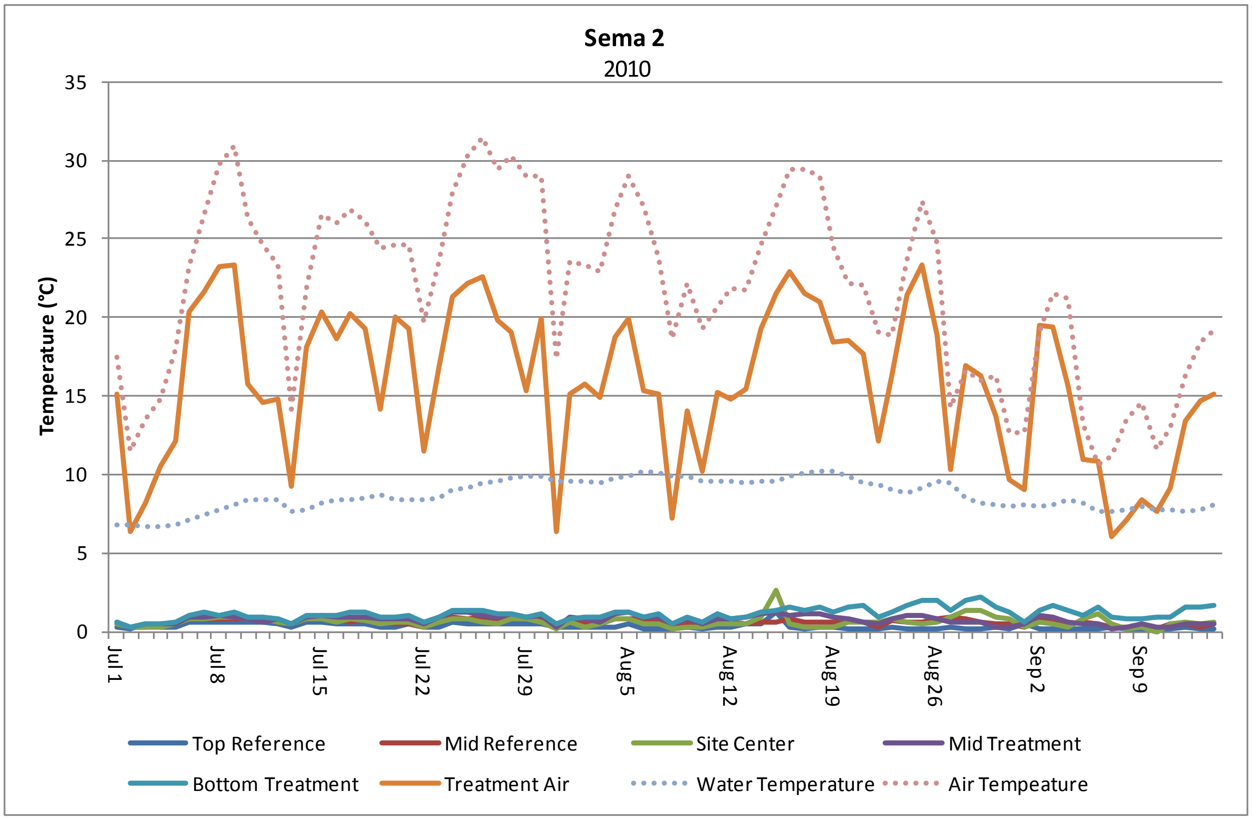
Water Temperature
Air Tempeature


Sema 2
2010
Temperature (°C)
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Top Reference
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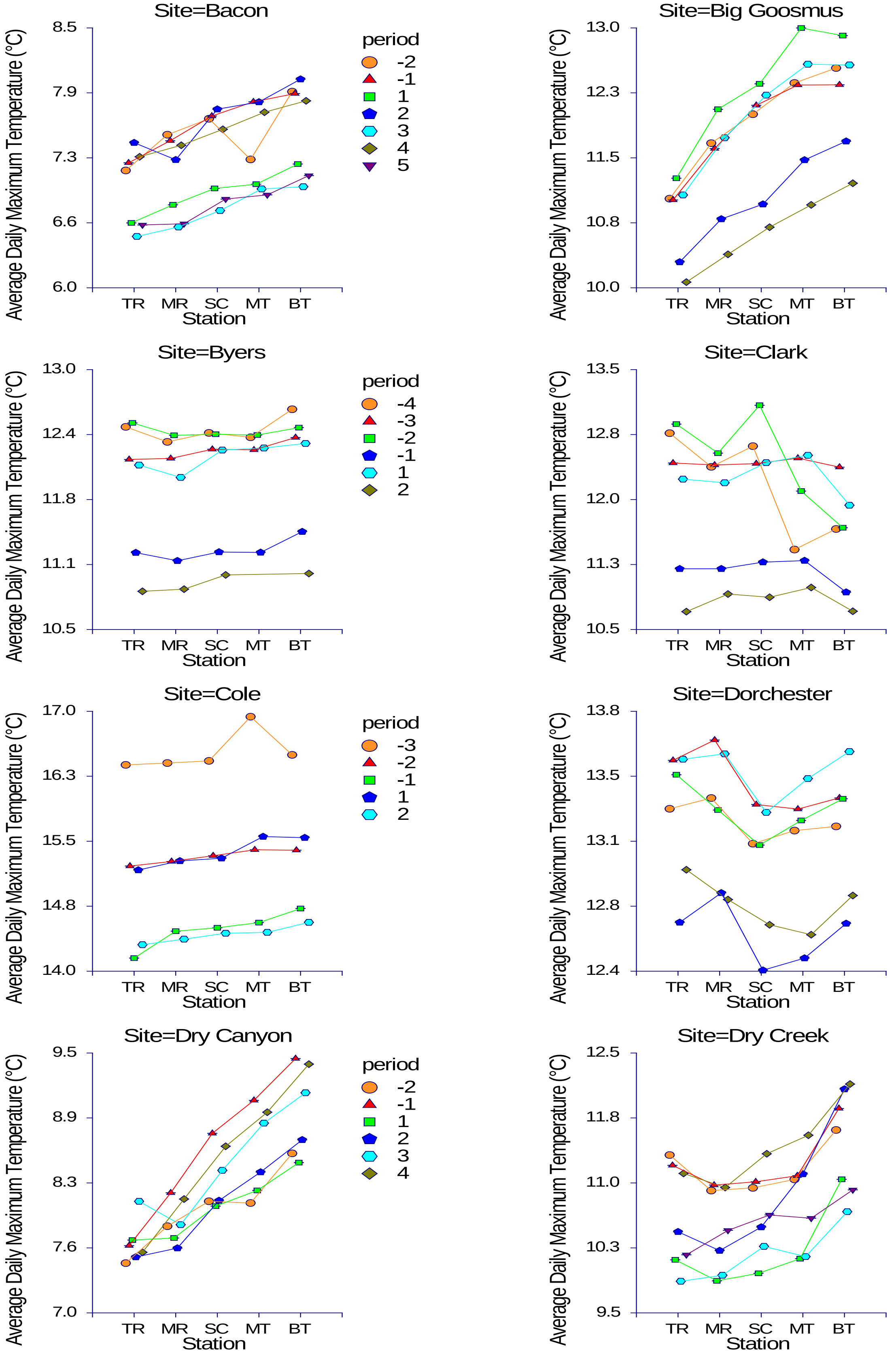
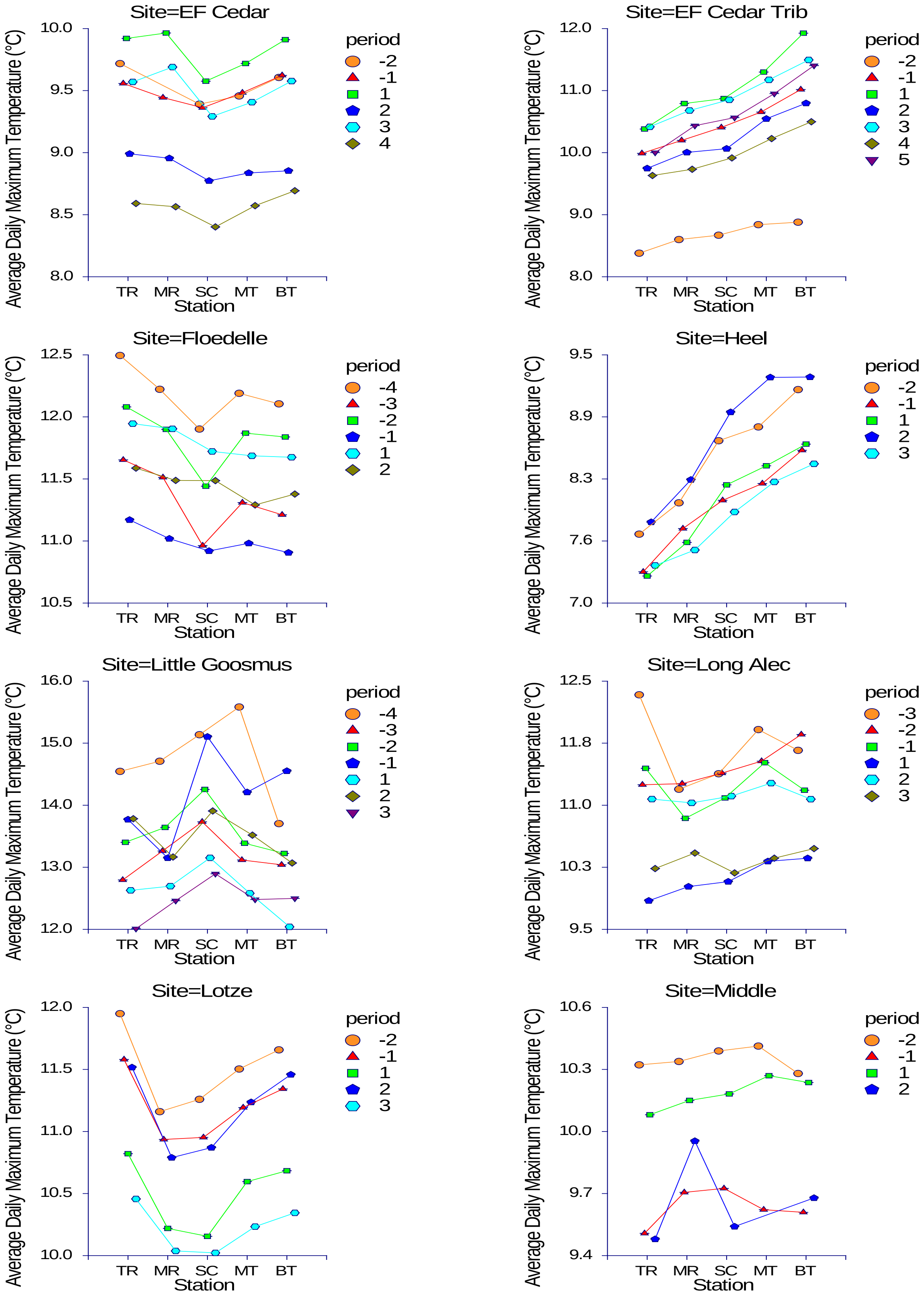
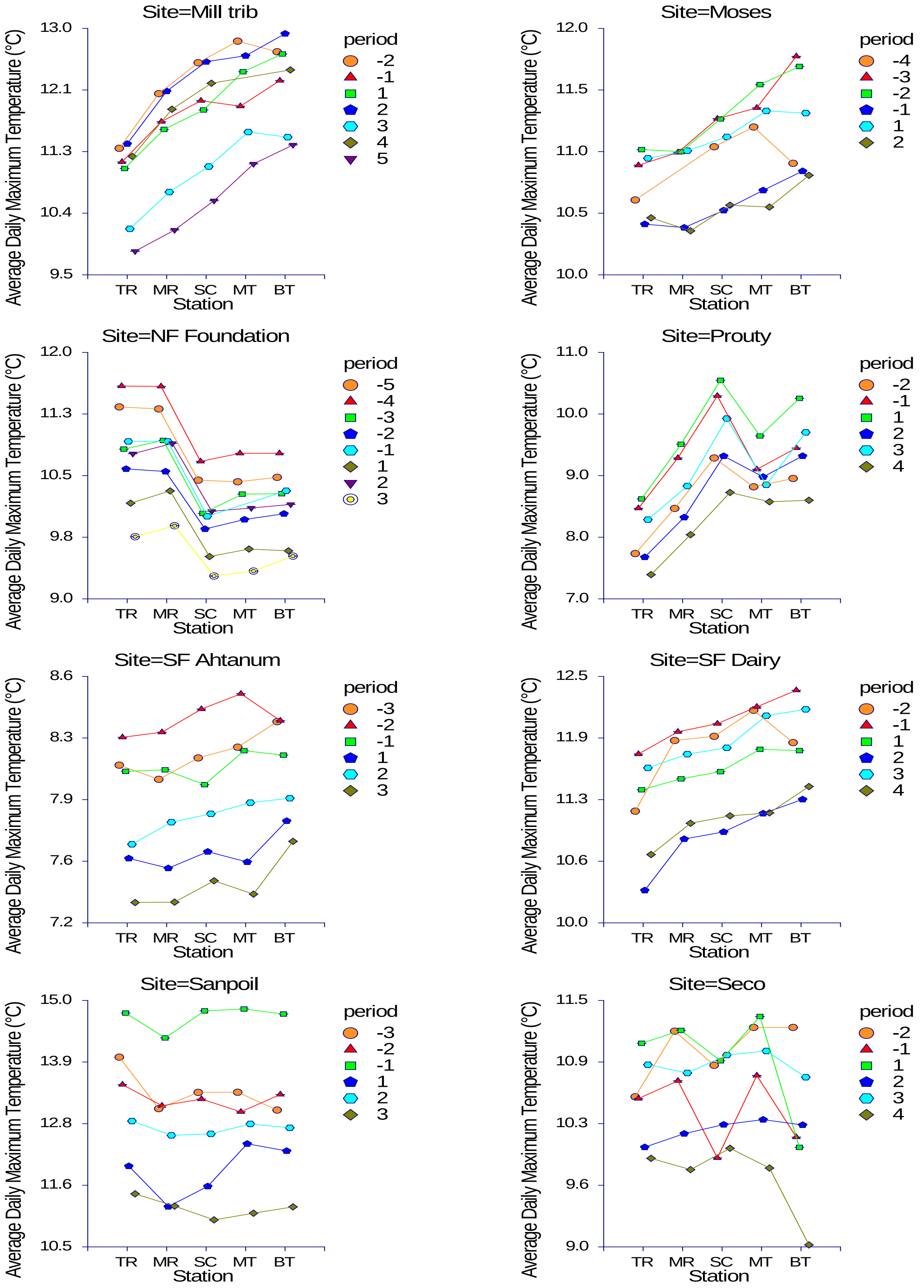
Mid Treatment
Bottom Treatment
Treatment Air
Water Temperature
Air Tempeature



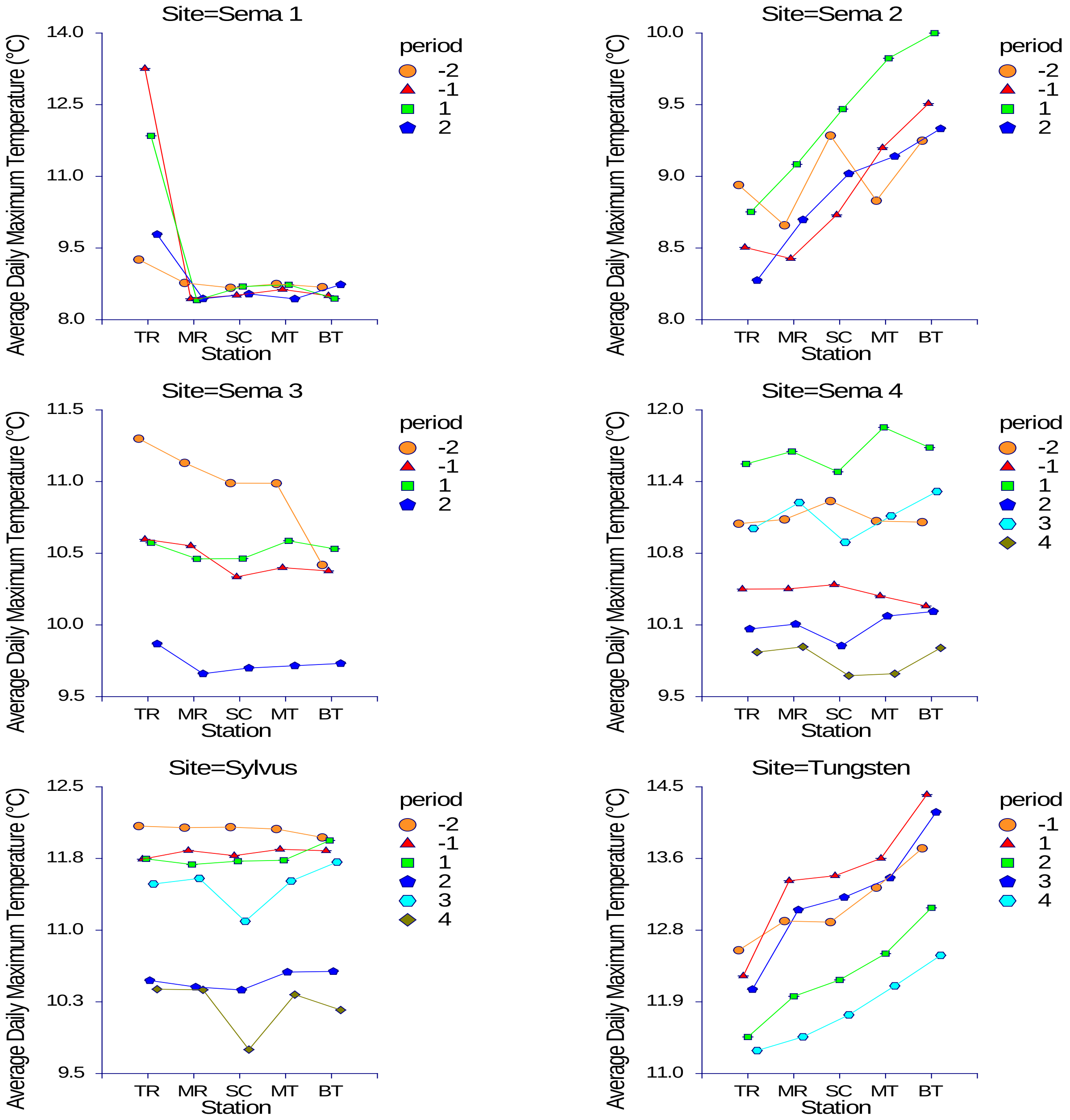
Appendix 4. Longitudinal profiles of average daily maximum stream temperature through study site Period represents pre-harvest (negative number) or post-harvest (positive number) sample period.



Appendix 4. Longitudinal profiles of average daily maximum stream temperature through study site Period represents pre-harvest (negative number) or post-harvest (positive number) sample period.



Appendix 4. Longitudinal profiles of average daily maximum stream temperature through study site Period represents pre-harvest (negative number) or post-harvest (positive number) sample period.



Appendix 4. Longitudinal profiles of average daily maximum stream temperature through study site Period represents pre-harvest (negative number) or post-harvest (positive number) sample period.

Appendix 5. Sample period mean maximum daily stream temperature (°C; range in parentheses) in reference and treatment reaches in study sites of the Eastern Washington Shade and Temperature Effectiveness study (1 of 4 pages).

	Reference Reach									
	Pre_5		**Pre_4**		**Pre_3**		**Pre_2**		**Pre_1**	
	All Available Shade Rule									
Bacon							7.6	(5.7-9.3)	7.7	(6-9)
Clark			12.6	(8.4-14.9)	12.4	(8.8-15.6)	13.1	(9.7-15.8)	11.3	(8.4-15.2)
Cole					16.4	(11.2-19.4)	15.3	(10.8-18)	14.5	(10.8-17.5)
Dry Canyon							8.1	(7.2-8.6)	8.7	(7.6-9.4)
Floedelle			11.9	(8.1-13.9)	11.0	(7.1-13.3)	11.4	(7.5-14.8)	10.9	(7.3-15.3)
Long Alec					11.4	(7.2-13.6)	11.4	(7.6-13.8)	11.1	(7-14)
Lotze							11.3	(8.3-13.1)	11.0	(8.6-12.6)
Mill							12.5	(8.5-14.8)	12.0	(8.3-15)
Moses			11.0	(9-12.2)	11.3	(8.8-13.1)	11.3	(9.7-12.7)	10.5	(9.2-12.8)
NF Foundation	10.4	(6.6-13.1)	10.7	(6.1-12.9)	10.0	(5.7-12.7)	9.9	(4.8-13.1)	10.0	(6.8-13.3)
Sanpoil							13.3	(8.7-16.1)	13.2	(8.9-16.1)
Seco							10.8	(8.6-13.2)	9.9	(7.8-11.3)
Sema 1							8.7	(7.6-9.6)	8.5	(7.3-9.5)
Sema 2							9.3	(7.6-11.1)	8.7	(8-9.4)
SF Ahtanum					8.1	(5.9-9.6)	8.4	(6.1-9.8)	8.0	(6-9.8)
Tungsten									12.8	(10.5-15.1)
	Standard Rule									
Big Goosmus							12.0	(8.5-14.4)	12.1	(8.8-15.2)
Byers			12.4	(8.4-14.7)	12.2	(8.9-15)	12.4	(8.8-14.9)	11.2	(8.1-14.9)
Dorchester							13.1	(9.5-15.1)	13.3	(9.7-15.3)
Dry Creek							10.9	(7.7-13.4)	11.0	(7.7-12.8)
EF Cedar							9.4	(7.1-11)	9.4	(7.4-11.3)
EF Cedar trib							8.7	(8.7-8.7)	10.4	(8.4-12.6)
Heel							8.6	(7-10.1)	8.0	(6.6-9.1)
Little Goosmus			15.1	(11.8-17.1)	13.7	(10.9-15.9)	14.3	(9.2-18)	15.1	(11.5-18.1)
Middle							10.4	(8-12)	9.7	(7-11.3)
Prouty							9.3	(7.5-11.1)	10.3	(7.8-12.4)
Sema 3							11.0	(8.3-12.9)	10.3	(7.9-12.1)
Sema 4							11.2	(8.3-14)	10.5	(7.9-12.9)
SF Dairy							11.9	(9.8-13.4)	12.0	(9.9-14.3)
Sylvus							12.1	(8-14.4)	11.8	(8.1-14.1)

Appendix 5. Sample period mean maximum daily stream temperature (°C; range in parentheses) in reference and treatment reaches in study sites of the Eastern Washington Shade and Temperature Effectiveness study (2 of 4 pages).

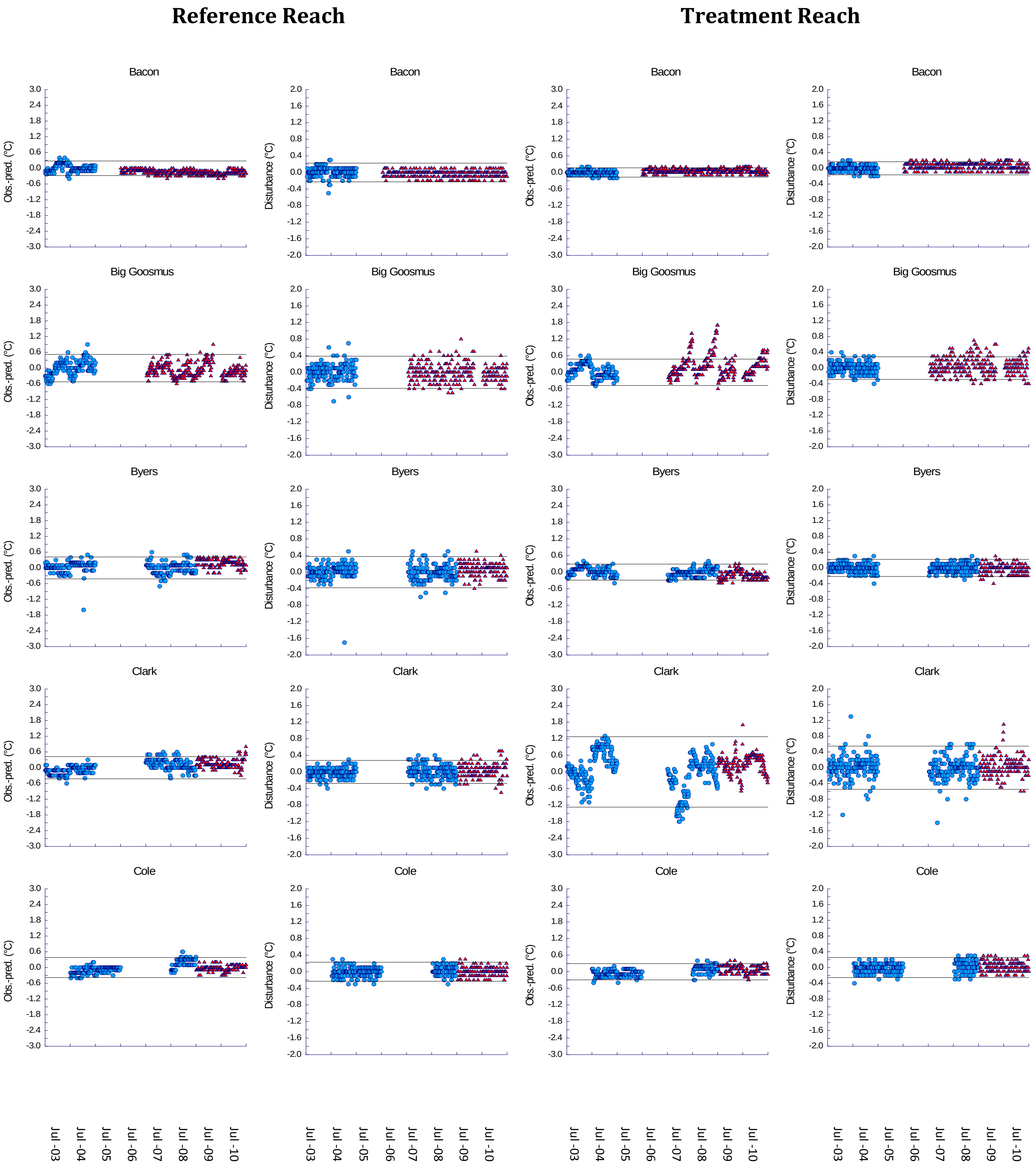
	Reference Reach									
	Post$_1$		**Post$_2$**		**Post$_3$**		**Post$_4$**		**Post$_5$**	
	All Available Shade Rule									
Bacon	7.0	(4.9-8.2)	7.7	(6.5-9.1)	6.7	(5.4-8.1)	7.5	(6-9)	6.9	(5.5-7.9)
Clark	12.4	(9.2-15.4)	10.9	(8.1-13.7)						
Cole	15.3	(11.5-18.8)	14.4	(10.8-17.7)						
Dry Canyon	8.0	(7.4-8.7)	8.1	(7.2-8.9)	8.4	(7.6-9.3)	8.6	(7.4-9.4)		
Floedelle	11.7	(8-14.6)	11.5	(7.5-14.8)						
Long Alec	10.1	(6.3-13.4)	11.1	(7.1-14.1)	10.2	(6.6-12.8)				
Lotze	10.2	(7.8-12.6)	10.9	(8.7-13.2)	10.0	(7.9-11.9)				
Mill	11.8	(9.3-14.7)	12.5	(9.7-15.1)	11.0	(8.5-15.2)	12.2	(8.9-15.1)	10.6	(7.5-13.1)
Moses	11.1	(9.2-12.9)	10.6	(8.5-12.3)						
NF Foundation	9.5	(6.1-12.5)	10.1	(6.6-13.3)	9.3	(6.1-11.7)				
Sanpoil	11.6	(8.5-15)	12.6	(9.5-15.2)	11.0	(8.4-13.5)				
Seco	10.9	(8.6-12.9)	10.2	(8.1-13)	10.9	(8.4-13.2)	10.0	(7.7-12.2)		
Sema 1	8.2	(6.8-9.9)	8.5	(7.5-9.5)						
Sema 2	9.5	(7.1-11.3)	9.0	(6.8-11.8)						
SF Ahtanum	7.6	(5.6-9)	7.8	(5.9-9.5)	7.4	(5.6-9)				
Tungsten	13.4	(10.6-15.9)	12.1	(9.6-15.9)	13.2	(9.9-16.1)	11.7	(8.9-14)		
	Standard Rule									
Big Goosmus	12.4	(9.3-14.8)	11.0	(8.7-14.5)	12.2	(9-14.7)	10.7	(8.3-12.9)		
Byers	12.2	(9-15.3)	11.0	(8.1-13.7)						
Dorchester	13.1	(10-15.9)	12.4	(9.6-15.3)	13.3	(9.8-15.8)	12.7	(9.3-15.5)		
Dry Creek	10.0	(5.8-13.8)	10.5	(8.6-13.2)	10.3	(7.2-12.6)	11.3	(7.8-13.7)	10.6	(6.8-14.3)
EF Cedar	9.6	(7.6-11.1)	8.8	(6.8-11.2)	9.3	(7.2-11.1)	8.4	(6.3-10.2)		
EF Cedar trib	10.9	(8.9-12.1)	10.1	(8.5-12.8)	10.9	(8.4-12.8)	9.9	(8.1-11.6)	10.6	(8.4-11.9)
Heel	8.2	(7.1-10.2)	8.9	(7.3-10.4)	7.9	(6.4-9.2)				
Little Goosmus	13.2	(10.3-16)	13.9	(10-17)	12.9	(9.2-16.1)				
Middle	10.2	(7.4-12.4)	9.5	(7-11.6)						
Prouty	10.5	(7.8-11.6)	9.3	(7.7-11.9)	9.9	(7.6-11.9)	8.7	(6.4-10.7)		
Sema 3	10.5	(8.2-12.4)	9.7	(7.5-11.7)						
Sema 4	11.5	(8.8-13.8)	9.9	(7.7-13.3)	10.8	(8.2-13)	9.7	(7.3-11.8)		
SF Dairy	11.5	(10.2-12.9)	10.9	(8.9-13.7)	11.8	(9.3-14.3)	11.1	(8.9-13)		
Sylvus	11.7	(8.6-14.5)	10.4	(7.7-13.9)	11.1	(8.4-13.5)	9.8	(7.6-12.7)		

Appendix 5. Sample period mean maximum daily stream temperature (°C; range in parentheses) in reference and treatment reaches in study sites of the Eastern Washington Shade and Temperature Effectiveness study (3 of 4 pages).

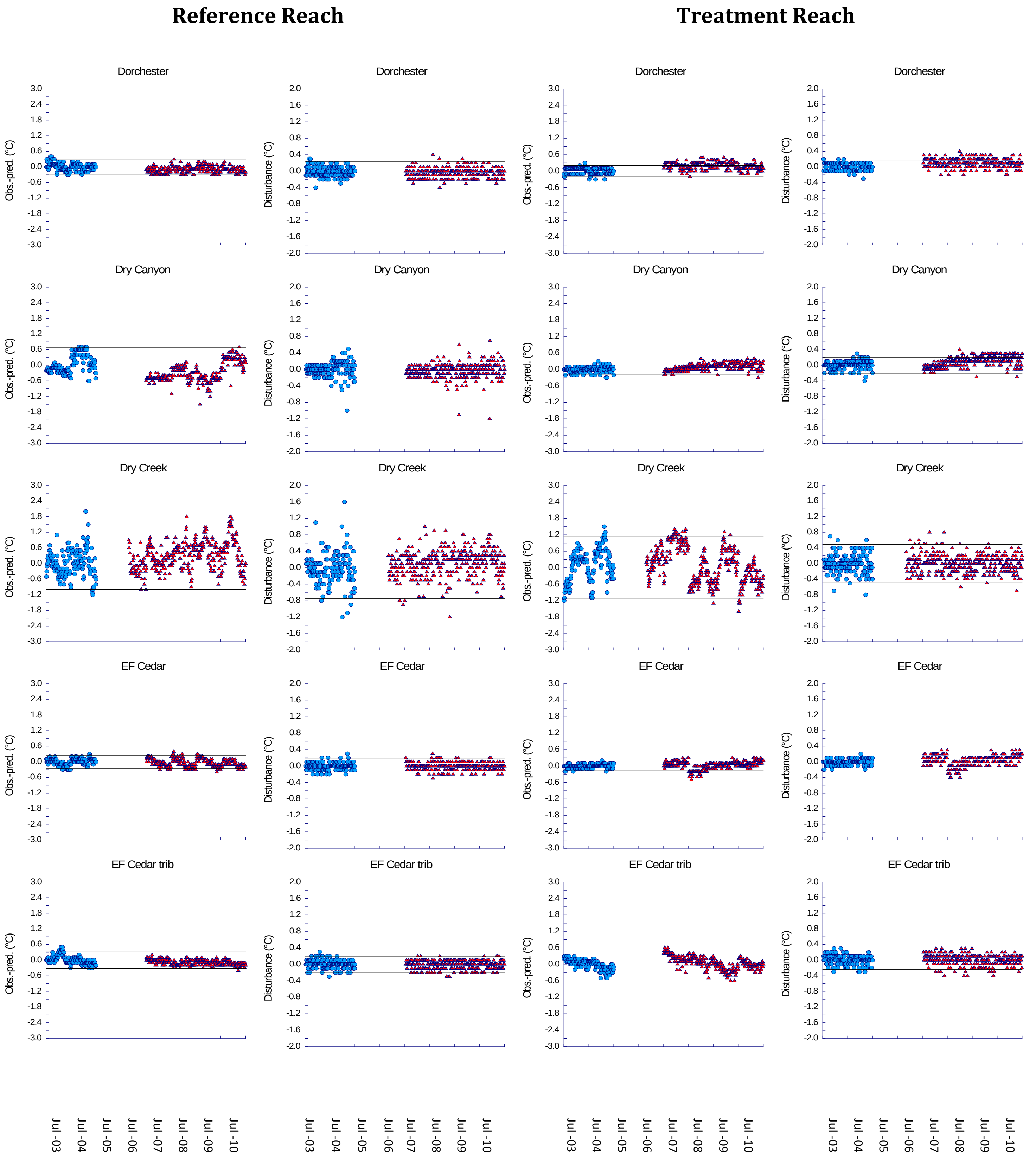
	Treatment Reach									
	Pre$_5$		**Pre$_4$**		**Pre$_3$**		**Pre$_2$**		**Pre$_1$**	
	All Available Shade Rule									
Bacon							7.9	(5.9-9.8)	7.9	(6.1-9.4)
Clark			11.7	(8-13.7)	12.4	(8.9-15.5)	11.7	(9.4-14.3)	10.9	(7.8-14.1)
Cole					16.5	(11.3-19.5)	15.4	(10.7-18.1)	14.7	(11-17.7)
Dry Canyon							8.5	(7.5-9.2)	9.4	(7.7-10.5)
Floedelle			12.1	(8.3-14.3)	11.2	(7.5-13.3)	11.8	(7.7-15.3)	10.9	(7.1-15.3)
Long Alec					11.7	(7.9-14.1)	11.9	(7.8-14.7)	11.2	(7.3-14.6)
Lotze							11.7	(8.2-13.6)	11.3	(8.7-13.4)
Mill							12.7	(9-14.7)	12.3	(8.6-14.9)
Moses			10.9	(9-12.1)	11.8	(8.9-13.9)	11.7	(10-13.4)	10.8	(9.4-13.2)
NF Foundation	10.5	(6.7-13.1)	10.8	(6.1-13.1)	10.3	(5.8-12.8)	10	(4.8-13.4)	10.3	(7-13.4)
Sanpoil							13	(8.4-15.9)	13.3	(9-16.2)
Seco							11.2	(8.8-13.3)	10.1	(7.4-12.4)
Sema 1							8.7	(7.8-9.7)	8.5	(7.6-9.1)
Sema 2							9.2	(6.9-11.1)	9.5	(8.9-10.1)
SF Ahtanum					8.3	(6.1-9.8)	8.3	(6.1-9.5)	8.2	(6.2-9.9)
Tungsten									13.7	(10.6-17)
	Standard Rule									
Big Goosmus							12.5	(9-14.9)	12.3	(8.9-15.4)
Byers			12.6	(8.7-15.1)	12.3	(9.1-15.3)	12.4	(9-14.9)	11.4	(8.6-15.2)
Dorchester							13.2	(9.5-15.2)	13.3	(9.6-15.3)
Dry Creek							11.6	(7.8-13.4)	11.9	(8.9-14.3)
EF Cedar							9.6	(7.2-11.3)	9.6	(7.7-11.7)
EF Cedar trib							8.9	(8.9-8.9)	11	(8.7-13.6)
Heel							9.2	(7.2-10.7)	8.5	(6.7-9.7)
Little Goosmus			13.7	(11.3-15.5)	13	(10.9-14.9)	13.2	(8.5-17.4)	14.6	(10.5-17.2)
Middle							10.3	(7.8-11.7)	9.6	(7-11.2)
Prouty							9	(7.8-10.3)	9.4	(7.8-10.7)
Sema 3							10.4	(8.4-11.8)	10.4	(7.9-12.1)
Sema 4							11	(8.3-13.4)	10.3	(7.8-12.8)
SF Dairy							11.8	(9.7-13.6)	12.4	(9.9-14.6)
Sylvus							12	(7.8-14.1)	11.8	(8.4-14)

Appendix 5. Sample period mean maximum daily stream temperature (°C; range in parentheses) in reference and treatment reaches in study sites of the Eastern Washington Shade and Temperature Effectiveness study (4 of 4 pages).

	Treatment Reach									
	Post$_1$		**Post$_2$**		**Post$_3$**		**Post$_4$**		**Post$_5$**	
	All Available Shade Rule									
Bacon	7.2	(5-8.4)	8	(6.9-9.5)	7	(5.6-8.4)	7.8	(6.1-9.4)	7.1	(5.8-8.2)
Clark	11.9	(8.6-14.5)	10.7	(7.8-13.3)						
Cole	15.5	(11.8-19.1)	14.6	(10.8-18)						
Dry Canyon	8.4	(7.7-9.2)	8.7	(7.6-9.8)	9.1	(8-10.4)	9.4	(7.8-10.5)		
Floedelle	11.7	(7.8-14.8)	11.4	(7.4-14.5)						
Long Alec	10.4	(6.5-13.5)	11.1	(7.8-14.3)	10.5	(7.2-13.2)				
Lotze	10.7	(8.1-13.7)	11.5	(8.8-14)	10.3	(8-12.5)				
Mill	12.6	(10.1-15.4)	12.9	(10.3-15.4)	11.5	(9.2-14.5)	12.4	(9.6-15)	11.3	(8.7-13.8)
Moses	11.3	(9.4-13.2)	10.8	(8.8-12.5)						
NF Foundation	9.6	(6.1-12.7)	10.1	(6.6-13.4)	9.5	(6.3-12.1)				
Sanpoil	12.3	(9.2-15.4)	12.7	(9.6-15.4)	11.2	(8.2-13.6)				
Seco	10	(7.8-12.9)	10.2	(8-13.1)	10.7	(8.1-12.6)	9	(7.1-10.8)		
Sema 1	8.3	(7.1-9.5)	8.7	(7.5-9.8)						
Sema 2	10	(7.9-11.7)	9.3	(7.1-11.3)						
SF Ahtanum	7.8	(5.8-9.2)	7.9	(6.1-9.5)	7.7	(5.8-9.7)				
Tungsten	14.4	(11-17.5)	13	(10-17.7)	14.2	(10.4-17.6)	12.4	(8.9-15.1)		
	Standard Rules									
Big Goosmus	12.9	(10.7-15.1)	11.7	(9.9-15.4)	12.6	(9.4-14.9)	11.2	(8.8-13.8)		
Byers	12.3	(9.2-15.2)	11	(8.2-13.6)						
Dorchester	13.3	(10.1-16.2)	12.7	(9.8-15.6)	13.6	(10-16.4)	12.8	(9.5-15.7)		
Dry Creek	11	(7.3-14.1)	12.1	(10.2-13.9)	10.7	(8-13.5)	12.1	(8.9-14.8)	10.9	(6.8-14.2)
EF Cedar	9.9	(7.9-11.4)	8.9	(7-11.5)	9.6	(7.2-11.4)	8.7	(6.4-10.6)		
EF Cedar trib	11.9	(9.7-13.6)	10.8	(8.9-14.1)	11.5	(8.6-13.7)	10.5	(8.4-12.6)	11.4	(8.7-13.3)
Heel	8.6	(7.3-10.9)	9.3	(7.5-10.6)	8.4	(6.7-10)				
Little Goosmus	12	(8.7-15.7)	13.1	(9.2-16)	12.5	(9.1-15.8)				
Middle	10.2	(7.4-12.4)	9.7	(7.1-11.7)						
Prouty	10.3	(8.2-11.1)	9.3	(7.9-12.3)	9.7	(7.9-11.4)	8.6	(6.5-10.2)		
Sema 3	10.5	(8.3-12.6)	9.7	(7.4-11.8)						
Sema 4	11.7	(8.7-14.4)	10.2	(7.6-13.7)	11.3	(8.3-13.5)	9.9	(7.5-12.1)		
SF Dairy	11.7	(10.4-13.2)	11.3	(9.1-13.9)	12.2	(9.6-14.8)	11.4	(9.1-13.5)		
Sylvus	11.9	(8.9-14.8)	10.6	(7.7-14.2)	11.7	(8.2-14.8)	10.2	(7.5-12.8)		



Appendix 6. Difference between observed and predicted daily maximum temperature and random disturbances in the treatment and reference reaches of all study sites. Data portrayed as blue circles were used to calibrate the regression model, while data portrayed in red triangles were used to test the interannual stability of the model at each study site reach. Dashed horizontal lines in the disturbance plots indicate 95% prediction limits estimated as ±1.96 S_u (S_u = standard deviation of $\hat{u}_t$): dashed horizontal lines in plots of differences between observed and predicted values show bands of ±1.96 S_e (where S_e is the standard error of the residuals from the regression).



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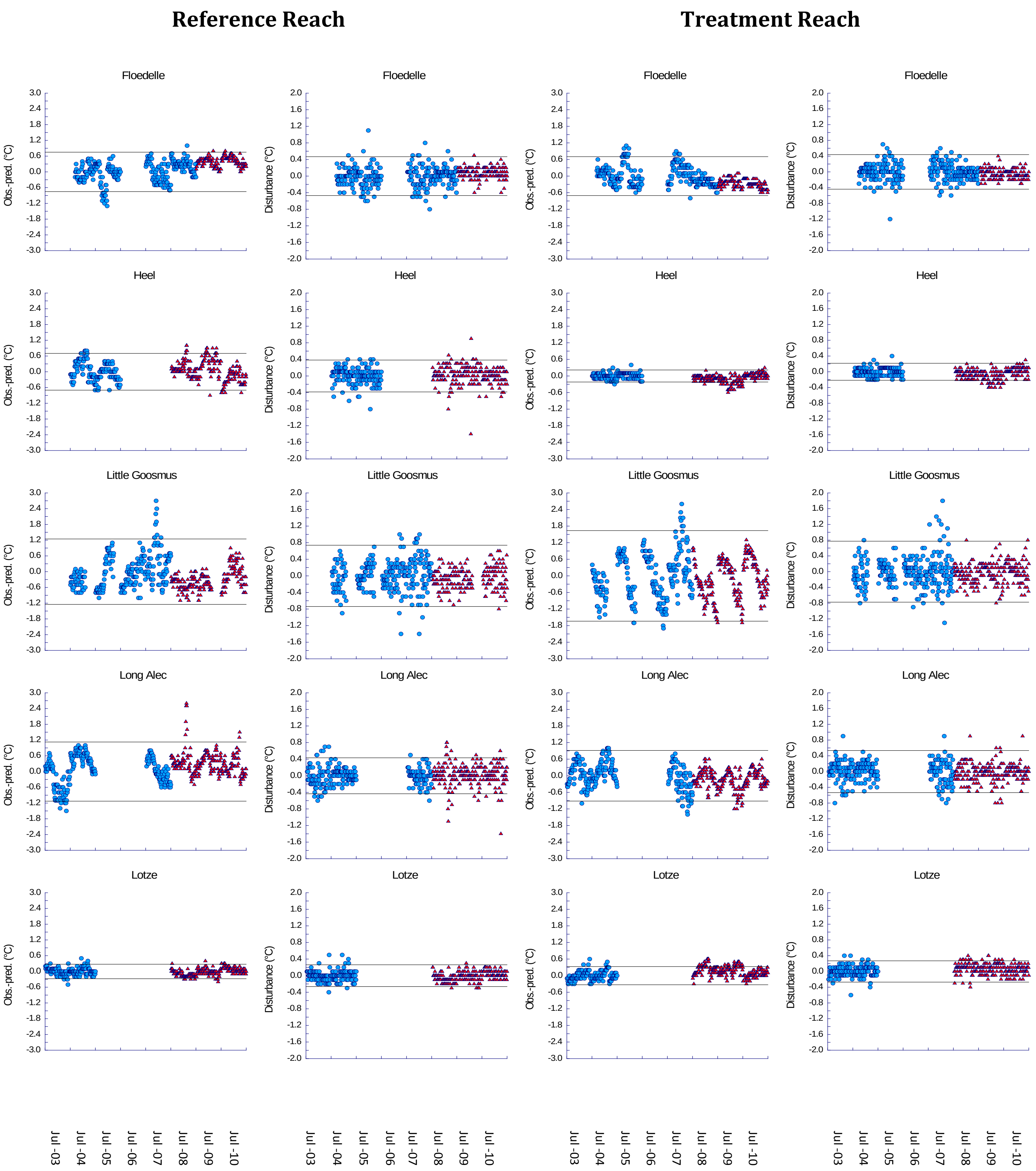

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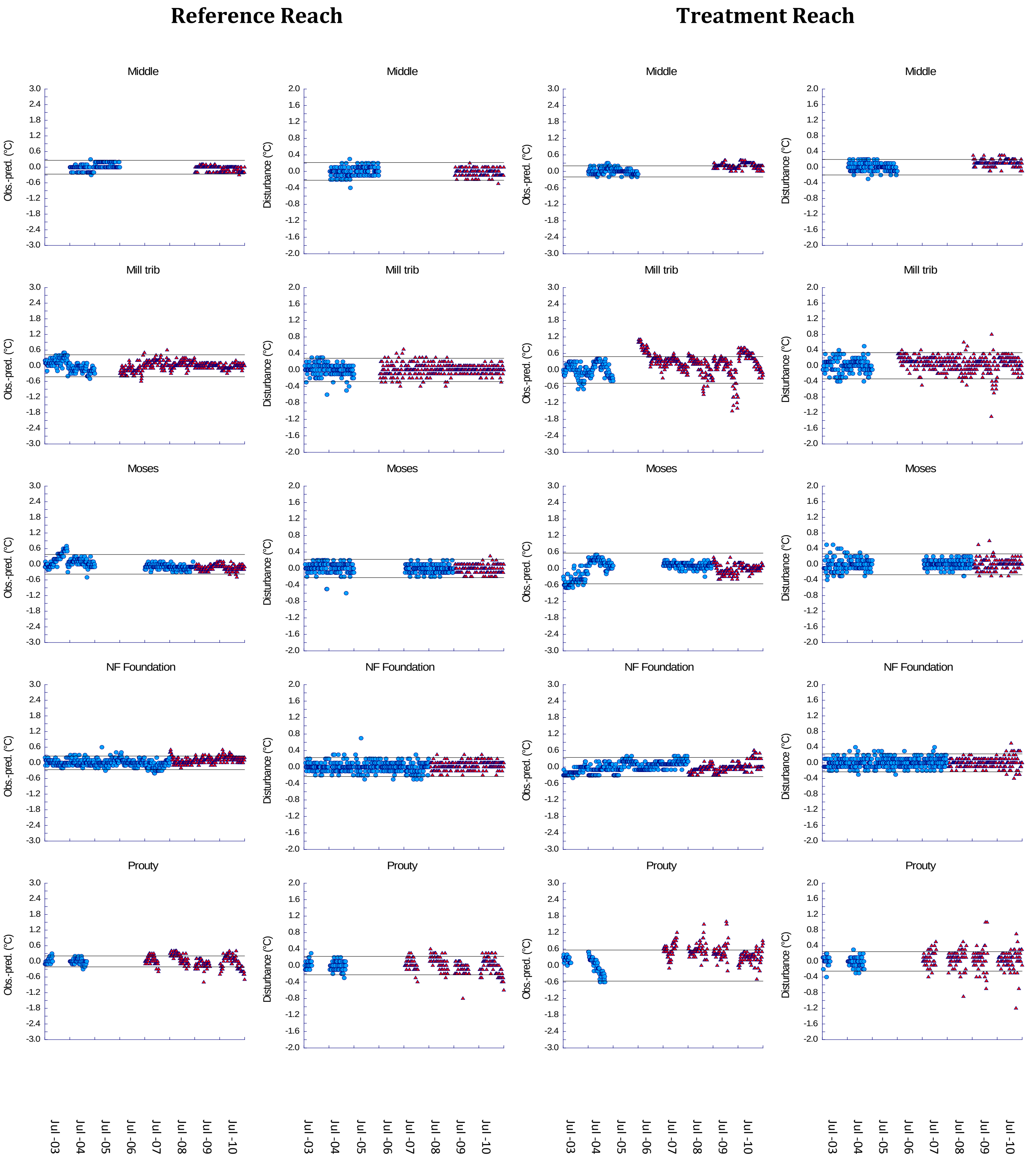

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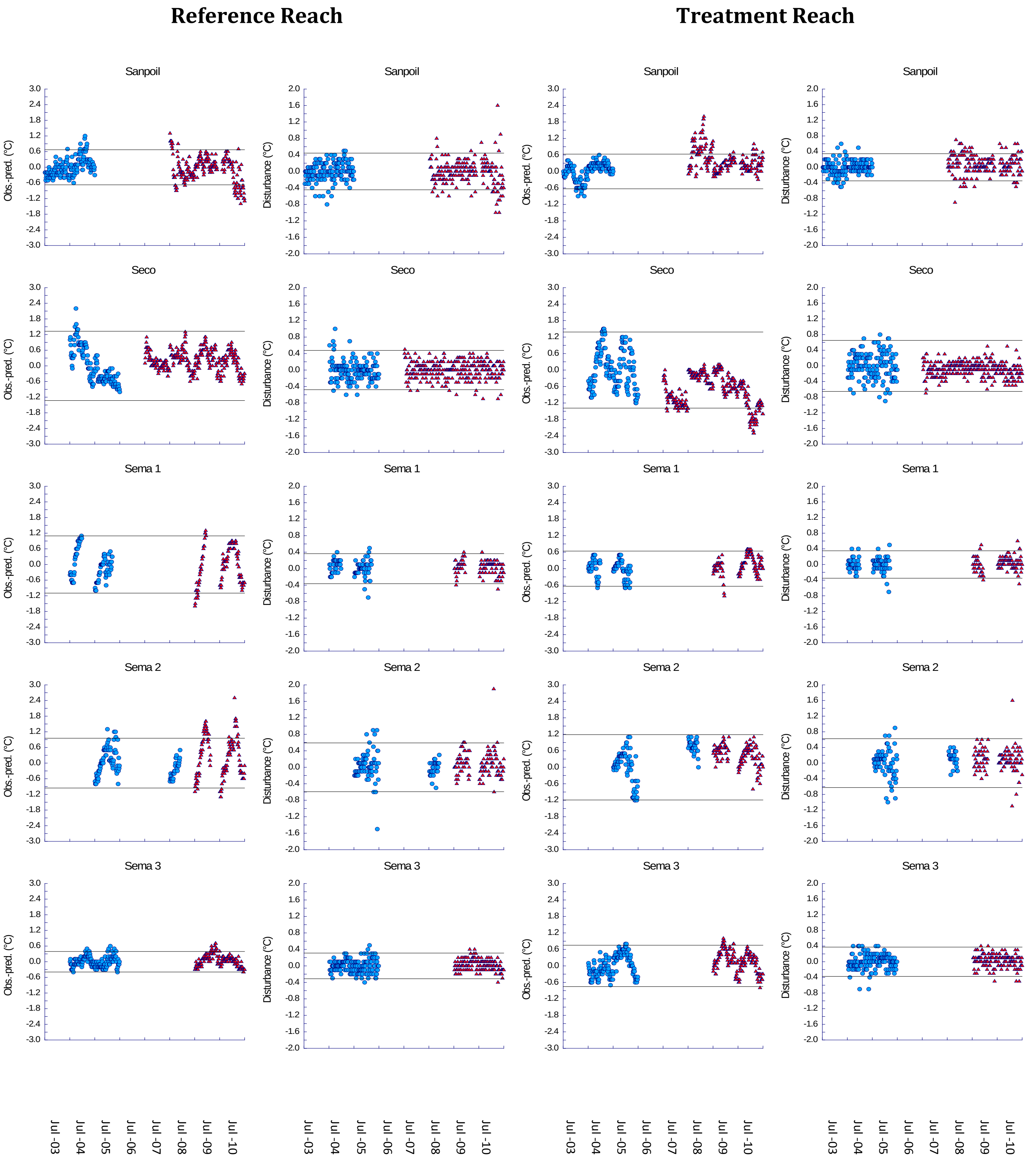

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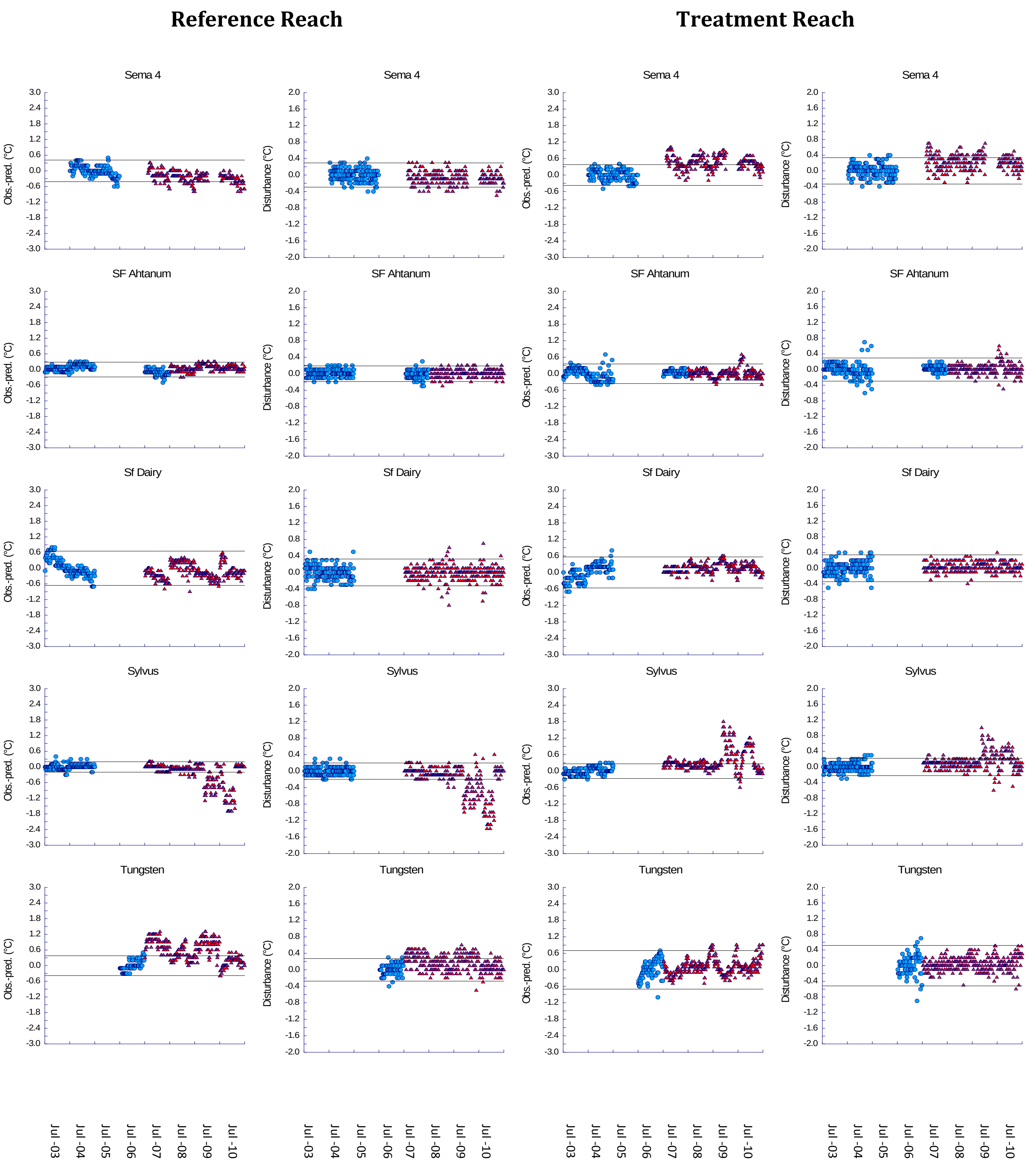

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