Sound Watershed Consulting

Creating Functional Water Environments

Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

Chapter 3

HEAT EXCHANGE FUNCTIONS

for

The California State Board of Forestry and Fire Protection

September 2008

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3) HEAT EXCHANGE FUNCTIONS

Scientific Literature Review of Forest Management Effects on Riparian Functions for Anadromous Salmonids

For

The California State Board of Forestry and Fire Protection

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EXECUTIVE SUMMARY

This document represents a comprehensive review of 34 scientific literature articles provided by the Board of Forestry to address a series of Key Questions relevant to riparian management for the protection of threatened and impaired watersheds in State and private forestlands in California. The review:

- summarizes recognized exchange function roles and processes as presented to us by the California Board of Forestry Technical Advisory Committee (CBOF-TAC 2007)
- responds to key questions posed by the Board
- describes key information gaps not covered within the reviewed literature
- discusses inferences for forest management to address heat exchange functions

The literature on riparian heat exchange tells us that shade provided by riparian vegetation is a key factor controlling heat input to streams, even though instream water temperatures are governed by a host of other complex physical factors that control heat transfer between air, water, and the streambed.

There is no single, fixed-width buffer or canopy closure prescription that will provide the desired heat regulation objectives for salmon in all cases. The relative importance of riparian vegetation to influence stream temperature varies by location (geographic province) and by site specific conditions (stream width, depth, flow, groundwater inflow, streambed substrate composition, valley orientation, topographic shading and watershed position). Stream temperature sensitivity to shade is dependent on location and physical conditions.

The science on heat exchange indicates that water temperature protection could be provided by varying the riparian shade requirements in relation to stream temperature sensitivity. This report provides some examples of approaches than can be used, and key variables to consider when designing strategies to manage shade in different settings.

In fish-bearing waters that are directly downstream of headwater streams, the literature indicates that temperature could be positively influenced by providing shaded conditions on headwater stream segments that extend from 500 to 650 ft (150 to 200 m) upstream from the confluence with fish-bearing streams. This distance is based on research findings outside of California, therefore this distance may need to be validated with studies in various California ecoregions.

Our interpretation of the reviewed literature suggests that managing to protect salmonid habitat conditions would require that targets be set for desired stream temperature, and that shade requirements vary in relation to the stream's specific sensitivity to shade as a thermal influence on temperature. The literature indicates that stream temperature is a major factor influencing population performance.

Shade is not static, but varies in response to stand growth dynamics and natural ecosystem processes and disturbances. Suitable thermal conditions could be maintained and hazards to salmonids avoided by altering the timing and spatial position of riparian management activities. Thermal conditions also respond to surrounding conditions as water flows downstream, so downstream stand conditions also influence stream temperature.

Riparian stand effectiveness for shading is a function of the forest canopy density, height, and species composition, which is related to stand type and age. Research shows that effective shading can be provided by buffer widths ranging from 30 to 100 ft (10 m to 30 m) depending on stand type, age, and location.

Timber harvest in or adjacent to riparian areas can influence microclimate, but microclimate changes have not been demonstrated to translate to changes in water temperature. Timber harvest in or near riparian areas can cause an increase in light penetration, decrease interception of precipitation, and increase wind speed, which can result in higher mid-day air temperatures and lower mid-day humidity near the forest floor and over the stream. These microclimate changes are hypothesized to influence water temperature, however validation is lacking.

Finally, heat exchange is only one riparian function that affects salmonids. Shade conditions can inversely influence biotic and nutrient exchange functions. Similarly, the canopy that provides shade also influences water exchange functions, and can be influenced by wood exchange functions. These dynamics between exchange functions are discussed in greater detail in Chapter 7 (Synthesis).

RECOGNIZED EXCHANGE FUNCTION ROLES & PROCESSES

Riparian vegetation in forested environments influences stream water temperature and riparian microclimate (air temperature and relative humidity). The relative importance of riparian forests in regulating water temperature and microclimate is governed by multiple interacting factors (biotic and abiotic) that have been described by CBOF-TAC (2007), and which form the foundation of our review. These principles include:

- Direct solar radiation to the water's surface is the dominant source of heat energy to surface water.

- Shade from vegetation that blocks incoming solar radiation (direct and diffuse) along the sun's path at solar elevation angles greater than 30 degrees is most effective for reducing radiant energy available for stream heating (Moore et al. 2005).

- Vegetation that blocks incoming solar radiation at low solar angles (i.e., at dawn and dusk, and during fall-winter seasons) is less important for reducing stream heating from direct radiation (Moore et al. 2005). The lower the angle, the more solar radiation is reflected.

- Riparian forest cover and understory vegetation influences on solar radiation, interception loss of precipitation, and wind velocity are the primary factors governing microclimate. In addition the stream effect on air temperature and humidity has a strong effect on the adjacent microclimate. Therefore all factors that influence stream temperature (see below) indirectly influence riparian microclimate.

- Stream surface exposure to incident solar radiation is also influenced by channel morphology (exposure decreases with increasing channel incision), channel width (exposure decreases with decreasing width), channel orientation (duration of high angle exposure decreases with east-west orientation, hence streams having a north-south orientation tended to be warmer than those with an east-west orientation.), and topography (exposure decreases with increasing ridge shadow) (Moore et al. 2005).

- Water temperature response to heat input is moderated by inflow from tributaries and groundwater, and the magnitude of response is dependent on the temperature difference between inflow and stream temperatures and on the relative contribution to discharge (Moore et al. 2005).

- Water temperature response to heat input is dampened by hyporheic exchange rate (i.e., streamflow below the streambed is cooled by heat exchange with subsurface water and substrate), which is a function of bed composition (alluvial gravel/cobble bed material enables increased hydraulic retention and increased sub-surface storage than occurs with bedrock; Johnson 2004) and channel morphology.

- Water temperature response to heat input is a function of depth, velocity, and discharge with sensitivity decreasing with increasing depth, velocity, and discharge (Moore et al. 2005).

- In general, riparian influence on water temperature declines with increasing stream size and increasing distance from the watershed divide. Streams that are too wide for canopy to influence temperature are wider than 36 m and located more than 70 km from the watershed divide (Lewis et al. 2000).

- Air temperature varies by location and elevation. Near the coast, air temp is more a function of distance from the coast rather than elevation. In the interior, air temperature follows the expected adiabatic trend; decreasing with increasing elevation (Lewis et al. 2000).

These points provide a context for considering the following Key Questions.

RESPONSES TO KEY QUESTIONS

The following Key Questions were provided to the Sound Watershed Team by the Board of Forestry staff and a Technical Advisory Committee. The responses to these questions are based on our interpretation of the literature provided by the Board for us to review. To support some points, we added citations to other supporting literature with which we are familiar. We appreciate that other literature may be available that might also address these issues, and that in some cases, such literature may conflict with the general trends we report here.

In the case of the heat exchange function, we found 14 of the 32 papers provided by the Board to be directly applicable to the questions in some manner. The remaining papers were indirectly helpful in addressing these questions, but in most cases did not provide information that directly informed the Key Questions. In general, the questions represent broad topic areas that would require an extensive and detailed treatment to fully address. Our responses focused on building upon the recognized exchange function roles & processes by focusing on new information or important considerations.

1) How do forest management activities or disturbances within the riparian area affect the temperature of forest streams?

Our review of the literature indicates that shade from riparian vegetation is a key factor influencing stream temperatures and that riparian shade prescriptions are an effective tool for protecting salmonid habitat. However, studies show that shade is only one of several interacting factors that govern water temperature. Therefore, simple buffer width and shade curves are not a reliable predictor of water temperature. Stream temperature sensitivity to shade and buffer prescriptions may best be obtained from empirical relationships or physical heat process equations that can incorporate relevant factors for various regional and local conditions.

In general, the influence of riparian vegetation on water temperature declines with increasing stream size and increasing distance from the watershed divide. The downstream temperature response from timber harvest in headwater streams is variable and is highly dependent on the volume of stream flow, substrate type, groundwater inflow, and hyporheic exchange.

It is not clear from the microclimate studies in this review that changes in microclimate can directly translate to changes in water temperature.

A) WHAT CONDITIONS OF CANOPY STRUCTURE, DENSITY, AND WIDTH, INFLUENCE WATER TEMPERATURE? HOW MIGHT THIS VARY WITH CALIFORNIA FOREST TYPES AND STREAM SIZE?

Riparian Condition Influences on Water Temperature

The primary function of riparian vegetation in controlling water temperature is to block incoming solar radiation (direct and diffuse). Direct solar radiation on the water's surface is the dominant source of heat energy that may be absorbed by the water column and streambed. Absorption of solar energy is greatest when the solar angle is greater than 30° (i.e., 90 to 95 % of energy is absorbed as heat) and absorption declines (i.e., reflection of radiation increases) as the solar angle declines. Therefore, riparian vegetation that blocks direct solar radiation along the sun's pathway across the sky is the most effective for reducing radiant energy available for stream heating (Moore et al. 2005).

The literature (Beschta et al., 1987, Sridhar et al. 2004) reports that the attenuation of direct beam radiation by riparian vegetation is a function of:

- Canopy height,
- density of vegetation, and
- Species composition.

Riparian buffer width is important for a given stand type and age, but is not a good predictor of stream shading among different stands because of differences in these key variables. For example, Beschta et al. (1987) showed that shade levels similar to old-growth forests could be obtained within a distance of 60 to 100 ft depending on stand types in Oregon (Figure 1). Similarly, Sridhar et al. (2004) using an energy balance model with empirical data, demonstrated that stream temperature is most sensitive to a stands leaf area index (i.e., an indicator of light attenuation by canopy density) followed by average canopy height (an indicator of direct beam light attenuation), and lastly buffer width. They found the most effective shading for temperature control in eastern and western Washington Cascade conifer stands was predicted for mature (high leaf-area-index) canopies close to the stream (i.e., within 10 m of the stream bank) and overall buffers of about 30 m. Buffer widths beyond 30 m had only minimal effect on stream temperature.

Direct beam solar radiation may also be effectively blocked by a layer of slash that may accumulate in headwater channels following clearcutting in adjacent riparian areas (Jackson et al. 2001). Understory shrub vegetation may provide shade and influence streamside microclimate conditions (Gravelle & Link 2007, Rykken et al 2007). Moore et al (2005) reports that validation of shrub effectiveness for shade is lacking, however Liquori and Jackson (2001) offer some evidence for the idea that shrub cover may yield lower temperatures for similar shade conditions.

Figure 1 Relationship between angular canopy density (a measure of shade) and buffer strip width for small streams in western Oregon (reproduced from Beschta et al., 1987). The Brazier and Brown study was conducted mostly in the coastal forests and a few sites were located in the southern Cascades (Umpqua National Forest). The Steinblum study was conducted in western Cascade forests at elevations of 2000 to 4000 feet.

The TAC literature does not provide much information on specific riparian vegetation conditions (i.e., canopy structure, density, width) that influence water temperature, aside from the information described above. Only one field study (James 2003), one synthesis (Lewis et al. 2000), and two modeling studies (Sridhar et al. 2004, Allen 2008) provided temperature responses in relation to a canopy cover or shade index. Most of the studies examine temperature responses in relation to a range of buffer prescriptions that are categorized by width and harvest treatment (e.g., no-cut, thinned, partial cut; Table 1).

Table 1. Summary of TAC literature concerning riparian vegetation influences on water temperature.

Reference	Location	Treatment	Relevant Finding For Buffers
Allen 2008	Fish streams, northern CA	Modeled basin wide temperature for: no riparian shade, or full old-growth shade	Model predictions and validation demonstrate the important interactions between relief, vegetation, and hydrology. For example, testing showed that local relief and aspect controls can offer sufficient shading to create intrinsically cool canyons and reaches on the mainstem that cool the flow. Also variation in groundwater inflow rates can reduce or amplify heating effects associated with either vegetation removal or growth to late seral stage.
Anderson et al 2007	Headwater streams, western OR coast and cascade range	Variable width buffers ranging from 9 m to 59 m with upslope thinned stands or patch openings	Buffers that extend to topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate. Aspect should be accounted for when using canopy cover as an index of potential shading of the stream, particularly under conditions where direct and indirect light are not strongly coupled.
Fleuret 2006	Headwater streams, OR coast range	clearcut and partial cut, buffers 6-60 m wide	Mean temperature gradient in treatment reaches was 0.4°C warmer than observed prior to harvesting. Percentage shade is strong predictor of summer temperature.
Gomi et al 2006	Headwater streams, BC coastal	experimental treatments: clearcut to edge, 10 m, and 30 m fixed buffers	Temperature response declined with increasing buffer width. At streams with 30 m buffer the maximum effects for maximum daily temperature was less than 2° C. Thermal recovery within two to four years depending on channel width.
Gravelle & Link 2007	Headwater streams, Northern Idaho	clearcut with 9-m equipment exclusion zone	There was a significant increase in peak temperatures that was negligible a few years after harvest. Understory vegetation response increased overall cover in clearcut reaches toward preharvest levels over the 4 years since harvest.

Reference	Location	Treatment	Relevant Finding For Buffers
Jackson et al 2001	Headwater streams, WA coast	treatments: unharvested 2nd growth, 15-21 m wide buffers, and clearcut to bank	Water temperature at 3 of the 7 clearcut sites were not significantly different, because a layer of slash effectively shaded the streams. At the buffered streams, two became warmer (1.6 - 2.4 °C) and one cooler (-0.3° C).
James 2003	Fish stream, northeastern CA, Sierra's	stand thinned to 50% canopy cover in 175-ft and 100-ft wide buffers	Treatment resulted in minor (+- 1.5°C) changes in the water temperature pattern in study reach. Treatments did not appreciably reduce angular or vertical cover even though 35% of timber volume was removed.
Macdonald et al 2003	Headwater streams, Interior BC	tested three variable retention treatments in 20- to 30-m wide buffers	Five years after the completion of harvesting, temperatures remained 4° to 6° C warmer than in the control streams regardless of treatment. Initially, the high-retention treatment mitigated the effects of the harvesting, but 3 successive years of windthrow was antecedent to reduced canopy density and increased temperature impacts.
Moore et al. 2005	Wide range of streams in Pacific Northwest	Literature review of wide range of riparian treatments	Based on the available studies, a one-tree-height buffer on each side of a stream should be reasonably effective in reducing harvesting impacts on both riparian microclimate and stream temperature. Narrower buffers would provide at least partial protection, but their effectiveness may be compromised by wind throw.
Sridhar et al 2004	Mid-order streams, western and eastern WA Cascades	Modeled effectiveness of buffers with different width and vegetation characteristics	Of the vegetation factors influencing water temperature; leaf area index had the greatest effect (especially for trees within 10 m of the stream bank), average tree height was second, and buffer width third. Buffer widths beyond 30 m had only minimal effect on stream temperature.

None of the field studies identify a riparian stand structure, density, or canopy cover that is sufficient to maintain water temperature; although James (2003) concluded that maintaining 50% canopy cover of the ground after thinning (minimum 80% angular canopy cover) had a minimal impact on water temperature in a Sierra stream. Several studies identified a buffer width among the various prescriptions tested that resulted in minimal impacts on temperature (e.g., 30 m, one-tree-height; Table 1). However, these recommendations are restricted to the stands types and climatic conditions examined and may not be applicable beyond the study locations.

Stand age has not been addressed explicitly, although Moore et al. (2005) cited studies in the Pacific Northwest showing shading recovery after timber harvest ranged from 10 to 20 years depending on stand type. This would suggest that submature stands can provide effective shade.

Interestingly, no recent study has developed a buffer width and shade relationship curve like the ones presented in Beschta et al. (1987; Figure 1), which were based on studies from the 1970's and early 80's. Furthermore, relationships between canopy cover or shade and common forestry metrics (i.e., stand density and basal area) are not well defined for specific sites or stand conditions (Anderson et al. 2007).

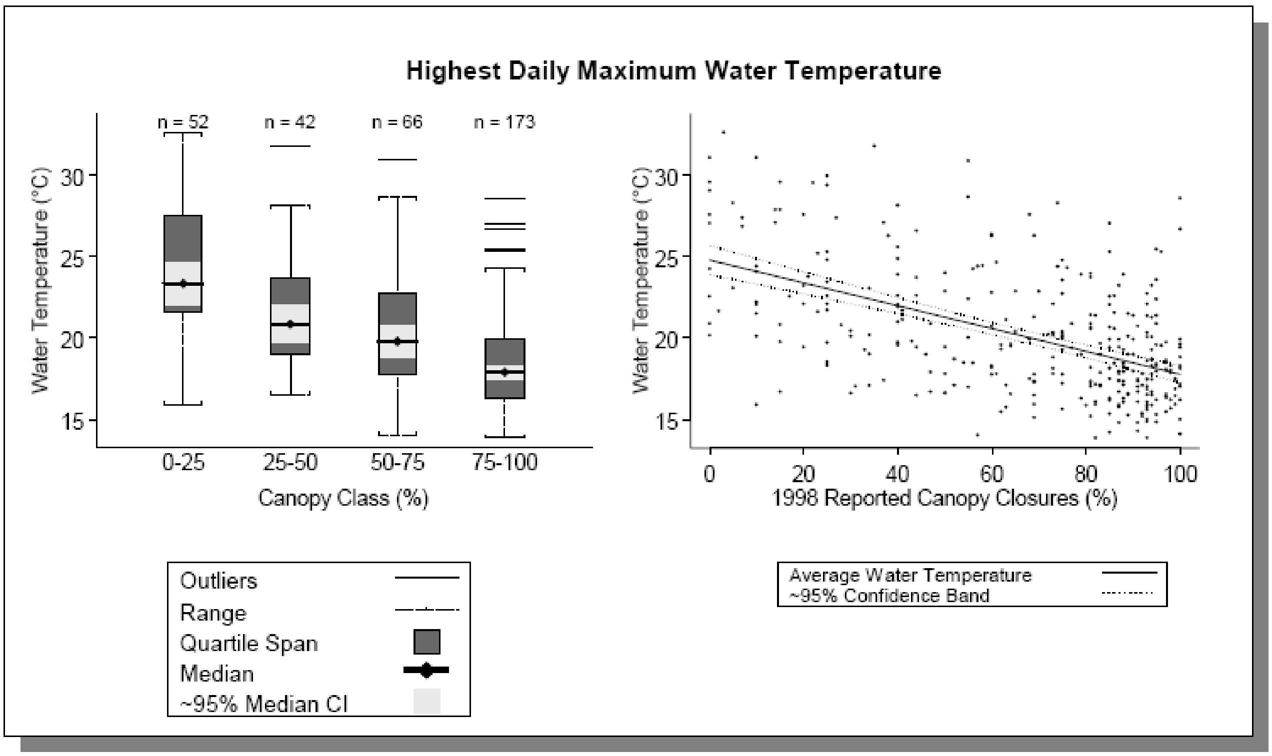

Figure 2 Relationship between stream temperature and canopy closure for streams in California. Regression R2 = 0.286, *p* ≈ 0. (Figure 9.9 from Lewis et al. 2000).

Research shows that water temperature is poorly correlated with shade because shade is only one of the several interacting factors that govern water temperature in streams. For example, Lewis et al. (2000) concluded that the weak, but significant, relationship between canopy closure and water temperature in California streams is due to the myriad of other factors influencing temperature (Figure 2). This finding, however, does not mean that shade is not important. Rather it shows that simple shade or canopy closure relationships are not adequate to predict temperature with high resolution and that other variables (e.g., flow, width, depth, substrate, ground water) need to be taken into account. Lewis et al. (2000) found that watershed position (i.e., surrogate for stream size) and air temperature (i.e., surrogate for location in or out of coastal zone or elevation) along with canopy closure were important factors that account for water temperature differences at the regional scale.

Accurate stream temperature predictions may best be obtained from empirical relationships or physical heat process equations that can incorporate relevant factors for various regional and local conditions (e.g., Cafferata 1990, Sullivan et al. 1990, Lewis et al. 2000, Sridhar et al. 2004, Moore et al. 2005, Allen 2008). Such predictive tools are available and compatible with existing GIS databases and modern timber harvest planning programs. For example, Allen (2008) showed how existing watershed data (DEM, hydrology, lithology) and stand characteristics (DBH, which is a surrogate for tree height) for tributaries of the Eel river can be used to evaluate temperature responses throughout the basin with different scenarios for riparian stands.

California Forest Types and Stream Size Influences on Water Temperature

The stream shading potential of riparian vegetation varies by forest type. For example, the leaf-area-index (i.e., an indicator of light attenuation by canopy density) for a mature stand of Douglas fir is about 15 and for lodge pole pine is about 5 (Sridhar et al. 2004). Beschta et al. (1987) showed that dense coastal stands of Oregon can provide adequate shade in a shorter distance from the stream than can mid-elevation conifer stands in the western Cascades (Figure 1). Similar comparisons among regions are not known for California. However, the coastal stands of redwood and Douglas fir are denser and have a greater potential to shade streams than do low-density lodge pole pine, ponderosa pine, and Jeffrey pine stands of the interior regions.

The effects of forest type on stream temperature are difficult to separate from other factors that influence the distribution of plant communities in California. Research by Lewis et al. (2000) shows that distance from coast and elevation have differential influences on water temperature depending on ecoprovince. In the Coastal Steppe Province (CSP) water temperature generally increases with increasing distance from the coast and in the Sierran Steppe-Mixed Forest-Coniferous Province (SSP) temperature declines with distance from the coast. Lewis et al. (2000) attributed these difference to the presence of fog and clouds in the coastal zone, which filters out solar radiation and moderates air temperatures. They point-out that water temperature is influenced by canopy closure in both regions (Figure 3). However, the relative importance of riparian vegetation in blocking solar radiation may vary between regions. Lewis et al. (2000) also showed that elevation influences water temperature, especially in the SSP where cooler air at higher elevations resulted in lower daily minimum temperatures than was observed in CSP streams.

In general, riparian vegetation influence on water temperature declines with increasing stream size and increasing distance from the watershed divide (Moore et al. 2005). Water temperature generally tends to increase in the downstream direction with stream size as a result of systematic changes in the important environmental variables that control water temperature. Also, as streams get larger, there is a corresponding decline in the effectiveness of riparian vegetation to provide shade. Cooler groundwater inflow also diminishes in proportion to the volume of flow in larger streams. In California, Lewis et al. (2000) found stream temperature increases with increasing channel width and with increasing distance from the watershed divide (Figure 4). They found that this relationship holds for all locations and that water temperatures in the zone of coastal influence are generally 1° to 2°C cooler than for streams sites outside of the zone of coastal influence, at similar divide distances (Figure 4). They estimated that as distance from the watershed divide approaches approximately 70 km, streams become too wide for riparian vegetation to provide adequate shading.

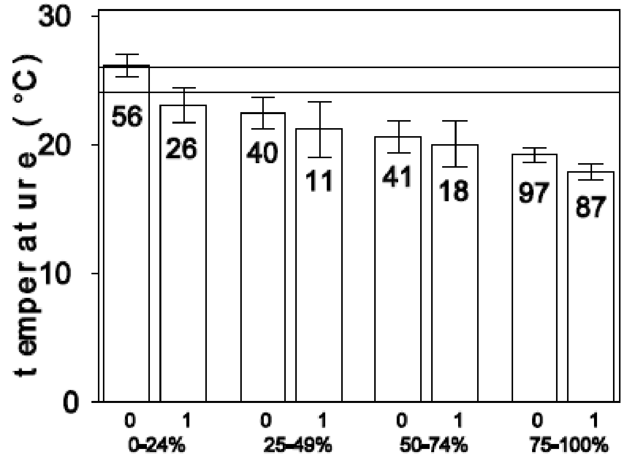

Figure 9.10. Highest 1998 daily maximum stream temperature for sites in four different canopy classes, grouped by whether the site was outside (0) or inside (1) the zone of coastal influence. Horizontal reference lines are drawn at 24°C and 26°C. Number of sites in each group are shown below error bars.

Figure 3 Relationship between maximum stream temperature and canopy closure outside (0) and inside (1) the zone of coastal influence. The influence of canopy cover on temperature is evident for both zones. Horizontal lines at 24° and 26°C correspond to thermal tolerance and lethal temperature thresholds, respectively for salmonids. Only streams in the 0-24% group have temperature maximums that approach lethal levels. (Figure 9.10 from Lewis et al. 2000).

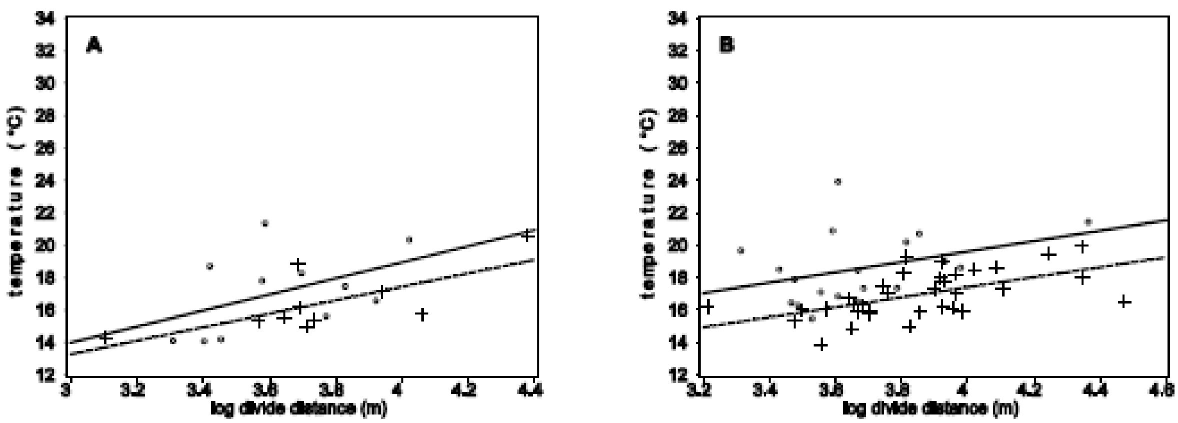

Figure 9.11. Variation in the highest 1999 daily maximum stream temperature with $\log_{10}$ distance from the watershed divide for sites with canopy values greater than or equal to 75%. Sites in the Mad River - Redwood Creek (A) and Big-Navarro-Garcia River (B) hydrologic units are presented. Linear regression lines were fit to sites outside (open circles) and inside (crosses) the zone of coastal influence. Solid lines and dashed lines represent linear regressions for sites outside and inside the ZCI, respectively.

Figure 4 Variation of maximum stream temperature with distance from the watershed divide for sites with canopy cover > 75% inside and outside of the zone of coastal influence. Note, the regression lines show what water temperatures are achievable under fully canopied conditions. (Figure 9.11 from Lewis et al. 2000).

B) ARE RIPARIAN AREA MICROCLIMATES AFFECTED BY FOREST MANAGEMENT WITHIN AND/OR ADJACENT TO FISH-BEARING STREAMS SUFFICIENT TO INFLUENCE WATER TEMPERATURE?

Timber harvest in or adjacent to riparian areas can influence microclimate, but microclimate changes have not been demonstrated to translate to changes in water temperature. Timber harvest in or near riparian areas can cause an increase in light penetration, decrease interception of precipitation, and increase wind speed (Moore et al. 2005), which can result in higher mid-day air temperatures and lower mid-day humidity near the forest floor and over the stream. These microclimate changes are hypothesized to influence water temperature, however validation is lacking.

The TAC literature list included seven documents that addressed the influence of forest management on riparian microclimate. Six of these documents described the riparian microclimate response to specific riparian and upslope treatments and one document (Moore et al. 2005) provided a synthesis of literature concerning water temperature and riparian microclimate responses to forest management in headwater streams (Table 2). The Moore et al. (2005) synthesis did not address the microclimate/water temperature question, but one paper (Brosofske et al. 1997) which was referenced in the synthesis does describe this relationship, so we included it here.

Only Brosofske et al. (1997) and one of the TAC studies (James 2003) examined both water temperature and microclimate responses to a specific riparian treatment. Brosofske et al. found that harvesting influenced microclimate gradients, but water temperature was not responsive to buffer width, except in one case where no riparian trees were retained. Also, water temperature was not correlated to microclimate variables (wind speed, relative humidity, solar radiation). However, a significant correlation between water temperature and soil surface temperature led Brosofske et al. to speculate that upland clearcutting may influence temperature in streams. James (2003) found that riparian thinning (i.e., maintained 50% of canopy closure in the riparian stand) resulted in small changes in average and maximum air temperature within 40 ft of stream (up to 0.5°C) and small changes in water temperature (+/- 1.5°C). Whether the increased water temperature in this study was a result of microclimate changes (i.e., increased air temperature) or of increased heating from direct beam radiation on the stream is unknown.

The other studies, which did not measure water temperature, showed that riparian microclimate may or may not be affected by forest management activities depending on buffer zone width and site specific characteristics (e.g., stream size, aspect, elevation, slope gradient, and upslope stand structure). Several of the studies show that microclimate is unaffected where the buffers extend to a slope break or are at least 30 m (one tree height) wide. In some cases where buffers were narrower or were thinned, air temperatures increased (e.g., 2-4°C) and relative humidity decreased along a gradient that extended away from the stream.

Even though air temperatures over streams may increase in some cases after timber harvest, the influence on water temperature is limited and is strongly affected by site specific conditions (i.e., relative humidity and wind). Moore et al. (2005) found that sensible and latent heat exchanges to be an order of magnitude lower than net radiation on sunny days in recent clear-cuts, thus the potential influence of microclimate on temperature is relatively small compared to direct radiation. They also point-out that heat fluxes, especially over small streams may be limited by the lack of ventilation from bank sheltering, particularly for narrow, incised channels. In California, Lewis et al. (2000) found a moderate correlation between daily mean water temperature and daily mean microair temperatures ($R^2 = 0.61$). However, they point-out that sensible and latent heat exchanges are too small to fully account for this correlation, rather the close correlation is caused largely by solar radiation which affects both water and air temperature.

We found no convincing evidence in the reviewed papers or the primer that forest management effects on microclimate are sufficient to substantially influence water temperature. The results from two studies in this review that actually measured microair and water temperature do not demonstrate a causal relationship. The other microclimate studies either show no effect or very small effects of riparian management on microair temperature. The heat exchange physics indicates the potential effects of microair temperature on water temperature are limited and highly dependent on favorable micro-conditions. Finally, water temperature is not only governed by incoming solar radiation and air temperature, but by factors that are unrelated to microclimate (e.g., incoming water temperature from upstream and tributaries, ground water input, and hyporheic exchange) that have a strong influence on stream temperature. Collectively, the current knowledge does not support the hypothesis that microclimate changes caused by logging influences water temperature

Our finding are consistent with an earlier review by regional experts (Ice et al. 2002) who concluded that research had not been able to measure a microclimate effect on water temperature where there was a buffer 15 m wide or greater. Where buffers are narrower or absent, it becomes impossible to separate the microclimate effect from the more significant solar insolation effect.

Table 2 Summary of TAC literature concerning riparian vegetation influences on microclimate and water temperature.

Reference	Location	Treatment	Microclimate response	Water temperature response
Anderson et al. 2007	headwater streams, OR coast & cascades	9-59 m buffers, upslope thinned	Buffers that extend to topographic slope break mitigate the impacts of thinning	NA
Brosofske et al. 1997	small streams, cascades wa	7-60 m buffers	affected near-stream microclimate gradients, increased temp and decreased rh	Water temp. not responsive to buffer width and not correlated to microclimate (wind speed, relative humidity, solar radiation). Water and soil temp. correlated.
Danehy et al 2005	low-order streams, eastern WA & OR	30-m buffer, upslope partial harvest	Vegetation density and structure did not exert as strong an influence on relative humidity (RH) as steep local topography	NA
Dong & Chen 1998	low-order streams, western WA cascade	16–72 m buffers, upslope clearcut	Air temperature at the stream was raised by 2–4°C after harvesting	NA
Erman & Erman 2000	headwater streams, CA Sierra range	unmanaged buffer, 2 of 8 partial harvest	Openings in canopy cover were directly translated to increases in air temperature and decreases in RH.	NA

Reference	Location	Treatment	Microclimate response	Water temperature response
James 2003	fish streams, northeastern CA	30-55 m buffer, upslope partial harvest	No significant change in daily RH within 40 ft of the stream after treatments	minor (+- 1.5°C) changes in water temp.
Moore et al. 2005	headwater streams in PNW	Literature review	Edge effects on solar radiation and wind speed decline within about one tree height	NA
Rykken et al. 2007	headwater streams, western OR cascades	30-m buffer, upslope clearcut	no significant treatment differences between the 30-m wide riparian buffer and the intact forest	NA

C) HOW AND TO WHAT EXTENT DO TEMPERATURES IN LOW ORDER STREAMS INFLUENCE TEMPERATURES IN DOWNSTREAM FISH-BEARING STREAMS?

Studies of headwater stream temperature influences on downstream fish-bearing waters are limited to the Caldwell et al. (1991) investigation of small streams in western Washington (cited by Lewis et al. 2000) and three studies that are identified on the TAC list (Table 2). Caldwell et al. (1991) found that headwater streams had minimal influence on the downstream water temperature because of the large size difference between headwater tributaries and receiving (typically fish-bearing) waters. Using a stream flow mixing equation and the relationship between distance from divide and discharge, they determined that a headwater stream could not affect the temperature in a typical fish-bearing stream by more than 0.49° C if the confluence of the receiving stream is more than 7 km (4.5 miles) distance from the watershed divide. Caldwell et al. (1991) reported that small streams are very responsive to localized conditions and that the longitudinal effect of any one headwater stream on downstream temperatures is limited to 150 meters or less. This study also evaluated the potential cumulative effects of multiple headwater streams feeding warm water into a fish stream. Based on a map analysis of tributary junctions, they found that spacing between tributaries often exceeded 150 m and concluded that no cumulative effect was likely to occur.

More recent investigations show that the downstream temperature response to timber harvest in headwaters is variable and is highly dependent on stream flow and channel characteristics

(Table 3). Downstream cooling in some stream segments was observed in all three of the studies in our review. This cooling was attributed to groundwater inflow, hyporheic exchange, or both. Research shows that ground water inflow will typically reduce stream heating by increasing the total discharge as well as cooling by conduction (Moore et al. 2005). In stream segments with alluvial substrate, hyporheic exchange promotes conductive cooling as a result of a longer flow path and increased travel time (Johnson 2004). In contrast, streams with bedrock substrate limit hyporheic exchange and may cause warming by reflecting solar energy off the streambed into the surface water (Johnson 2004). Dent et al. (2008) showed that these factors and others (e.g., canopy cover, channel gradient, instream wood jam volume) influence temperature patterns at small reach scales (0.5-2 km in length) and account for the reach-to-reach variability that is common in headwater streams.

None of the TAC listed studies were performed in California, but the explanation for factors governing downstream temperature response are consistent, and suggests that the primary drivers would apply anywhere. Story et al. (2003) recommended that:

> "*efforts to manage the thermal effects of forestry on aquatic habitat should consider the hydrologic characteristics of specific streams and their catchments, since these factors may account for much of the variability in thermal response to forest disturbance and, in particular, may control the potential for downstream cooling in shaded reaches*."

In a related study of large streams in the north coast region of California, Lewis et al. (2000) demonstrated that the temperature of a mainstem stream (5^{th} order or larger) that is receiving flow from a large tributary stream (e.g., 4^{th} to 5^{th} order) is a function of the ratio of flows and that the downstream extent of temperature influence is dependent on the ratio, physical characteristics of receiving water environment, and climatic conditions. They observed that cool tributary inflow (ranged 2.2° to 7.7° C below receiving stream) decreased the receiving water temperature for distances ranging from 3,000 to 35,000 ft (900 m to 10,700 m) downstream of the tributary junction.

These studies lead us to conclude that the downstream temperature response from timber harvest in headwater streams is variable and is highly dependent on a host of factors (i.e., volume of stream flow, canopy cover, substrate type, in-stream wood volume, groundwater inflow, and hyporheic exchange) in both the headwaters and downstream reaches. For example, the potential for downstream temperature impacts would be greater where canopy cover from riparian vegetation and topographic shading is low, tributary or groundwater inflow is low, woody debris jams are sparse, and if substrate is dominated by bedrock. On the other hand, potential temperature impacts would be reduced or eliminated if these characteristics were the reverse.

Table 3) Summary of TAC literature that address downstream water temperature response to timber harvest in headwater streams.

Reference	Location	Treatment	Response downstream	Findings explanation
Gravelle & Link 2007	northern ID	1st and 2nd-order watersheds 50% clearcut or 50% partial cut	No significant increase in temperature maxima, slight cooling in post-treatment peak temperatures	Suspect that temperature increases in clearcut reaches were ameliorated downstream as a result of groundwater inflows and hyporheic exchange
Johnson 2004	western OR	Experimental shading of a 150-m reach, second-order stream	Response depended on substrate type: bedrock reach had higher maximum temperatures, lower minimum temperatures, and wide diurnal fluctuations; alluvial reach had lower maxima, higher minima, and dampened temperatures	Cooling in alluvial reach is attributed to hyporheic exchange and a longer flow path and travel time
Story et al. 2003	interior BC	Variable retention (thinning) in upstream 10 to 30-m wide buffers	Downstream cooling in the daily maximum temperature was observed in two study reaches over a distance of 200 m.	Downstream cooling was strongly influenced by stream flow, groundwater, and hyporheic exchange

2) How and where are the potential temperature effects from forest management likely to impact salmonid species of concern?

The Primer's review of Sullivan et al. (2000) and related research shows that the effects of temperature on salmonids are a function of magnitude and duration of exposure. Generally temperatures above 26° C are lethal depending on duration of exposure and species tolerance (e.g., 50% mortality at 26°C for 96 hours). Temperatures in the 22° C to 26° range are stressful and may result in loss of appetite and failure to gain weight, competitive pressure and displacement by other species better adapted to prevailing temperatures, or disease. Physiologic tolerance improves at lower temperatures and optimal temperatures occur over a range that depends on food availability (Figure 5). Optimal temperatures for growth are in the range of 14 to 17° C, depending on species (Sullivan et al. 2000). This knowledge, which is based on a large body of literature, indicates that the potential effects of forest management depends on the temperature regime at a particular location and on the spatial temperature patterns within a watershed or across regions. For example, Sullivan et al. summarized temperature data from forested, rural, and urban streams throughout the Pacific Northwest and concluded that temperatures high enough to cause direct mortality were rare, and that sublethal effects (i.e., influences behavior or growth) were common. In fact, they found that the majority of temperatures experienced by salmonids are suboptimal.

In California the potential occurrence of temperature impacts in forested areas is probably similar to the Northwest. Temperature data in Lewis et al. (2000) shows that water temperature at 80% of the study sites (N =154) never exceed lethal levels (i.e., 26° C; Sullivan et al. 2000) and of those that do, only a smaller proportion are likely to have continuous lethal temperatures long enough to cause mortality. Note, all of the streams that had temperatures near lethal levels had canopy cover levels (i. e., < 24%; Figure 3) that were well below CA forest practice standards (minimum 50%). Given this context, the majority of forest management activities in CA are likely to influence stream temperatures in the sublethal range and potential temperature related impacts will vary accordingly. The magnitude of salmonid response to temperature changes in the sublethal range are more a function of changes in the temperature regime rather than a change in the annual maximum (see Section 2a for more information on sublethal temperature effects in California). For example, Sullivan et al. found that large differences in maximum temperatures among sites did not translate to big differences in the overall growth potential of salmonids. This is because growth reflects the net cumulative effect of energy intake (feeding) and loss (respiration and waste products) which is regulated by the temperature regime over long periods (weeks to months). Therefore the duration of favorable and unfavorable temperatures, not short-term (hours) maxima, governs the overall growth response. The optimum or favorable temperature for growth varies in relation to food availability; in cases of high food abundance warmer temperatures are more favorable for growth and when food is sparse, cooler temperatures are preferred.

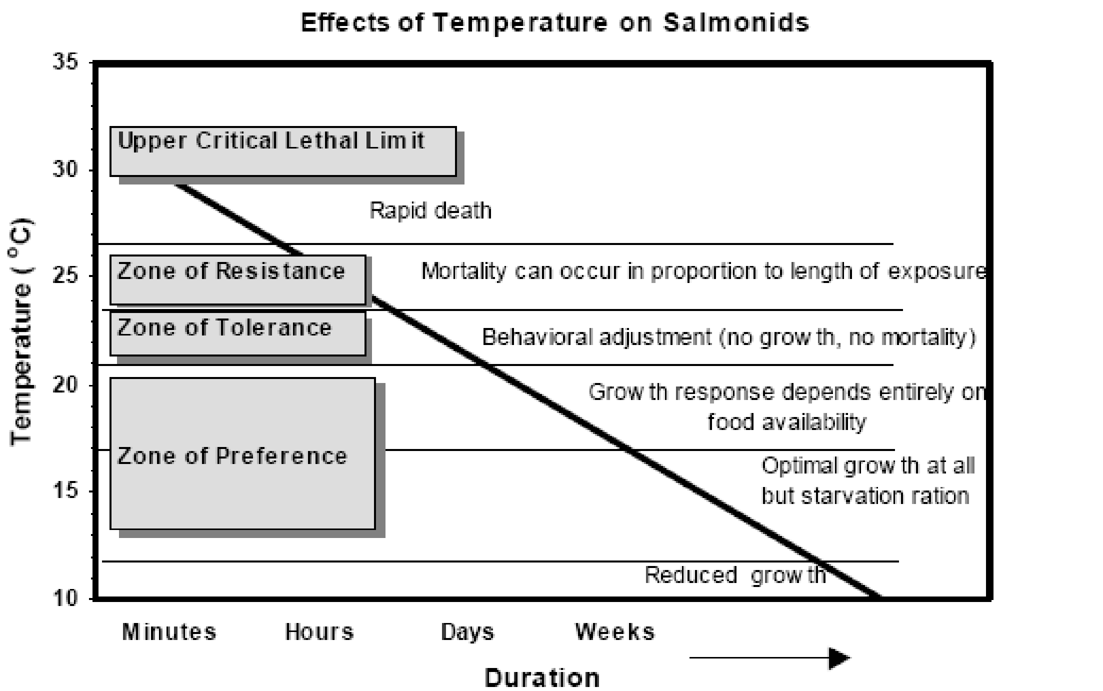

Figure 2.1 General biological effects of temperature on salmonids in relation to duration and magnitude of temperature.

Figure 5. Summary of temperature effects on salmonids. Note, this is a generalized depiction of temperature effects on salmonids. Specific temperatures dividing the zones varies by species. (Figure 2.1 from Sullivan et al. 2000)

The literature on where salmonids may be impacted by forest management influences on temperature in California is limited (see 2a below) and is insufficient to address this question. However the literature about temperature effects and our knowledge of heat exchange mechanisms provides a good clue to the type of streams and locations that would be more or less sensitive to shade loss. In other words, some streams need more shade to maintain a suitable temperate regime than others because of its location and physical characteristics. This does not mean that canopy cover is not important, only that the amount of canopy cover necessary to maintain adequate temperatures will vary. In California, the stream location, inside or outside of the zone of coastal influence, is important because streams located outside of the zone of coastal influence would be more sensitive to temperature effects from forest management than would streams inside of the coastal zone. For example, low-order tributaries to rivers in the central valley and inland rivers along the North Coast outside the zone of coastal influence are particularly vulnerable to shade loss. Within both geographic zones, shade is important, but stream sensitivity to shade loss is a function of reach-scale physical characteristics. For example, streams with high sensitivity may have one or more of the following characteristics: low elevation, no topographic shading, shallow, wide, bedrock substrate. In contrast, streams with lower sensitivity to shade loss would generally occur at higher elevations (especially outside of the zone of coastal influence), where there is topographic shading, where the channel is deep or narrow, and with alluvial substrate. Streams with high sensitivity to shade loss may naturally have temperature regimes that are stressful to salmonids. Therefore small changes in temperature caused by shade loss could have larger impacts on growth, survival, and fish distribution than would an equivalent change of temperature in a stream with a cooler temperature regime. Similarly, streams that are naturally cool may become more favorable for growth as a result of shade reduction and stream warming, Clearly, stream temperature sensitivity to shade loss and the biological consequence of temperature change need to be considered (see below) in determining how and where management could impact salmonid populations.

2A) IS THERE INFORMATION FROM CALIFORNIA ECO-REGIONS INDICATING THE EFFECTS OF OBSERVED TEMPERATURE ON SALMONIDS?

Information in the TAC literature that documents the effects of observed temperature on salmonids in California is limited. Four of the TAC listed studies, plus one additional paper (i.e., Hayes et al. 2008), address temperature effects in the coastal regions (Table 3). The findings from one study are also applicable to the central valley region.

Researchers from two of the studies observed that juvenile coho distribution in north coast watersheds may be restricted by high water temperatures during summer. Welsh et al (2001) concluded that stream reaches with a maximum weekly maximum temperature (MWMT) greater than 18.0°C precluded the presence of juvenile coho in the Mattole River. Similarly, Madej (2006) postulates that coho do not occur further than 20 km upstream in Redwood Creek because high summer water temperature (MWMT ranges 23° to 27°C) in the middle portion of the watershed are unsuitable for juvenile rearing. Water temperature in the lower portion of the watershed is cooler as a result of the coastal fog zone and intact riparian timber stands. The thermal regimes of both the Mattole River and Redwood Creek appear to be recovering from watershed disturbances caused by historic logging and farming activities.

The effects of different temperature regimes on juvenile salmonid growth was measured or estimated by Willey (2004) and Hayes et al (2008). Using empirical temperature data from north coast streams and a bioenergetic model, Willey (2004) calculated that juvenile coho had the best growth potential when daily average water temperatures ranged from 14.7°C to 15.7°C, and that growth potential is less where average temperatures are either cooler (<15°C) or warmer (>17°C). Interestingly, Hayes et al. (2008) found that juvenile steelhead growth was highest in an estuary–lagoon near the mouth of Scott Creek (central coast) where summer temperatures ranged from 15° to 24°C. The differences between studies regarding temperatures that are best for growth is partly explained by different species examined and to food availability. Sullivan et al (2000) demonstrated that the optimum growth temperature for steelhead is greater than for coho. Hayes et al (2008) report that food availability in the coastal lagoon was more productive than in the stream, and probably offset the negative effects from higher temperatures.

The effects of interspecific competition by Sacramento pikeminnow (occurs in central valley and large coastal streams [e.g., Eel River]) on juvenile steelhead growth was examined in a laboratory study by Reese & Harvey 2002. They found that the growth of juvenile steelhead was unaffected by Sacramento pikeminnow in cool water (15–18°C), but interspecific competition increased between species in warmer water (20-23°C) causing a density dependent effect on steelhead growth.

All of the studies in this review deal with sublethal effects of temperature and illustrate that changes in temperature regime can influence population growth potential and alter spatial patterns of habitat use by salmonids, and competing species in California. Some of the studies indicated that population responses to increased water temperature were a consequence of historic logging and removal of riparian timber stands. None of the studies document the effects of modern forest management, although temperature recovery is occurring in some cases (e.g., Madej 2006); presumably as a result of mandated buffers. These studies also suggest that a simple temperature threshold may not be desirable for all eco-regions because the salmonid response varies by species, watershed productivity, and thermal regime.

In addition to the California studies, the TAC literature included two non-California studies that are relevant for assessing temperature risk to salmonids, regardless of location. Sullivan et al. (2000) introduced a bioenergetics approach for assessing temperature risk to salmonids that is based on estimated population growth potential during the juvenile rearing phase. They showed how the annual temperature regime and food availability determines growth potential, and how the growth potential for several salmonid species could be equated to a range of temperature metrics (e.g., summer maximum weekly average temperature [MWAT]). They also showed how the bioenergetics approach could be used to quantitatively evaluate the risk for growth loss as a consequence of temperatures that are not optimal or are altered due to management activities. Further, they suggested that a specified growth loss (e.g., 10% below optimum) could be used as a biological-based threshold for management.

Table 4) Summary of literature that examined the effects of temperature on salmonids in California.

Reference	Region	Fish response to temperature
Hayes et al. 2008	North Central Coast	In Scott Cr, juvenile steelhead grew much faster in the estuary where summer temperature ranged 15–24°C than in upstream reaches where summer temperature were 14–18°C
Madej 2006	North Coast	The apparent juvenile coho distribution in Redwood Cr. may be limited by summer temp patterns (MWMT 23° to 27°C), but relationship is not quantitative.
Reese & Harvey 2002	Coast & Central Valley	Elevated stream temperature may results in a density dependent effect on juvenile steelhead growth caused by interspecific competition with pikeminnow, which prefer waters 20–23°C
Welsh et al 2001	North Coast	Temperature threshold (i.e., MWMT of 18.0°C or less or MWAT of 16.7°C or less) affected juvenile coho distribution within the Mattole River watershed.
Willey 2004	North Coast	Calculated energy allocated to growth of juvenile coho was maximum when daily average water temperatures ranged from 14.7°C to 15.7°C. Calculated growth conversion efficiency declines in either cold (12-15°C) or warm (>17°C) temperature regimes.

The biological threshold concept was examined by Neiltz et al. (2008) for classifying streams in British Columbia. They used the Sullivan et al. bioenergetics model and other empirical models (i.e., to assess growth potential, hatching success, and disease resistance) as tools to assess the temperature effects of streams with different thermal regimes. They also developed empirical temperature models, similar to Lewis et al. (2000), that related the temperature regime of streams in different regions of BC with watershed size, watershed elevation, and air temperature. The empirical and biological models were then used in combination to assess the biological risk of timber harvest in different regions with different thermal sensitivity. Such an approach could be used in California to set regional temperature targets.

2B) ARE THERE CONDITIONS THAT ADEQUATELY AMELIORATE THE OCCURRENCE OF ADVERSE TEMPERATURES?

Yes, several factors, alone or in combination, can reduce stream temperature sensitivity to changes in riparian shading. The occurrence of adverse water temperatures is minimized by:

- climatic influences
- geomorphic/topographic shading, and
- hydrologic dampening

Within the zone of coastal influence (, the fog layer attenuates incoming solar radiation resulting in water temperatures that average 1°C to 2°C cooler than for streams of similar size that are outside the zone of coastal influence (Lewis et al. 2000). The inland extent of the zone of coastal influence ranges from 2.8 to 32 km and varies daily, seasonally, and yearly. Stream network data show that water temperatures decline as a stream flows into the zone of coastal influence (Lewis et al. 2000, Madej 2006). Empirical data shows that riparian canopy cover does influence water temperature in the zone of coastal influence, but the level of adequate shading is not well defined (Lewis et al. 2000).

Outside the zone of coastal influence, water temperature (especially daily minima) tends to decrease with increasing elevation as a result of adiabatic cooling (i.e., air temperature declines with increasing elevation) processes (Lewis et al. 2000).

Adverse temperatures can be minimized by geomorphic and topographic factors that block or reduce incoming solar radiation (Allen 2008). Exposure to incident radiation decreases with increasing channel incision because the water surface may be shaded by the streambank. The area of stream surface exposed decreases with decreasing stream width, which minimizes heat loading. The duration of exposure to high angle incident radiation (i.e., results in greatest heating potential) is least for streams with an east-west valley orientation, and is greatest for streams with a north-south orientation. Exposure decreases with increasing height and decreasing distance of the watershed ridge line on the southside of a basin.

Hydrologic factors that dampen water temperature response to heat input include hyporheic exchange rate (i.e., streamflow below the streambed is cooled by heat exchange with subsurface water and substrate), groundwater inflow, and stream discharge. Streambeds composed of alluvium (sand, gravel and cobble substrate) have greater hydraulic retention and increased sub-surface storage (i.e., greater hyporheic exchange) than do streams with bedrock substrate (Johnson 2004). Also, hydraulic obstructions (e.g., logjams) and meandering channels create complex flow paths that promote hyporheic exchange that can have a reach-scale cooling effect on water temperature (Johnson 2004, Dent 2008). Groundwater inflow, which is associated with lithology (Allen 2008) can cause cooling depending on the ratio of inflow volume to surface flow volume. Similarly, as stream discharge increases the potential effects of shade loss on temperature decreases because the increasing thermal capacity of the stream is less sensitivity to heat inputs.

There are several physical factors that can ameliorate the effects of reduced riparian shading on stream warming. Some of these factors may be generalized at the regional scale, and their location or probability of influence are generally predictable. Other factors are more relevant at the reach-scale and, while important, can be very difficult to evaluate in the field in any quantitatively detailed manner. The effectiveness of some factors (i.e., hyporheic exchange, groundwater inflow) to ameliorate temperature response needs further investigation.

3) What bearing do the findings of this literature review have on riparian zone delineation or characteristics of riparian zones for protecting water temperature?

The findings of this literature review indicate the following about riparian zone delineation:

1. **Shade is substantially more relevant than canopy closure as a variable for managing stream temperature risks.** Buffer design should identify the width of thermal influence based on the shade that block high angles (>30°) of incoming solar radiation along the southern exposure in temperature-sensitive streams. Riparian canopy

shading that blocks direct solar radiation along the sun's path at solar elevation angles greater than 30 degrees is most effective for reducing radiant energy and protecting stream temperature. North-side buffers do not provide shade and evidence for the effectiveness of shade from small trees and understory vegetation is mixed. Note, shade refers to the attenuation of direct beam radiation and should not be confused with riparian canopy cover or canopy closure which is the percentage of area that is covered by the overstory canopy. (California Forest Practices Rules, Title 14, California Code of Regulations, Chapter 4, 916.5(e) "I").

2. **Effective riparian shading is a function of the forest canopy density, tree height, and species composition, which is related to stand type and age.** Because stand type and age may vary by region and disturbance history the buffer width that is adequate for shading will likely vary regionally as well, and therefore regional generalizations may apply. This fact is clearly illustrated by the shade/width curves in Figure 1 and demonstrates that one-size-fits-all (i.e., fixed width) prescription are not applicable to the diverse forest types of California. The shading effectiveness varies in relation to the canopy density and tree height potential of each forest type. Therefore tall-dense coastal stands of redwood and Douglas-fir provide more shade for a given buffer width than would shorter Ponderosa pine mixed-conifer stands in the Sierra's. This difference in shade effectiveness by stand type also indicates that a single canopy cover rule (e.g., 50% cover in CA) will not result in similar shading among different forest types. In fact, 50% cover in a coastal forest will result in more effective shade than will 50% cover in a Sierra forest for buffers of equal width.

   Research, mostly from outside of California, shows that effective shading can be provided by buffer widths ranging from 10 m to 30 m depending on stand type, age, and location. We suspect similar widths may be applicable to California forest, but quantitative relationships between buffer width and shade for typical forest types and stand age classes in California are not reported in the literature. A riparian stand metric (e.g, density, relative density, basal area, quadratic mean diameter) that may function as a reliable surrogate for shade has not been developed.

3. **Stream heating effects in the near-headwater portion of fish-bearing streams could be managed by shade buffers along the upstream headwater stream segments.** The length of buffer necessary to protect

temperature is variable and depends on the stream discharge, substrate type, groundwater inflow, and hyporheic exchange. The findings of research outside of California, suggests that protections/considerations extending from 150 to 200 m upstream may be adequate.

4. **The relative importance of riparian shade for protecting water temperature depends on a suit of physical factors, such as region, elevation, stream size, channel morphology, hydrology, and valley orientation.** Stream temperatures are affected by a wide array of variables, and some streams are more sensitive to shade than others. For example, less shade would be needed to maintain cool water for a stream in the zone of coastal influence than would be needed for a stream of equal size in the interior provinces.

   Identifying shade targets for streams may be best achieved by developing empirical relationships or physical process-based calculations that incorporate local and/or regional factors. Such relationships can accommodate a broader suite of important variables, and may improve the accuracy of predictions over simple canopy closure values. Lewis et al. (2000) and more recently Allen (2008) showed that stream temperatures can be modeled for the zone of coastal influence and interior provinces, although more data are needed to improve their accuracy.

Riparian microclimate factors do not appear to have sufficient influence on water temperature to warrant special rules. Stream temperature is more strongly influenced by other variables, including topography, elevation, flow characteristics, geology, etc. Therefore, buffer design should focus on maintaining trees to block high angle radiation and not be overly concerned about factors influencing microclimate (e.g., decrease interception of precipitation, and increase wind speed).

Inferences for Forest Management

The literature on riparian heat exchange tells us that shade from riparian timber stands is a key factor controlling heat input to streams. Therefore, maintaining riparian vegetation to block direct solar radiation (i.e., shade) is the intent of forest practice prescriptions for protecting stream temperature during the summer. However, water temperature is a function of a host of physical factors that control heat transfer between air, water, and the streambed. Consequently, the relative importance of riparian vegetation to influence stream temperature varies by location (geographic province) and by site specific conditions (stream width, depth, flow, groundwater inflow, streambed substrate composition, valley orientation, topographic shading and watershed position). This spatial variability indicates that a simple fixed-width buffer or canopy closure prescription (e.g., minimum 50% canopy cover as required in CA) will probably not achieve management goals in all cases. For example, Lewis et al. (2000) showed that California streams with canopy closure in the 50% to 75% range had maximum water temperatures that ranged from about 14° C to 30° C (see boxplot 50-75% class; Figure 2). Clearly, some of these streams had adequate temperature protection and some did not, even though all of the streams had canopy cover that met the California Forest Practice rules. Some of the streams in the Lewis et al. study were located inside the ZCI where stream temperature is less sensitive to shade reduction because heat input is attenuated by the fog layer and some were located outside of the ZCI where temperature is more sensitive to shade levels. Furthermore, some of the streams may be narrow and at higher elevations where channel incision or topography limits solar exposure and where air temperature is lower, and some streams may be wide and shallow at lower elevations where exposure and air temperature has a greater influence on the stream. The key point is, stream temperature sensitivity to shading is dependent on location and physical conditions.

The science on heat exchange indicates that water temperature protection could be provided by varying the riparian shade needs in relation to stream temperature sensitivity. For example, Washington uses a temperature, elevation, and shade relationship (nomograph) to determine minimum riparian shade needs by stream elevation and region (east and west of Cascade divide; Washington Forest Practice Board Manual). The Washington approach incorporates two key factors (elevation and geographic province) that are applicable and easily adaptable to California. However, since Washington developed the nomograph in the 1990's, we have greatly improved our understanding of how other physical factors influence temperature sensitivity as shown in this review. Therefore, it is feasible to incorporate other physical factors that influence temperature sensitivity for determining shade requirements of riparian stands. In addition to geographic province (i.e., inside or outside of ZCI) other watershed- and reach-scale (reaches are one to several miles long) drivers, such as elevation, distance to divide, stream size, and channel orientation, could be used for assessing temperature sensitivity and general shade requirements. Geographic Information System (GIS) maps that show temperature sensitivity categories could be developed through the use of models that are appropriately calibrated for California. Specific shade requirements could be determined by combining a reach-scale sensitivity ranking with an assessment of site-specific conditions. Factors such as topographic shading, channel incision (e.g., canyon or flood plain area), streambed substrate, and groundwater influence could be used to further assess temperature sensitivity and to determine a minimum shade requirement that would meet the goals of the BOF. The latter could be accomplished with a model or by an appropriately designed decision tree that assessed risk (i.e., relative importance of shade for temperature protection) based on the presence/absence and characteristics of site-specific factors(e.g., Allen 2008). Finally, the amount of shade that may be removed by timber harvest would depend on the difference between the pre-harvest shade level and the site specific shade requirements.

In fish-bearing waters that are directly downstream of headwater streams, the literature indicates that temperature could be protected by buffering the upstream headwater stream segments. The findings of research outside of California, suggests that buffers extending from 150 to 200 m (500 to 650 ft) upstream may be adequate to protect water temperature in low order streams. Whether this buffer is adequate for California streams and regions would need to be validated. Information on temperature sensitivity, as discussed above, would benefit such validation and could probably be used in a screen for determining the potential need of headwater buffers. A site specific assessment similar to that described above could be used to determine the headwater buffer length.

The shade requirement for streams should not only be based on stream temperature sensitivity to shade, but on the water temperature goals or standards that need to be maintained for the protection of salmonid populations. The literature indicates that stream temperature is a major factor influencing population performance and that population performance can be quantitatively evaluated by a probabilistic risk assessment (e.g., Sullivan et al. 2000). Therefore, the suitability of an existing thermal regime for maintaining salmonid populations could be assessed and temperature goals could be defined in terms of the potential to protect or improve population performance. For example, Willey (2004) showed how coho growth was limited in certain California coastal streams by either cool or warm temperature regimes and was maximum in streams with an intermediate temperature regime. This type of information along with a temperature sensitivity assessment, as discusses above, could be used by resource managers to determine where populations may be vulnerable to shade removal or where shade removal could enhance population performance. Ideally, managers could conduct such an analysis at the watershed scale and use this information to guide riparian harvest or restoration plans that would be the most effective in terms of improving population performance. Suitable thermal conditions could be maintained and hazards avoided by altering the timing and spatial position of riparian management activities.

Finally, riparian stand effectiveness for shading is a function of the forest canopy density, height, and species composition, which is related to stand type and age. Because stand type and age may vary by geographic province and disturbance history the buffer width that is adequate for shading will vary as well. This fact undermines the one-size-fits-all (i.e., fixed width) prescription that is commonly applied in forest management. Research shows that effective shading can be provided by buffer widths ranging from 10 m to 30 m (30 to 100 ft) depending on stand type, age, and location. However, quantitative relationships between buffer width and shade for typical forest types and stand age classes in California are not reported in the literature. Potential quantitative relationships between stand density and shade or basal area and shade are lacking. Consequently a riparian stand metric that may function as a reliable surrogate for shade has not been developed.

KEY INFORMATION GAPS

The findings of research outside of California, suggests that buffers extending from 150 to 200 m upstream may be adequate to protect water temperature in low order streams that drain into fish bearing waters. Additional research is needed in California to validate or refine this relationship. More information about recovery distances would also help establish criteria for patch treatments (i.e., canopy openings) that may be used to meet other riparian goals.

Lewis et al. (2000) and Allen (2008) showed that stream temperatures can be modeled for the zone of coastal influence and interior provinces, although more data are needed to improve their accuracy (e.g., temperatures at low flow, low flow hydraulic geometry) and to identify the key watershed factors (e.g., lithology) controlling temperature. These data could be used to develop GIS maps for classifying stream temperature sensitivity at the reach/watershed scale and to build a hierarchal decision tree for classifying stream temperature sensitivity at the site scale.

A quantitative approach for assessing biological risk of temperature exposure on salmonid population performance should be adopted. The level of population performance or risk of performance loss that is considered acceptable for maintaining populations that are vulnerable to temperature impacts should be defined by Policy. This would facilitate a quantitative and transparent approach for assessing the effectiveness of management strategies and for developing water temperature thresholds.

Additional research into the effect of shade provided by shrub cover and understory vegetation would help to establish the value of other riparian vegetation in meeting stream temperature management objectives.

Additional research into potential factors influencing the relative sensitivity of water temperature to microclimate variables is desirable. Under what conditions or locations, if any, would microclimate variables have a strong influence on water temperature.

GLOSSARY

adiabatic trend
: The rate of change of air temperature with elevation; sometimes called the adiabatic lapse rate. The average environmental rate is about 2.0 deg. C per 1000 ft.

angular canopy density
: The percentage of time that a given point on a stream will be shaded between 10 AM to 2 PM local solar time

bioenergetic model
: A numerical model of an organisms metabolic energy budget. It can be used to calculate the energy available for growth

canopy closure/cover
: The percentage of ground covered by a canopy of vegetation directly overhead. This definition does not account for the density of the vegetation within the area, but rather can be considered an outline of a plant's branches and foliage. Overlapping canopies are not counted, therefore the maximum canopy closure value possible is 100 percent.

canopy density
: The amount of the sky that is blocked by vegetation. Multiple layers of foliage, deep crowns, and interlocking tree branches can enhance canopy density. Its value can exceed 100 percent.

Coastal Zone
: 1) The zone of maritime influence; 2) The zone of jurisdiction of the California Coastal Commission, which varies in width from a few hundred feet to about 5 miles. See: http://www.coastal.ca.gov/

Zone of coastal influence
: Defined by Lewis et al. (2000) as the maximum inland extend of the coastal cooling effect. The inland extent of the ZCI ranges from 2.8 to 32 km and varies daily, seasonally, and yearly.

densiometer
: An optical device for measuring the percentage of canopy coverage at a given point. May use a convex or a concave mirror.

fog zone
: The zone of maritime influence with morning fog on most days during summer months. Lewis et al. (2000) found that the zone of coastal

influence is the best approximation of the fog zone.

hyporehic exchange The exchange of surface water with subsurface water that is flowing through interstitial spaces within the stream bed or banks. It can have a strong influence on water temperature and nutrient cycling.

leaf area index The ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. The LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest.

light attenuation The rate at which light is absorbed by a tree canopy or column of water; varies with wave-length

microclimate Climate on a scale of meters or tens of meters. Effects of tree canopy, cold air drainage, wind, proximity to a water body, etc. may be important

regression lines A line through a set of data points in a X-Y plot such that the sum of squares of the Y distance from each point to the line is a minimum

sighting tube A device for measuring canopy closure or cover at a point directly above an observer. An estimate of percentage canopy closure can be obtained by taking multiple readings that are evenly spaced along a transect. Also called a "densitometer".

solar pathfinder A device for mapping the path of the sun and its interception by tree crowns, for a given date at a given point along a stream. The device is commonly used to measure shade or solar radiation.

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