

II. Effects of Riparian Management Strategies on Stream Temperature

Science Review Team Temperature Subgroup

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Background

The Science Roundtable Team (SRT) of technical experts was requested by the Interagency Coordinating Subgroup (ICS) to evaluate models that predict changes in shade and stream temperature as a result of the removal of trees in riparian areas. The management concern is that stream temperature in the summer may increase as a result of riparian management activities and negatively affect coldwater fishes, including salmon, trout, and associated aquatic ecosystems. The area of interest includes conifer forests of the Oregon Coast Range, but the findings of the SRT are intended to be applicable to a broader range of forests in western Oregon and Washington. The ICS requested information on what is known and not known about the effects on shade and water temperature of various riparian management strategies that employ no-cut buffers of various widths and thinning of trees at different intensities. In contrast to the well-documented impacts of clearcuts on shade and stream temperature, the effects of partial cutting and removal of trees in riparian areas have not been well studied and are more difficult to predict than the effects of clearcuts. Mechanistic models that predict changes in stream temperature as a result of increases or decreases in solar radiation provide a foundation for addressing the questions posed by the ICS, and empirical studies provide additional insights into the complexities of applying these models in the field. In this document, we summarize pertinent scientific theory and empirical studies to address the following tasks specified by the ICS:

Define the effects of various riparian management strategies on stream function, with a focus on temperature.

- *Describe effects associated with “no cut” buffers of various widths and alternative thinning regimes (e.g., skips and gaps, different thinning intensities).*
- *Characterize the distance at which thinning affects downstream temperature.*
- *Describe how unstable landforms and existing riparian roads can affect the conclusions reached in the above analysis.*

To address the management concerns outlined by the ICS, we focus on stream temperature during the summer when reductions in shade due to the removal of trees could potentially cause increases in the maximum or average daily temperature that exceed the thermal tolerances of aquatic organisms (Beschta et al. 1987). We begin by defining the physical factors that influence the thermal regime of streams, and then we specifically examine the scientific literature that describes the effects associated with alternative riparian management strategies. We then explain the complexities of determining downstream impacts of riparian management strategies

in the stream network. We also identify special considerations for evaluating these effects in the context of landslides and roads in riparian areas. Finally, we identify areas of uncertainty that make it difficult to predict the effects of various riparian management strategies without extensive knowledge of factors that are difficult to quantify and expensive to measure in the field.

Factors influencing stream temperature

Stream temperature is influenced by multiple anthropogenic and non-anthropogenic factors that occur above the water surface, in the streambed, within the water column, and in the surrounding landscape (Poole and Berman 2001, Caissie 2006) (**Figure 1**). These factors can be grouped in four general categories: (1) atmospheric conditions, (2) the streambed, (3) stream discharge, and (4) topography (Caissie 2006). The interactions among these factors make predicting changes in stream temperature response to human alteration of the landscape a challenging task, particularly if precise estimates of thermal impacts are required to inform management decisions (Johnson 2003; Hester and Doyle 2011).

Heat exchange processes in streams

The interactions among factors that influence water temperature in streams are complex, but the actual physics of stream heating can be summarized relatively simply as exchanges of energy at the air/water surface and at the streambed/water interface (**Figure 2**). The relative importance of the various heat exchange processes in **Figure 2** varies with respect to the factors identified in **Figure 1**. However, solar radiation is generally the dominant component of the energy budget in terms of heat gain (Moore and Wondzell 2005, Cassie 2006). Inputs of heat energy from solar radiation can be large compared to the losses associated with heat exchange. Therefore, most of the solar energy is stored in the stream, thereby causing an increase in water temperature in a downstream direction. Accordingly, the most efficient method to maintain low stream temperatures is to reduce heat loading from solar radiation. Shade prevents stream warming by reducing inputs of heat energy from solar radiation.

The removal of heat energy from the stream requires heat exchange of the water with the surrounding environment through which energy moves out of the “warm” stream via processes associated with the second law of thermodynamics (i.e., energy travels from high to low concentrations). Inputs of cold water from the streambed, seepage areas on the stream bank, and tributaries can be large components of the net energy budget and can help cool the stream on hot summer days if they are sufficiently large relative to the stream discharge (Wondzell 2012). Energy gained from solar radiation also leaves the stream through long-wave radiation, evaporation, convection (air and water), and conduction (air, water, streambed) (**Figure 1**) (Caissie 2006).

Stream temperature and riparian management strategies

The effects of riparian vegetation on shade and stream temperature have been studied extensively, and it is generally accepted that removing trees in riparian areas reduces the amount of shade which leads to increases in thermal loading to the stream (Moore and Wondzell 2005).

This increase in thermal loading from direct solar radiation after the removal of shade may or may not lead to measurable increases in stream temperature depending on the net effect of the multiple factors described in the following sections.

What are factors are most relevant?

We focus on shade and the factors that influence its spatial extent, temporal duration, and quality. The primary factors that influence shade are riparian vegetation (Groom et al, 2011b) and the surrounding terrain (Allen et al. 2007). Note that riparian vegetation, upland shading, and aspect (i.e., stream orientation) are grouped under the general category of topography because both trees and the surrounding landscape constitute vertical structure that affects the transmission of solar radiation to the stream (**Figure 1**). We also consider (1) the physical characteristics of the stream itself and how they affect heat flux at the water surface, and (2) the role of direct transfer of energy to and from the stream through groundwater, tributary inflow, and hyporheic exchange.

Why are these factors important?

Although many other factors affect stream temperature (**Figure 1**), we focused on (1) shade, (2) heat flux at the water surface, and (3) groundwater–surface water interactions because these factors are often directly associated with riparian management activities (Webb et al. 2008). Other factors are not addressed because (1) they are difficult to measure in the field and incorporate into predictive models, and (2) they compose a relatively small part of the heat budget in the streams that are most likely to be encountered in the forested landscapes pertinent to this report (Johnson 2003).

Shade in riparian areas

In order to assess the ability of riparian vegetation to create effective shade over a stream, three characteristics of the “shade” need to be evaluated: (1) spatial extent, (2) temporal duration, and (3) quality. Shade spatial extent is the spatial area over which a shadow is cast over a stream. Shade temporal duration is the length of time during which a portion of stream is shaded. Shade quality is a function of the canopy density (including the stems), where lower canopy density is associated with lower shade quality. The removal or modification of trees in riparian areas can affect the spatial extent, temporal duration, and quality of shade on a stream.

Vegetation height and topography

The height of the vegetation directly influences the spatial extent of shade. On flat ground, the distance over which a tree can cast a shadow during the summer in the Pacific Northwest varies from approximately 50-200% of the tree height, depending on the time of day (see discussion below on temporal variability). Depending on sun angle and tree height, there is a threshold distance from the stream at which shadows from even the tallest trees will no longer reach the stream from mid-day to late afternoon when thermal loading from solar radiation is greatest. Wherever streambanks are higher than the stream, the effective height of vegetation includes not just the height of the tree but also the elevation of its base above the stream. Thus, shadow

length is longer for vegetation located on streambanks above the stream. In steep, narrow headwater catchments, a large proportion of shade may be created by topographic relief alone; however, at broader scales, and at most locations within a watershed, the largest component of shade is typically derived from riparian vegetation (Allen et al. 2007, Allen 2008). Because shade conditions in streams are a function of shade produced by the vegetation and shade produced from topography, both factors must be considered in evaluating potential effects of removing trees in riparian areas.

Density of vegetation

The density of vegetation in riparian areas affects shade and thermal loading to a stream due to the penetration of solar radiation through gaps in the canopy and among the branches and stems (Brazier and Brown 1973, DeWalle 2010). Riparian stands with few trees and low canopy and branch density reduce shade quality. The removal of vegetation through “thinning” activities results in an initial lowering of the vegetation density in the riparian stand. In low-density stands (i.e., more open stands), wider buffers can compensate for decreased canopy density and help achieve the same shade quality as would be achieved given similar vegetation with a closer spacing of trees.

Width of buffer

The width of the band of vegetation along the stream bank influences the amount of solar radiation that reaches the stream. Wide buffers create more shade than narrow buffers, as measured by angular canopy density (Brazier and Brown 1973, Wooldridge and Stern 1979, Steinblums et al. 1984, Beschta, et al. 1987). However, there is a high degree of variability in this relationship, particularly at narrower buffer widths where the effect on shade is greatest. For instance, data from Brazier and Brown (1973) and Steinblums et al. (1984) indicate that a 15-m buffer width might provide anywhere from 18 to 80% shading (**Figure 3**). In addition, these studies also showed that 75-90% shade can be achieved with a wide range of buffer widths, ranging from approximately 9 to 43 m. The high variability in buffer width and shade condition is a function of the many variables that influence the amount of shade produced by riparian vegetation. As described above, low-density stands with limited vertical distribution of branches and foliage may require wider buffer widths to produce the same amount of shade as high-density stands.

Temporal variability

Shade duration is dependent on day of the year and the height and distance at which the shade-producing feature is located from the stream. Shade duration can be calculated based on physical attributes of the tree (i.e., height and distance to stream) and the location of the sun in the sky, which varies daily and seasonally, and the azimuth of the stream. The intensity of solar radiation on the surface of the earth also varies daily and seasonally based on the vertical angle of the sun in the sky. The shadow length from riparian vegetation is the shortest at mid-day when the sun is high in the sky, and the shadow length increases during other parts of the day as the sun is lower in the sky. In the Pacific Northwest, the greatest amount of energy generally occurs between the hours of 10:00 to 14:00 and in July and August (Beschta et al 1987). However, heat loading

from solar radiation during other periods of the day constitutes a significant part of the energy budget (~40%) and therefore is influential on stream temperature. Tools that are typically used to measure and model solar radiation incorporate both the surrounding topography (e.g., aspect and elevation) as well as daily and seasonal variation (Moore et al. 2005, Allen et al. 2007, Boyd and Kasper 2003). These methods provide estimates of total shortwave energy for a given day or time period. Such estimates of total shortwave energy are necessary in order to compare the thermal impacts of riparian management scenarios.

Stream channel dimensions and heat flux at the water surface

The effect of solar radiation at the stream surface on water temperature depends on stream width, and depth, and the flow velocity (Beschta et al. 1987, Sullivan et al. 1990). For a given stream discharge, a shallower, wider stream will heat up faster than a deeper, narrower stream, so it is important to consider the morphology of the channel itself in determining the potential effects of increased solar radiation resulting from riparian management strategies. Furthermore, the exchange of heat energy to the stream from solar radiation depends on the length of stream that is exposed and the time that it takes for water to pass through that area (i.e., a function of velocity). The shadow length associated with a short tree might be sufficient to “cast a shadow” over a narrow stream channel, but this same tree may be insufficient to shade a wider stream channel. Accordingly, stream width is an important factor to consider in determining thermal loading associated with a particular riparian stand.

Groundwater and surface water interactions

Groundwater inputs, tributary inflow, and hyporheic exchange can directly influence stream temperature because they involve advective transfer of relatively cool or warm water to the stream. The size of the effect is a function of the amount of water entering (or exchanged with) the stream relative to the stream discharge (Johnson and Jones 2000, Story et al. 2003, Wondzell 2006, Wondzell 2012) and the difference in temperature between the stream and the inflowing water. For example, small amounts of cold water can have large effects on stream temperature in warm streams if they are large relative to the size of the receiving stream’s discharge or if they are very cold relative to the receiving stream’s temperature. Such cold-water inputs can be distinct point sources (e.g., groundwater seeps), or they can be diffuse (e.g., hyporheic exchange) (Poole and Berman 2001; Poole et al. 2001, Wondzell 2012). If the net effect of these inputs over a given stream distance is large relative to the stream discharge, they can have significant effects on downstream reaches. Thus, the magnitude of temperature response associated with riparian management is directly related to these processes, which can either increase or decrease stream temperature.

Effects associated with riparian management strategies

Removal of trees in riparian areas increases shortwave thermal loading to streams through its effects on (1) shade quality (i.e., thinning of the stand to reduce the stand density), and (2) shade temporal duration (i.e., reducing the average vegetation height as a result of thinning from “above”) (Groom et al 2001b). The specific shade response to tree removal depends on pre-harvest vegetation, including its composition, structure, and location relative to the stream, and

on the number and location of trees that are removed. Therefore, specific trends described below only provide *approximate* guidelines of shade conditions associated with various buffer conditions given the variability of conditions in the forests pertinent to this report. In addition, the effects of riparian management on stream temperature are even more variable (Moore et al. 2005a, Moore et al. 2005b, Moore and Wondzell 2005, Janisch et al. 2012).

No-cut buffers adjacent to clearcut harvest units

Substantial effects on shade have been observed with “no-cut” buffers ranging from 20 to 30 m (Brosofske et al. 1997, Kiffney et al. 2003, Groom et al. 2011b), and small effects were observed in studies that examined “no-cut” buffers 46 m wide (Science Team Review 2008, Groom et al. 2011a). For “no-cut” buffer widths of 46-69 m, the effects of tree removal on shade and temperature were either not detected or were minimal (Anderson et al. 2007, Science Team Review 2008, Groom et al. 2011a, Groom et al. 2011b) (**Figure 4**). The limited response observed in these studies can be attributed to the lack of trees that were capable of casting a shadow >46 m during most of the day in the summer (Leinenbach 2011; Appendix C of this document). Reductions in shade and increases in stream temperature were more apparent at ~30 m “no-cut” buffer widths, as compared to the 46-69 m wide buffers, but the magnitude and direction of response was highly variable for both shade and stream temperature (Kiffney et al. 2003, Gomi et al. 2006, Science Team Review 2008, Groom et al. 2011a, Groom et al. 2011b). At “no-cut” buffer widths of <20 m, there were pronounced reductions in shade and increases in temperature, as compared to wider buffer widths. The most dramatic effects were observed at the narrowest buffer widths (≤ 10 m) (Jackson et al. 2001, Curry et al. 2002, Kiffney et al. 2003, Gomi et al. 2006, Anderson et al. 2007).

Thinning in riparian buffers adjacent to clearcut harvest units

Reductions in shade and increases in stream temperature were associated with thinning activities occurring within riparian buffers, along with the narrowing of the buffer (Mellina et al. 2002, Macdonald et al. 2003, Wilkerson et al. 2006, Science Team Review 2008, Kreutzweiser et al. 2009) (**Figure 5**). However, the response varied from no effects to large effects which appeared to be related to differences in the intensity of thinning, with stronger effects associated with higher thinning intensities. However, the limited number of studies that have specifically evaluated thinning in riparian buffers makes it difficult to generalize, particularly given the many different possible combinations of thinning intensity and buffer width.

No-cut buffers adjacent to thinning harvest units

The width of the inner “no-cut” riparian buffer was shown to affect the potential consequences of thinning in the “outer” buffer regions, with wider “no-cut” buffers resulting in lower reductions in stream shade conditions (Anderson et al. 2007, Science Team Review 2008, Park et al 2008) (**Table 1**). In addition, the canopy density of the inner “no-cut” buffer zone appeared to have an ameliorating effect on thinning activities within the “outer” thinning buffer zone, with higher “protection” associated with greater canopy densities in the inner zone. Finally, higher residual vegetation densities within the “outer” thinning zone were shown to result in less shade loss. Once again, the limited number of studies that have specifically evaluated these buffer conditions

make it difficult to generalize, particularly given the many different possible combinations of thinning intensity, buffer widths, and stream sizes.

Other associated effects

Secondary effects of thinning in riparian areas can potentially reduce shade and potentially lead to increases in stream temperature. For example, trees that are left after thinning may be vulnerable to blowdown (Chan et al. 2006), which has been shown to decrease shade and increase stream temperatures (MacDonald et al. 2003). Similarly, “no-touch” riparian buffers have also been shown to be vulnerable to windthrow following harvest activities (Jackson et al. 2007), resulting in much lower stream shade conditions (Schuett-Hames et al. 2011). Windthrow effects can be long term. For example, windthrow was shown to impede the “recovery” of stand density (i.e., shade conditions) for over eight years following both “heavy” and “moderate” thinning treatments (Curtis Relative Density [RD] of 8.3 and 16.0, respectively), but recovery was observed over the same period in “lightly” thinned stands (RD of 27.8). Secondary effects of thinning and associated road building on microclimate, sediment loads to the stream, and subsurface drainage patterns adjacent to riparian areas are poorly understood but may influence advective transfer and heat exchange in water that enters the stream as shallow groundwater (Story et al. 2003, Brosofske et al. 1997, Anderson et al. 2007).

Potential downstream effects

The spatial extent to which riparian management affects stream temperature downstream of harvest units depends on the spatial context of the stream reach in terms of hydrology and geomorphology and how these factors interact in the stream heat budget (Poole et al. 2001, Johnson 2003). For example, in stream reaches with cold tributary inflows and groundwater inputs that constitute a large percentage of the stream discharge (i.e., “gaining” reaches), the distance may be short to bring the temperature back down to what it would have been prior to the reduction in shade resulting from the removal of trees (Story et al. 2003). Similarly, reaches with extensive hyporheic exchange (Wondzell 2006, Wondzell 2012) via the streambed and floodplain may show no effects of increased solar radiation on stream temperature (Janisch et al. 2012). In contrast, bedrock-dominated stream channels are likely to require very long recovery distances because they are not buffered by hyporheic exchange (Johnson and Jones 2000). Thus, it is not possible to characterize the exact distance at which thinning activities will affect downstream temperature without accounting for all of the factors that influence stream temperature. However, the rate of heat loss via convection and evaporation at the surface of small streams is very slow, as compared to the heat exchange rate associated with solar radiation loading. Therefore, the heat added to a stream by the sun will not be readily dissipated, and the distance over which elevated temperatures may extend downstream may be much longer than the length of the “treatment”.

Considerations for unstable landforms and existing roads

In riparian areas with unstable landforms and existing roads, precautions are necessary to ensure that enough shade will be available in the event of future landslides that could remove forest vegetation and reduce shade on the stream. Thus, the removal of shade needs to be evaluated on

the basis of how much shade is currently present because further riparian management activities in a “disturbed” stand can have a larger impact on shade conditions than what would be expected from the same level of disturbance in an “undisturbed” stand (Chan et al. 2004b). Disturbed stands that have been subjected to tree removal before thinning activities may already have low canopy density, and hence already provide limited shade. Furthermore, the removal of trees on unstable slopes may lead to increased vulnerability of neighboring trees to windthrow and landslides, which both can lead to reductions in shade and potential increases in stream temperature (Pollock et al. 2009). All kinds of landslides can topple and remove trees and, therefore, have the potential to reduce canopy density and shade (Oregon Department of Geology and Mineral Resources 2008). Debris flows are also of concern because they often remove stream- adjacent trees, alluvium, wood and soil along the debris flow track, creating a wide, shallow and generally featureless bedrock channel. Riparian shade is removed, the growth of future stream-adjacent trees is inhibited because soil is lacking, the cooling effect of hyporheic exchange is minimized because there is no alluvium, and the potential for future accumulations of alluvium is reduced because there is little large wood in the system to retain alluvium, and there are no large riparian trees to provide large wood (Montgomery 1997, Pollock et al. 2009). Depositional areas from debris flows also have the potential to inundate riparian floodplain forests with water and sediment and cause increased tree mortality. Thus, where debris flows and landslides have occurred, the effects on stream temperature may last for centuries.

Although estimates of impacts of thinning near existing roads and unstable landforms need to be conservative to account for potential future losses of shade, it may be very difficult to weigh the advantages and disadvantages of such thinning activities within the broader context of landscape disturbance and its role in aquatic ecosystems (Reeves et al. 1995, Montgomery 1997). For example, landslides and debris flows can reduce shade, but may provide large accumulations of wood and sediment, which can have variable effects on stream geomorphology, depending on the location and condition of the pre-existing habitat where deposition occurs (May and Gresswell 2003). Thus, in the context of landscape management, there are multiple physical effects of landslides and debris flows that need to be considered, and these effects vary with landscape position.

What is not known or uncertain

Extensive research on the effects of forest management on shade and stream temperature provides a foundation for predicting the effects of thinning in riparian areas. However, because the effects of thinning are lesser in magnitude compared to complete removal of riparian vegetation, landscape context (e.g., geology, geomorphology, and hydrology) plays a greater role and can make it more difficult to determine cause and effect (Thompson 2005). Furthermore, thinning may occur at different intensities and in various spatial configurations which may be difficult to model and evaluate experimentally.

There are no examples of studies in the literature on the effects of riparian thinning on stream temperature that match the specific characteristics of management activities likely to occur in riparian areas on federal forest lands. Field studies that can address these challenges may require watershed-scale, long-term manipulative experiments to detect effects over spatial and temporal scales that are relevant to the ecological, hydrological, and geomorphological processes of

interest. However, shorter-term studies that evaluate potential effects of thinning intensity and buffer width on shade and stream temperature can be conducted by substituting space for time (Pickett 1989) in which sites representing a wide range of thinning intensities and buffer widths are examined in relation to the relative amounts of shade that they produce. Although the results of such studies cannot elucidate causal relationships, they would still provide a foundation for evaluating potential downstream cooling distances in riparian areas under various thinning scenarios. These field studies could be designed to test hypotheses about where downstream cooling distances would be expected to be long or short. Recently available technologies such as lidar remote sensing, thermal IR remote sensing, and distributed temperature sensing could be used to better quantify shade and evaluate stream temperature response to various thinning treatments (Lutz et al. 2012, Torgersen et al. 2012).

Spatially explicit models and landscape analysis tools that consider many different factors at multiple spatial and temporal scales may be used to evaluate potential cumulative effects of riparian management scenarios (Cissel et al. 1999, Benda et al. 2007). However, these landscape analysis tools need to be better integrated with stream temperature models (see Allen et al. 2007). Many different models exist for predicting stream temperature response to changes in shade; for descriptions of these models and their relative strengths and weaknesses, see Caissie 2006, Allen et al. 2007, Chapter 2 in Allen 2008, Webb et al. 2008, and Torgersen et al. 2012. The most commonly applied stream temperature model in western Oregon is HeatSource (Boyd and Kasper 2003), which was developed by the Oregon Department of Environmental Quality and the U.S. Environmental Protection Agency. This model has been used effectively to evaluate effects of shade on water temperature in streams of various sizes and types, and it is currently the most accessible stream temperature modeling tool for land managers because of the availability of technical support from government agencies. A limitation of HeatSource and most other stream temperature models is that they require data on the physical and hydrological characteristics of the stream (width, depth, and velocity) which may be difficult to acquire in the field, particularly in forested streams that may be inaccessible due to dense vegetation, steep topography, and a lack of roads.

Another modeling tool that is increasingly used by federal forest managers is NetMap (Benda et al. 2007; www.netmaptools.org). It is important to note, however, that NetMap does not predict stream temperature; it provides information only on spatial variability of thermal loading as a function of shade from trees (based on tree height and buffer width) and/or the surrounding topography. NetMap has immense potential for evaluating the potential effects of riparian thinning on thermal loading across landscapes; however, these predictions may be limited by the data on forest structure (i.e., stem and canopy density) and topography (e.g., digital elevation models) on which the model is based (see Appendix D on the appropriate use of geospatial data and models in resource management). It is possible that tools such as NetMap will provide more precise estimates of thermal loading based on lidar-derived high-resolution measurements of forest structure and topography; however, these datasets are not widely available. Field studies are needed to “ground-truth” NetMap predictions of thermal loading in varied landscape settings and with different spatial scales of forest structure and topographic data (e.g., 1-5-m lidar data versus 10- and 30-m digital elevation models).

Field studies as well as the spatially explicit modeling and landscape analysis tools described above are needed to address the following uncertainties associated with predicting the effects of thinning in riparian areas on shade and stream temperature:

Effects of thinning intensity and “skips and gaps”

The intensity of thinning activities has an impact on the amount of shade produced by the riparian stand. Thinning from “below” (i.e., removing small trees) primarily affects shade quality by increasing the transmission of solar radiation from the side, whereas thinning from “above” by removing large trees that cast long shadows most likely affects both shade quality and duration. Implementing a “skips and gaps” thinning scheme (i.e., leaving patches of undisturbed riparian forest along the stream) may reduce shade conditions and potentially increase stream temperature; however, this scenario may have less of an impact if the cut patches are located farther away from the stream. Additional field studies and spatially explicit modeling in a variety of forest and hydrological settings are needed in this area.

Groundwater and hyporheic exchange

Tools and techniques for measuring the vertical and horizontal structure of forest vegetation and the underlying ground surface are advancing rapidly (e.g., ground-based and airborne lidar), and it is likely that within the next decade, it will be possible to develop highly detailed shade models for entire small watersheds. Such information may solve many of the problems associated with measuring the transmission of solar radiation through the forest to the stream. However, the most significant challenge to predicting the effects of thinning in riparian areas is the lack of information on processes below the water surface and in the floodplain. This problem has been addressed in modeling of stream temperature in larger rivers by using remote sensing of water temperature to identify thermal anomalies associated with groundwater and surface water interactions which then can be incorporated into a spatially explicit stream temperature model (Boyd and Kasper 2003). Unfortunately, airborne remote sensing of water temperature is not possible in small forest streams where dense overhanging vegetation may block the view of the stream. Thus, in these streams, it will be necessary to use in situ methods and hydrologic modeling to quantify thermal heterogeneity in water temperature associated with groundwater inputs and hyporheic exchange. With the recent dramatic improvements in stream temperature sensor technology (e.g., mobile probes and temperature-sensitive fiber-optic cable), it is now possible to quantify thermal heterogeneity in small streams at relatively low cost. These new techniques are capable of mapping stream temperature at a fine spatial resolution (1 m) over several kilometers and can be used to improve the accuracy and precision of (1) models that predict potential effects of riparian thinning on stream temperature and (2) monitoring of water temperature in response to riparian forest management.

Acknowledgments

Comments from S. Wondzell and M. Fitzpatrick on earlier versions of this document greatly improved the clarity and precision of the material presented in this summary. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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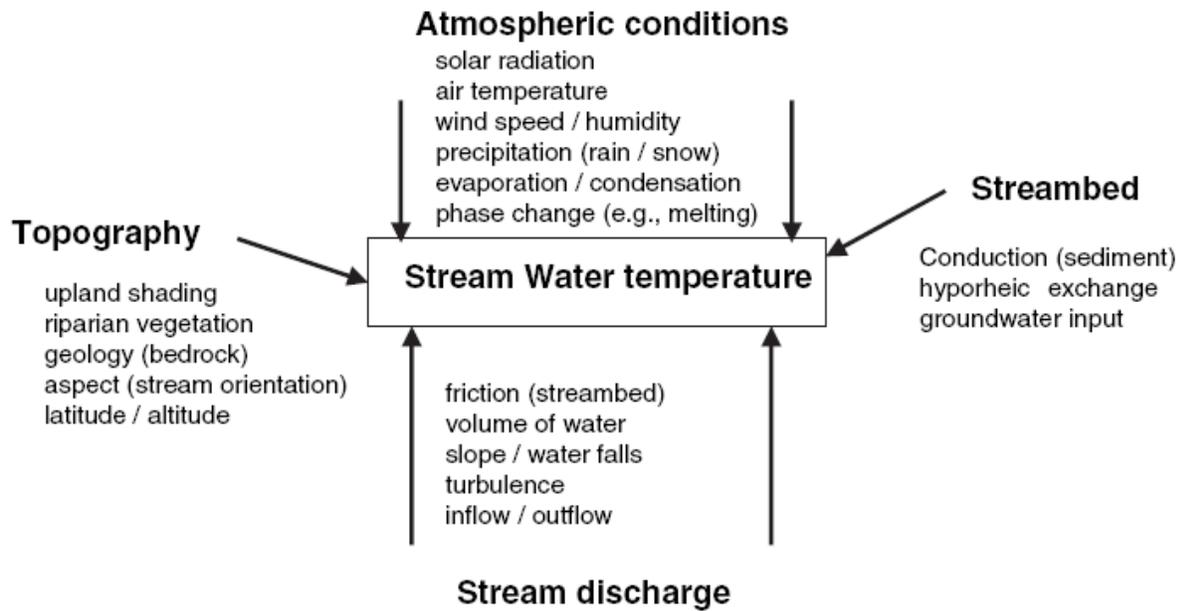


Figure 1. Factors influencing the thermal regime of rivers and streams (Caissie 2006).

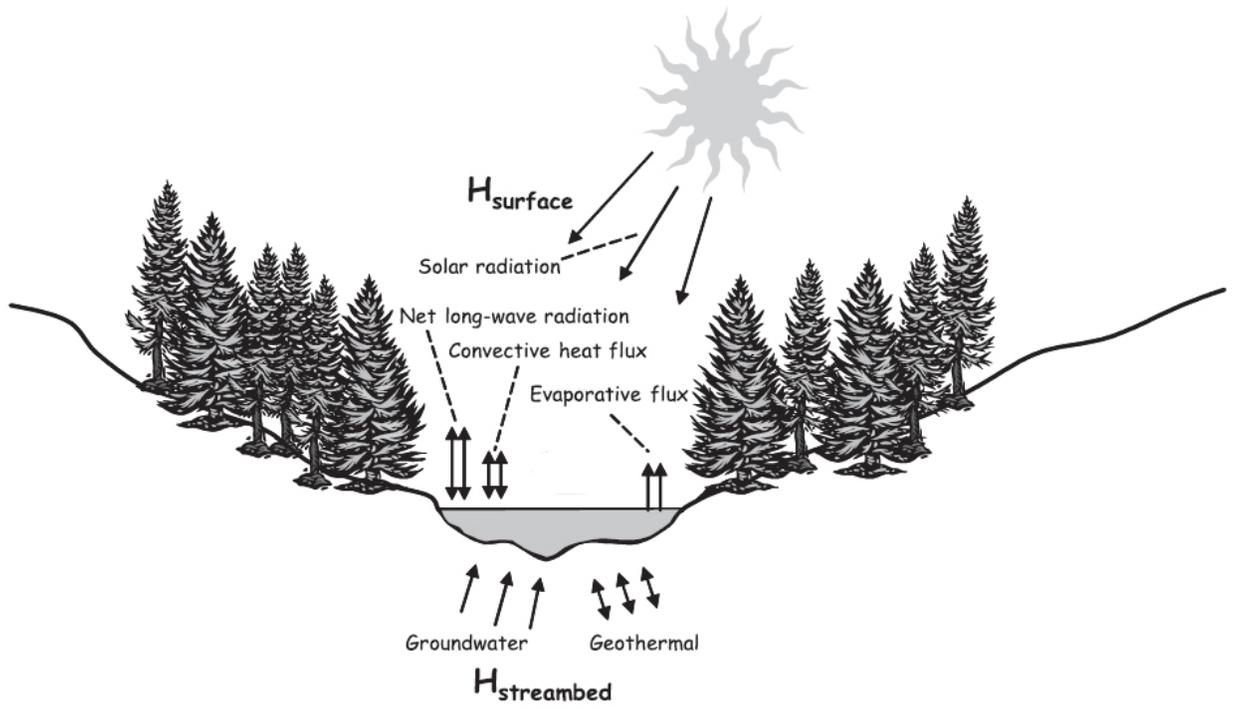


Figure 2. River and stream heat exchange processes (Caissie 2006).

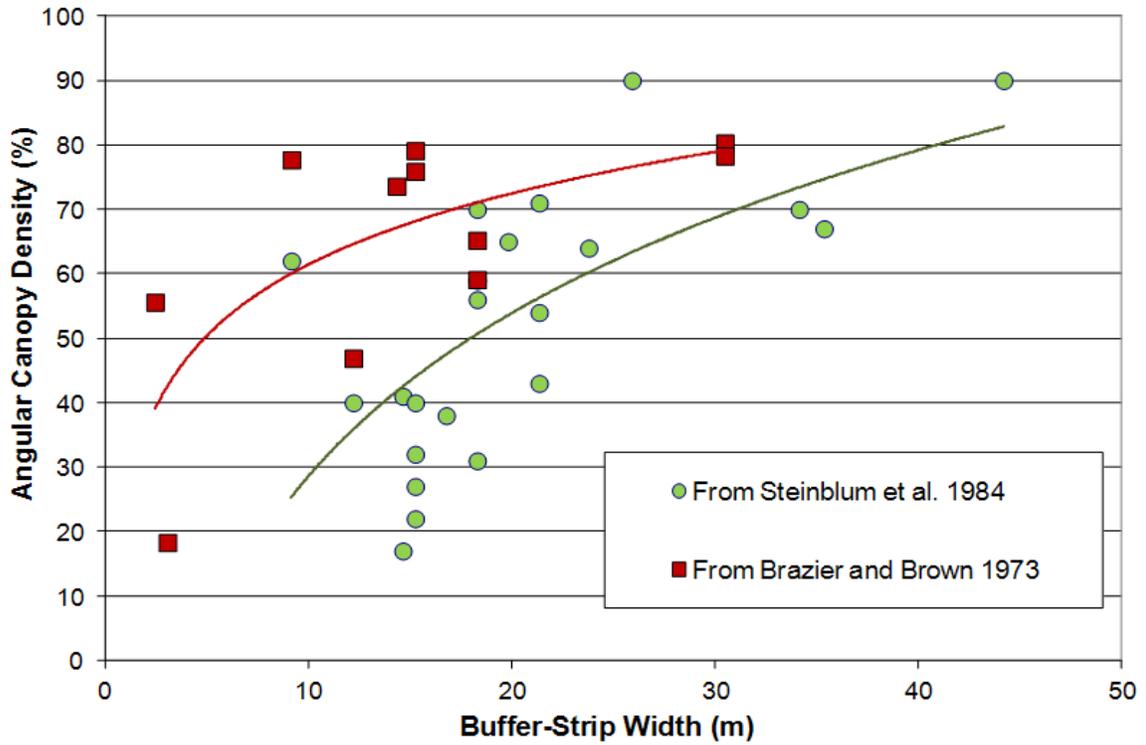


Figure 3. Relationship between angular canopy density (ACD) and riparian buffer width.

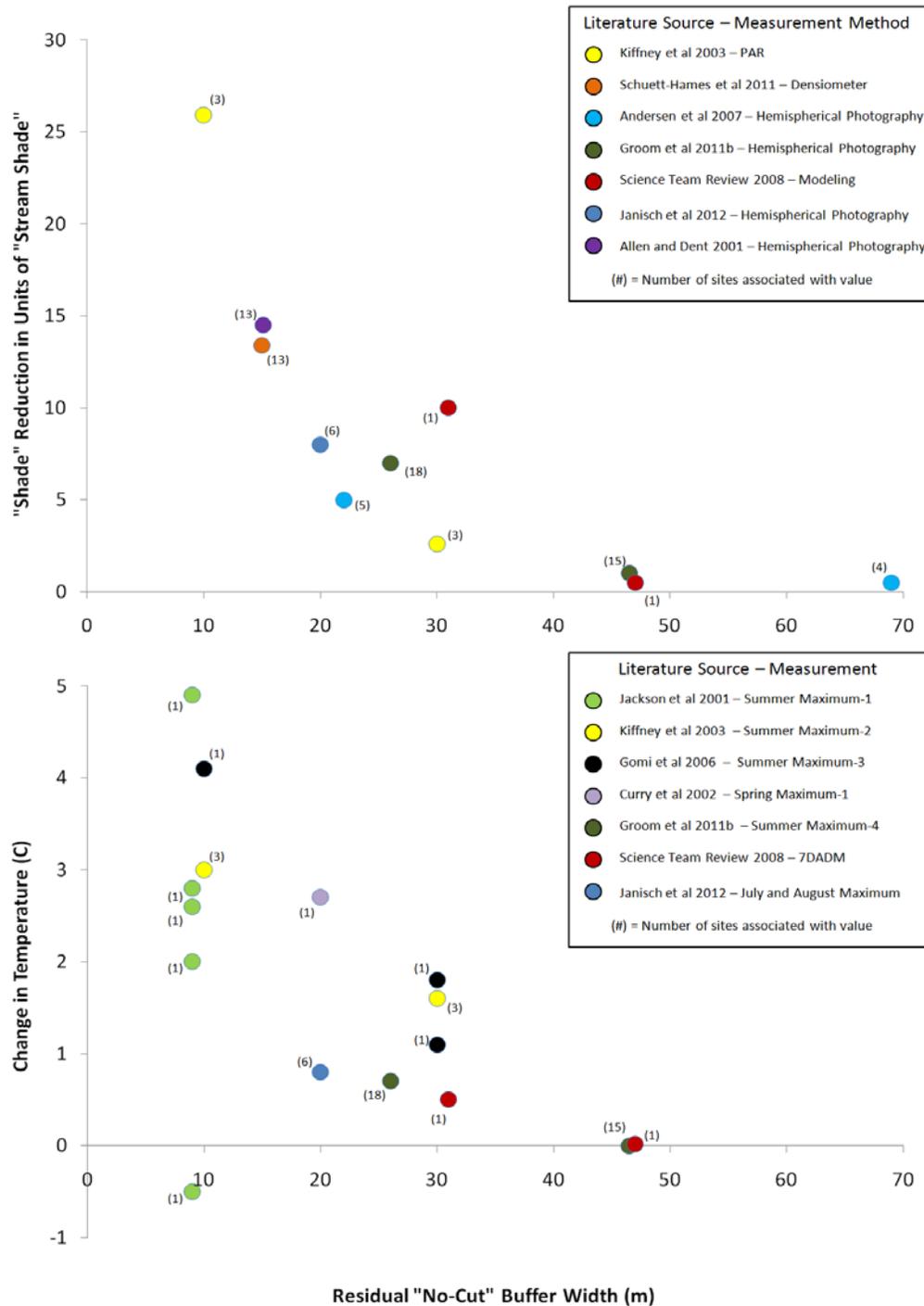


Figure 4. Observed “shade” and temperature response associated with “no-cut” riparian buffers with adjacent clearcut harvest. Note that many of these studies evaluated correlates of shade (e.g, canopy density) as opposed to direct measurements of shade. Corresponding references and measurement methods and types are listed in the legend. Abbreviations: PAR = photosynthetically active radiation; 7DADM = seven-day moving average of daily maximum temperature.

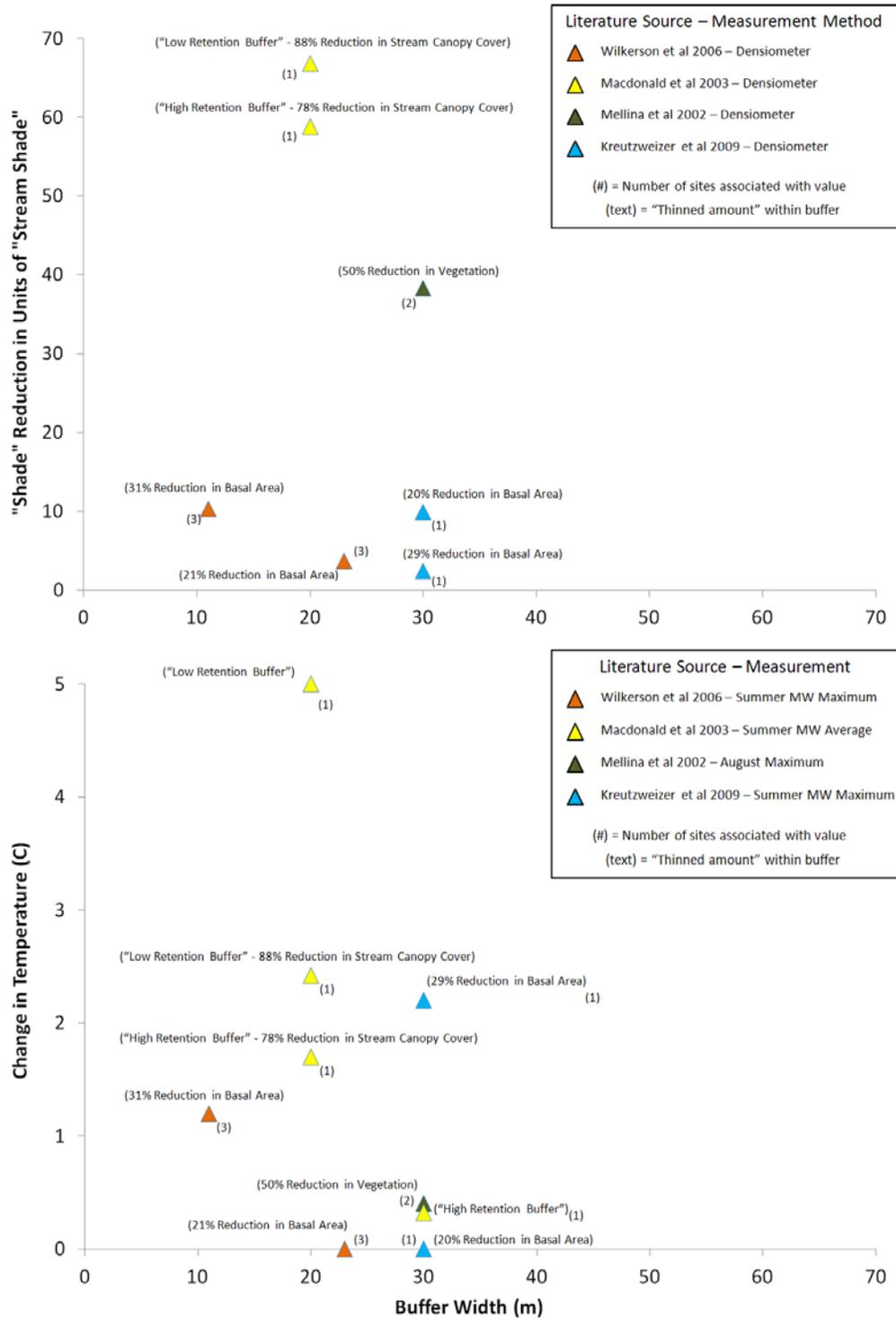


Figure 5. Observed “shade” and temperature response associated with “thinned” riparian buffers with adjacent clearcut harvest. Corresponding references and measurement methods and types are listed in the legend. Abbreviation: MW = mean weekly.

Table 1. Observed shade and temperature response associated with “no-cut” buffers adjacent to “thinned” harvest units.

Total distance (m)	Inner “No-touch” zone distance (m)	Inner “no-touch” zone stand condition	Outer “thinned” zone distance (m)	Thinning target	Resulting units of “shade” reduction	Resulting temperature change (°C)	Number of sites	Source
120	22	500-750 tph	98	198 tph	≈ 2.5% Open Sky	Not Measured	4	Anderson et al. 2007
120	9	500-750 tph	111	198 tph	5% Open Sky	Not Measured	5	Anderson et al. 2007
46	18	65-80% CC	27	50% CC	4 ES	0.2 7DADM	1	ODEQ Memorandum 2008
31	18	65-80% CC	12	50% CC	12 ES	0.6 7DADM	1	Science Team Review 2008
55	24	530 tph	31	321 tph	-0.9 and 0.7 ACD ¹	Not Measured	1	Park et al. 2008
55	18	530 tph	37	321 tph	-0.3 and 0.2 ACD	Not Measured	1	Park et al. 2008
55	12	530 tph	43	321 tph	1.8 and 2.0 ACD	Not Measured	1	Park et al. 2008
55	6	530 tph	49	321 tph	2.9 and 9.3 ACD	Not Measured	1	Park et al. 2008

Abbreviations: tph = trees per hectare; CC = riparian canopy cover (planar view); 7DADM = seven day moving average of daily maximum stream temperature; ACD = angular canopy density.

¹ Harvest activities occurred on only one stream bank in this study (Park et al. 2008), whereas the other studies had harvest activities on both stream banks. Accordingly, a doubling of the “shade” results associated with Park et al. (2008) would allow for a more direct comparison of results with the other studies.

Metric conversions

Meters	Feet	Meters	Feet	Meters	Feet	Meters	Feet
1	3	34	112	67	220	100	328
2	7	35	115	68	223	101	331
3	10	36	118	69	226	102	335
4	13	37	121	70	230	103	338
5	16	38	125	71	233	104	341
6	20	39	128	72	236	105	344
7	23	40	131	73	239	106	348
8	26	41	134	74	243	107	351
9	30	42	138	75	246	108	354
10	33	43	141	76	249	109	358
11	36	44	144	77	253	110	361
12	39	45	148	78	256	111	364
13	43	46	151	79	259	112	367
14	46	47	154	80	262	113	371
15	49	48	157	81	266	114	374
16	52	49	161	82	269	115	377
17	56	50	164	83	272	116	380
18	59	51	167	84	276	117	384
19	62	52	171	85	279	118	387
20	66	53	174	86	282	119	390
21	69	54	177	87	285	120	394
22	72	55	180	88	289	121	397
23	75	56	184	89	292	122	400
24	79	57	187	90	295	123	403
25	82	58	190	91	298	124	407
26	85	59	194	92	302	125	410
27	89	60	197	93	305	126	413
28	92	61	200	94	308	127	417
29	95	62	203	95	312	128	420
30	98	63	207	96	315	129	423
31	102	64	210	97	318	130	426
32	105	65	213	98	321	131	430
33	108	66	216	99	325	132	433