Total Maximum Daily Loads for the Lower Columbia-Sandy Subbasin

Technical Support Document Appendix G: Stream Buffer Width Literature Review

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State of Oregon
DEQ Department of Environmental Quality

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1. Influences on stream temperature

The current theory to explain the nature of heat is called the kinetic-molecular theory. The modern version of this theory was developed in the mid-19th century by Rudolf Clausis, James Clerk Maxwell, and Ludwig Boltzmann. The theory relies on the assumption that all matter is composed of tiny populations of molecules that are always in motion. The molecules in hot objects move faster and hence have greater kinetic energy than the molecules in cold objects. Individual molecules have a certain amount of kinetic energy based on their mass and velocity. The thermal energy of an object is determined by adding up the kinetic energies of all the molecules in that object. When a hot and cold object contact each other, their molecules collide and kinetic energy flows from molecules with more kinetic energy to those with less kinetic energy. This type of kinetic energy flow is called heat.

Temperature is an intensive property and much like concentration measures “strength” of kinetic energy rather than “quantity”. The temperature of an object is the measure of the average kinetic energy of all molecules in that object.

Water temperature change (ΔTw) is a function of the heat transfer in a discrete volume and may be described in terms of changes in heat per unit volume (**Equation 1**). Conversely, a change in volume can result in water temperature change for a fixed amount of heat exchange. With this basic conceptual framework of water temperature change, it is possible to discuss stream temperature change as a function of two variables: heat and mass transfer.

Water Temperature Change as a Function of Heat Exchange and Volume,

$$\Delta Tw = \frac{\Delta Heat}{Density \times Specific\ Heat \times \Delta Volume}$$

Equation 1

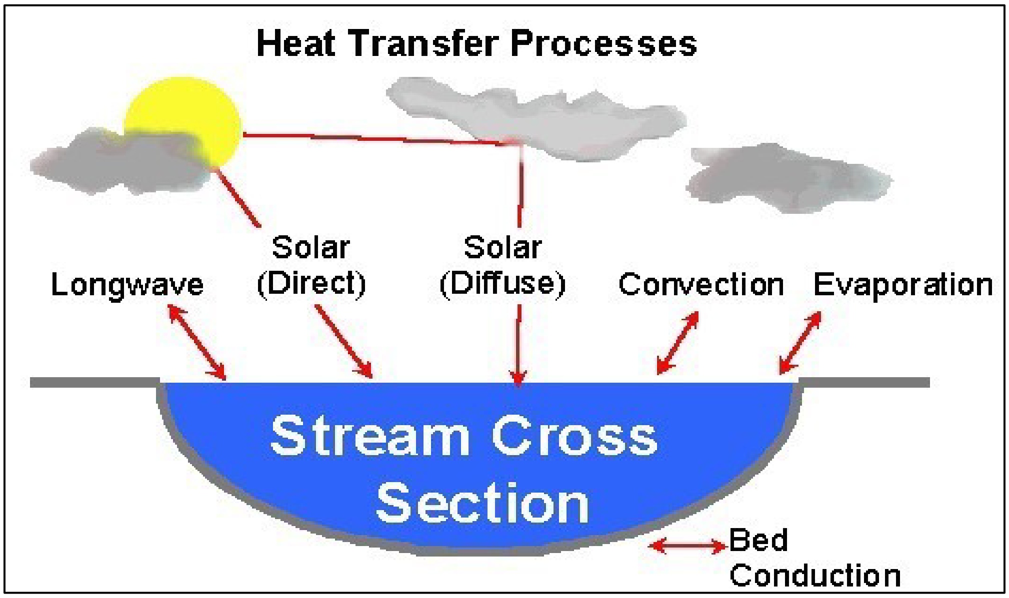

Figure 1-1: Major heat transfer processes.

Heat transfer relates to processes that change heat in a defined water volume. Several thermodynamic pathways may introduce or remove heat from a stream. Their various processes are shown in **Figure 1-1**. For a given stream reach, heat exchange is closely related to the season, time of day, surrounding environment, and stream characteristics. Heat transfer is dynamic and may change over relatively small distances and time periods. **Equation 2** describes the several heat transfer processes that affect stream temperature (Wunderlich, 1972; Jobson and Keefer, 1979; Beschta and Weatherred, 1984; Sinokrot and Stefan, 1993; Boyd, 1996; Johnson, 2004; Hannah et al., 2008; Benyahya et al., 2012).

$$\Phi_{total} = \Phi_{solar} + \Phi_{longwave} + \Phi_{streambed} + \Phi_{convection} + \Phi_{evaporation} \qquad \textbf{Equation 2}$$

Where,
Φ_{total} = Net heat energy flux (+/-)
Φ_{solar} = Shortwave direct and diffuse solar radiation (+ only)
$\Phi_{longwave}$ = Longwave (thermal) radiation (+/-)
$\Phi_{streambed}$ = Streambed conduction (+/-)
$\Phi_{convection}$ = Stream/air convection[1] (+/-)
$\Phi_{evaporation}$ = Evaporation (+/-)

Mass transfer relates to downstream flow volume transport, instream mixing, and the addition or removal of stream water. For example, inflow from a tributary will result in temperature change if the tributary and receiving water temperatures differ. Mass transfer commonly occurs in stream systems due to:

- Advection,
- Dispersion,
- Groundwater exchange,
- Hyporheic flows,
- Surface water exchange (e.g. tributary input, precipitation), and
- Other human related activities that alter stream flow volume.

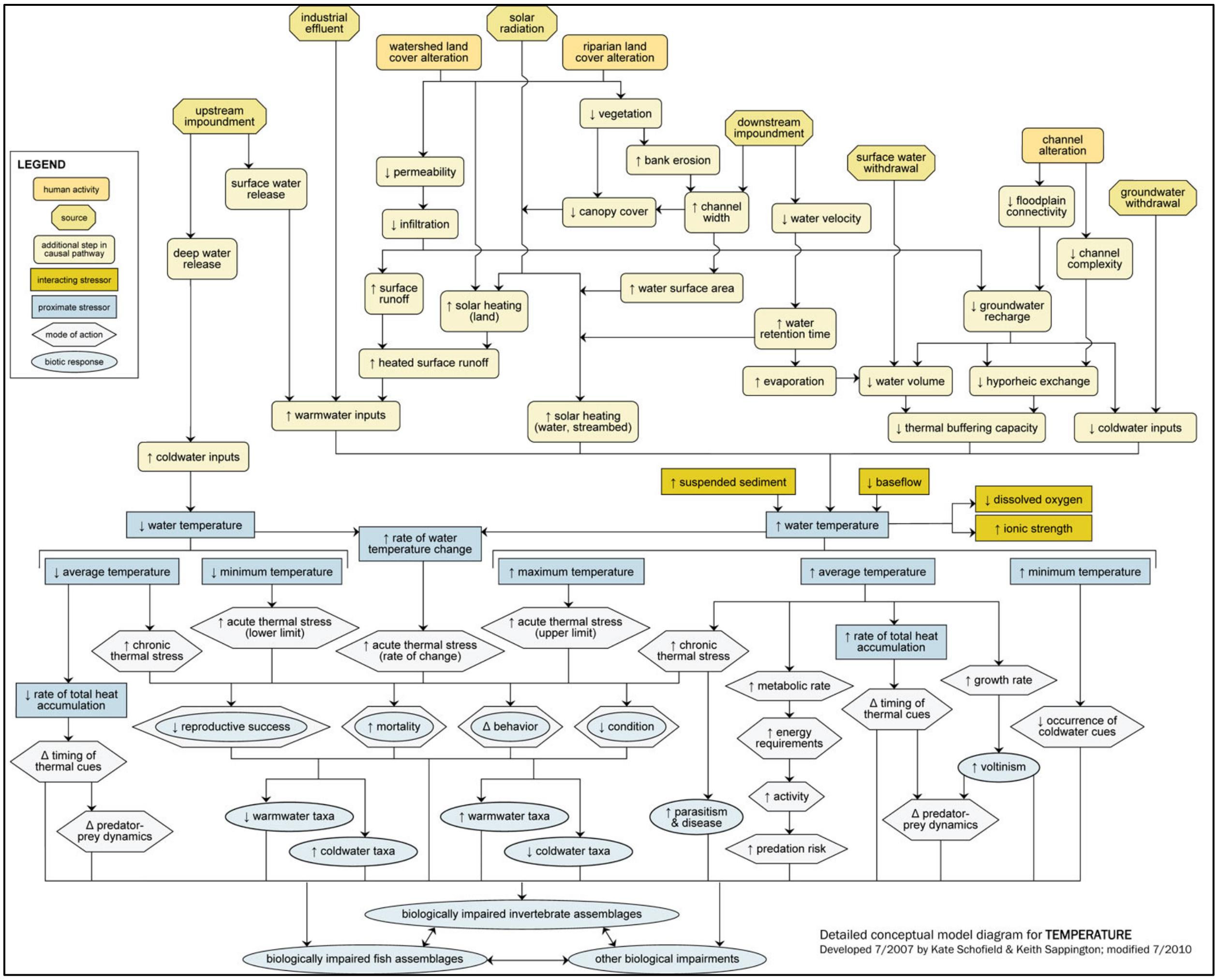

Figure 1-2: Conceptual diagram that identifies the key processes and variables that drive stream temperature changes and the associated biological responses (Schofield and Sappington, 2010).

Stream temperature is influenced by both human and natural factors that occur above the water surface, in the streambed, within the water column, and in the surrounding landscape (Poole and Berman, 2001). **Figure 1-2** is a conceptual diagram developed by Schofield and Sappington (2010) that identifies the key process and variables that drive stream temperature. Human sources and natural sources are identified. Near the bottom of the diagram the biological responses are identified.

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 solar radiation loading to the stream (Moore and Wondzell, 2005). Increased solar radiation is a result of vegetation removal and is generally the dominant component of the energy budget in terms of heat gain (Johnson, 2004; Caissie, 2006).

The magnitude of temperature increases from increased direct solar radiation after the removal of shade depends on the net effect of multiple factors, including the volume and depth of the river, the temperature of the river prior to solar radiation loading, and the amount of groundwater/hyporheic input into the reach (Poole and Berman, 2001; Caissie, 2006; Janisch et al., 2012). Accordingly, stream temperature response to riparian disturbance is often variable in reported literature.

1.1 Impact of riparian buffer width change on stream temperature

ODF (Cowan et al., 2019; Coble et al., 2020), Quinn et al. (2020), and Leinenbach et al. (2013) extracted the temperature response to different riparian buffer width treatments from published articles and reports, including Brazier and Brown (1973), Dent and Walsh (1997), Gomi et al. (2006), Veldhuisen and Couvelier (2006), Volpe (2009), Groom et al. (2011), Janisch et al. (2012), Cole and Newton (2013), and Bladen et al. (2017). This information was provided to DEQ by these sources and subsequently DEQ added additional published results, including Groom et al. (2018), McIntyre et al. (2018), and Ehinger et al. (2021). DEQ combined all the results and plotted the data. These results are presented in **Figure 1-3**. Buffer width, shown on the x-axis, can be reported as a horizontal distance or as a slope distance. Horizontal distance means that the buffer width is applied and measured in the field horizontally, regardless of slope. Slope distance means that the buffer width is applied and measured in the field along the slope within the buffer area. Slope distance will be larger than horizontal distance the steeper the slope. The studies summarized in **Figure 1-3** used a combination of horizontal distance and slope distance to report buffer width. Not all studies reported which method was used. For the studies that did, the majority of sites used slope distance. Buffer widths in **Figure 1-4** are all measured using slope distance.

These figures indicate that there is high observed stream temperature response variability at the individual site level, but the general temperature response trend is similar to that indicated by the Bayesian model in Groom et al. (2018) (**Figure 1-4**). The results of these studies show that stream temperatures increase at a greater rate as the buffer width gets smaller. Of all the studies, Groom et al. (2011) and Groom et al. (2018) had the largest number of study sites (n=33), all located in Western Oregon. Both studies relied upon on the same field data. The data plotted from Groom et al. (2011) are field measured results while the data from Groom et al. (2018) are based on results of a Bayesian model (**Figure 1-4**). Specifically, this Bayesian model describes the expected stream temperature response resulting from the narrowing of the riparian buffer after harvest. The black line indicates the mean response at the 33 sites, the dashed black line and dashed grey line represents a 50% and 95% Credible Interval (CI), respectively. The horizontal grey line indicates a 0.3 °C temperature increase. Based on these results, a slope distance buffer width of 27.4 meters (90 ft) produced mean temperature increase of 0.3 °C. A slope distance buffer width of about 36 meters (120 ft) had no increase in mean temperatures. The results in **Figure 1-3** that include all studies show a similar result at 120 ft.

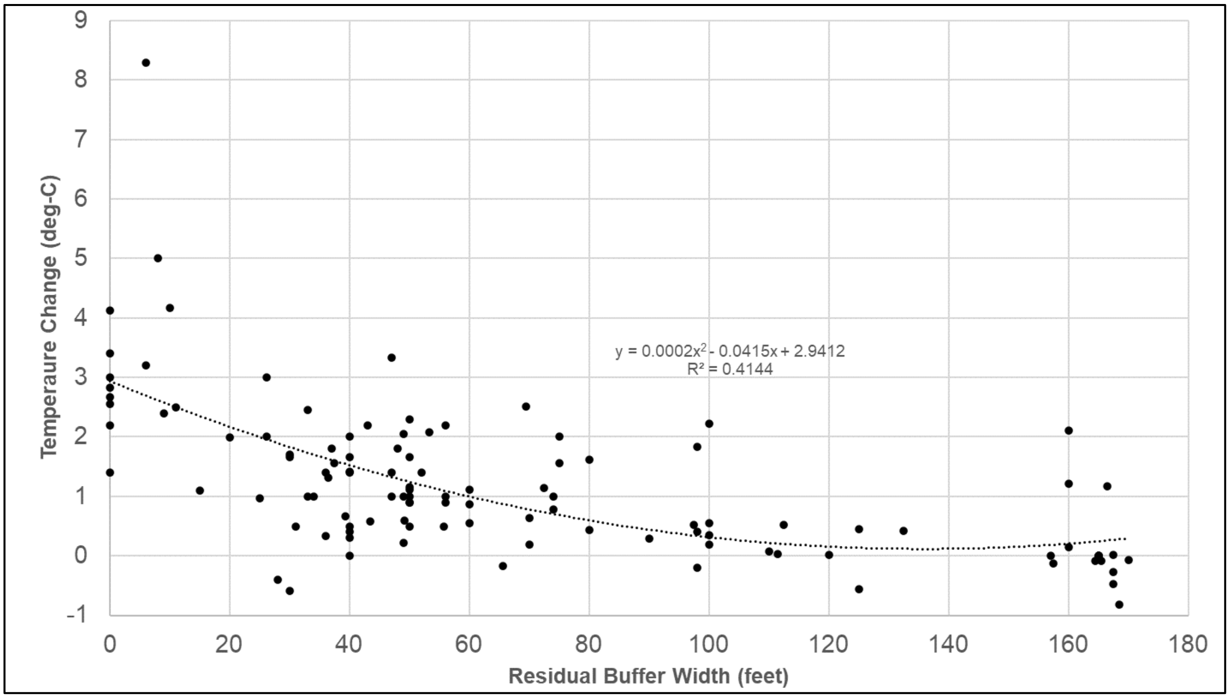

Figure 1-3: Reported stream temperature increase following buffer width narrowing resulting from forest harvest.

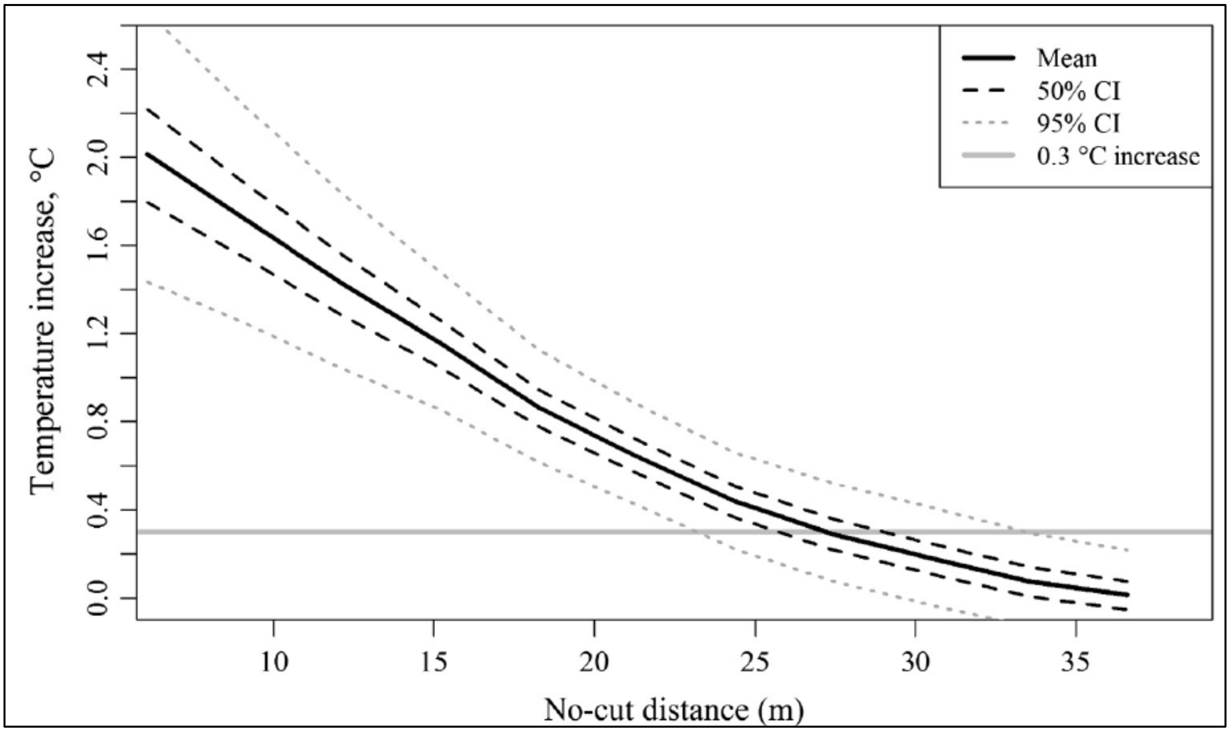

Figure 1-4: Mean temperature responses among all sites to simulated harvest using a slope distance two-sided buffer width (Groom et al., 2018).

1.2 Impact of riparian buffer density change on stream temperature

Roon et al. (2021b) determined that stream temperature response to riparian forest thinning was positively associated with the intensity of thinning treatments, and the downstream propagation of these local responses extended from 100 m to over 1000 m and was dependent on the magnitude of the temperature increase from thinning activities. This study also reported that more intensive thinning resulted in an extended pulse of increased stream temperatures that were transported downstream and attenuated gradually at variable distances. Collectively, they determined that riparian forest thinning influenced downstream thermal conditions to varying extents depending on the intensity, scale, and spatial proximity of treatments.

Leinenbach et al. (2013) presented results of field studies that evaluated stream temperature changes associated with riparian buffer thinning activities, along with the narrowing of the buffer (Mellina et al., 2002; Macdonald et al., 2003; Wilkerson et al., 2006; Kreutzweiser et al., 2009) (**Figure 1-5**). Similar to results of Roon et al. (2021b), the observed temperature response varied from no effects to large increases which appeared to be related to differences in the intensity of thinning, with stronger effects associated with higher thinning intensities, however this observed trend on thinning effects is partially confounded from the situation that these studies also included buffer narrowing harvests. Regardless, these studies indicate that riparian thinning actions can results in increased stream temperature and these effects are dependent on the intensity, scale and spatial proximity of treatments.

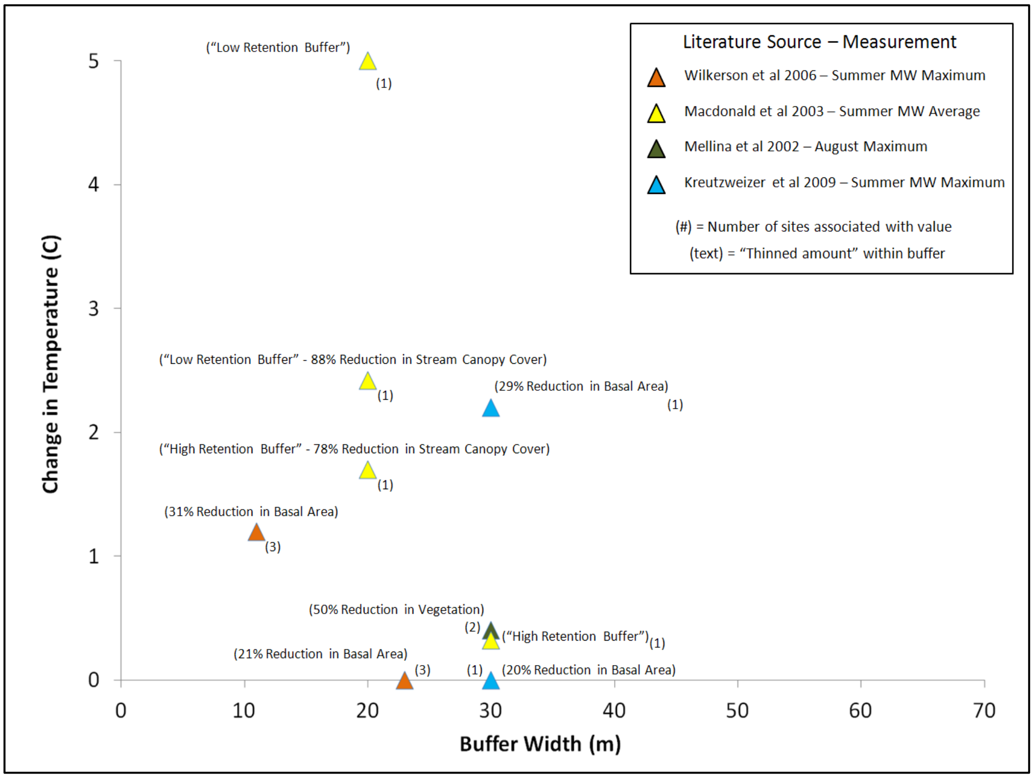

Figure 1-5: Observed temperature response associated with "thinned" riparian buffers with adjacent clearcut harvest. Corresponding references and measurement methods and types are listed in the legend. Abbreviation: MW = mean weekly (Leinenbach et al., 2013).

2. Influences on effective shade

Effective shade is the percent of potential daily solar radiation flux that is blocked by vegetation and topography (Boyd and Kasper, 2003; McIntyre et al., 2018). It is a useful metric to measure for assessment of vegetation change and direct solar radiation. Effective shade can be measured with a solar pathfinder instrument (Solar Pathfinder 2016). The measurement methods and quality control procedures are outlined in the Water Quality Monitoring Technical Guide Book (OWEB, 1999) and the solar pathfinder manual (Solar Pathfinder, 2016). Effective shade can also be measured using hemispherical imagery and analysis software. Methods for use of hemispherical imagery and analysis software are described in WADOE (2019a), and WADOE (2019b).

Physical and ecological factors affecting effective shade include, vegetation height, vegetation buffer width, vegetation density, stream width, topographic elevation, stream aspect, cloudiness, and latitude. The latter four factors are generally not influenced by human activity. This review focuses on the factors that can be influenced by human activity.

The response of shade to vegetation removal will depend on the interaction of vegetation height, density, and buffer width. Generally, vegetation cover and shade is negatively correlated with riparian vegetation removal. The amount of stream shade produced by riparian vegetation is a function of three characteristics of the “shade”: (1) shade extent; (2) shade duration; and (3) shade quality. Shade extent is the spatial area over which a shadow is cast over a stream. Shade duration is the length of time during which a portion of stream is shaded. Shade quality is the density of the shade produced by the vegetation.

The removal or modification of trees in riparian areas can affect the spatial extent, duration, and quality of shade on a stream. In particular, the extent and duration of stream shade associated with riparian vegetation is dependent on: (1) the tree height; and (2) the stream channel width, while the shade quality is primarily dependent on: (1) vegetation buffer width (i.e., the path-length of the sun rays traveling through the riparian stand); and (2) the canopy density of trees within the riparian stand that the sun passes through (i.e., as indicated by angular canopy density).

Vegetation height has influence on stream shade because it affects the length of the shadow produced by the vegetation (Cristea and Janisch, 2007; DeWalle, 2008; DeWalle, 2010; Li et al., 2012) and therefore taller trees will be able cast a shadow on a stream in locations further away from the stream than shorter trees. In addition, vegetation density and vegetation buffer width is positively corelated with increased attenuation of solar radiation traveling through the canopy resulting in higher stream shade (DeWalle, 2008; DeWalle, 2010; Groom et al., 2011; Garner et al., 2014; Groom et al., 2018; McIntyre et al., 2018; Ehinger et al., 2021). Allen and Dent (2001) found that important variables in predicting stream shade were a combination of basal area, stand density (trees/acre), species composition, average stand diameter, and live crown ratios and the interaction between stand structure and aspect. Groom et al. (2011) determined that stream shade was best predicted by riparian basal area and tree height, and reported that sites with higher stocking levels, wider uncut buffers, or fewer stream banks harvested had greater basal area and higher stream shade levels.

In practice, field and modeling studies have shown that the response of shade change to vegetation removal will depend on the interaction of vegetation height (Allen and Dent, 2001; DeWalle, 2008; DeWalle, 2010; Groom et al., 2011), vegetation density (Allen and Dent, 2001;

Sridhar et al., 2004; Cristea and Janisch, 2007; DeWalle, 2010; Groom et al., 2011; McIntyre et al., 2018; Roon et al., 2021a; Ehinger et al., 2021), and vegetation buffer width (Cristea and Janisch, 2007; DeWalle, 2010; Janisch et al., 2012; Groom et al., 2018; McIntyre et al., 2018; Ehinger et al., 2021). Generally, these studies indicate that shade loss is positively correlated with riparian vegetation removal/disturbance and the response is an interaction between changes in vegetation height, vegetation density and buffer width.

1.3 Impact of riparian buffer width change on stream shade

Quinn et al. (2020) and Leinenbach et al. (2013) extracted the shade response to different riparian buffer width treatments from published articles and reports, including Allen and Dent (2001), Janisch et al. (2012), Groom et al. (2015) – published in Groom et al. (2018), Bladen et al. (2017), and Shuett-Hames et al. (2012). This information was provided to DEQ by these sources and subsequently DEQ added additional published results, including Groom et al. (2011), McIntyre et al. (2018), Ehinger et al. (2021), and Reiter et al. (2020). DEQ combined all the results and plotted the data shown in **Figure 2-2**.

The data summarized by Quinn et al. (2020) and Leinenbach et al. (2013) are presented in **Figure 2-1**. This plot summarizes the reported stream shade loss caused by riparian buffer width narrowing following harvest activities, as reported in model and field study documents and literature. This figure indicates that shade loss occurs at higher rates at narrower buffer width conditions, and that a lower rate of shade loss occurs when the retained buffer widths were greater than 110 ft.

Through implementing a BACI[1] study at 33 forested sites in Western Oregon, Groom et al. (2011) determined that stream temperatures increased following harvest activities when stream effective shade changes were greater than 6 percentage points (i.e., 6%), otherwise stream temperatures directionality fluctuated (i.e., no apparent temperature increase). As can be observed in **Figure 2-1** and **Figure 2-2**, stream shade loss was below 6 percentage points at buffer widths greater than 120 ft, indicating that stream temperature increases resulting from harvesting outside of 120 ft might not result in stream temperature increases.

Buffer width can be reported as a horizontal distance or as a slope distance. Horizontal distance means that the buffer width is applied and measured in the field horizontally, regardless of slope. Slope distance means that the buffer width is applied and measured in the field along the slope of the riparian area. When buffer widths are reported using horizontal distance, as the slope increases, the effective width (i.e. distance along the slope) of the conservation area in the field also increases. The studies summarized in **Figure 2-1** and **Figure 2-2** used a combination of horizontal distance and slope distance to report buffer width.

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[1] Before After Control Impact

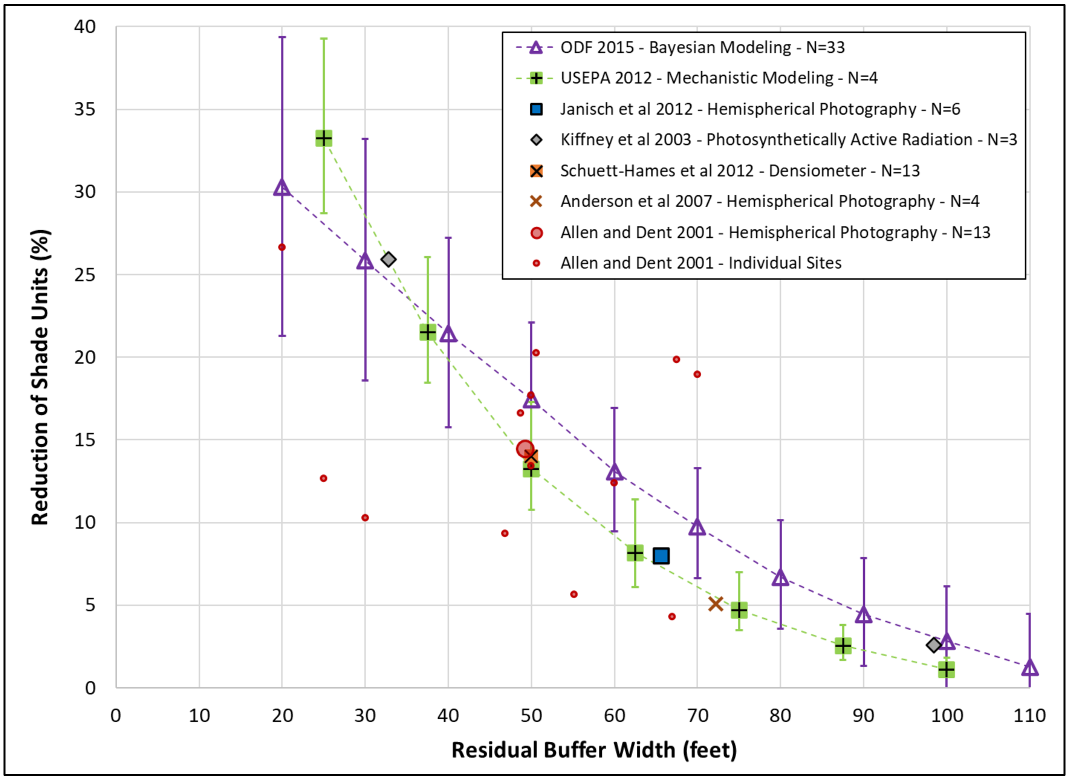

Figure 2-1: Average observed shade associated with "no-cut" riparian buffers with adjacent clearcut harvest (Obtained from Quinn et al., 2020, Page 91).

[Only field studies that employed a Before-After-Control-Impact design and conducted in Pacific Northwest forests are included and Bayesian modeling results (and 90% credible intervals) presented in this figure were derived from data collected as part of Groom et al. (2011).]

Using many of the same studies presented in **Figure 2-1**, along with several more recent studies, **Figure 2-2** illustrates the relationship between buffer width and stream shade loss at the individual sites within each of these studies (Allen and Dent, 2001; Groom et al., 2011; Shuett-Hames et al., 2012; Bladon et al., 2017; Groom et al., 2018; McIntyre et al., 2018; Reiter et al., 2020; Ehinger et al., 2021). This figure illustrates that a range of stream shade loss can occur from narrowing of the riparian vegetation buffer width, which is likely due to interacting effects of multiple factors that vary between the individual sites in each study which subsequently impact stream shade production (i.e., Differences in stream aspect, riparian canopy density, topography, channel width, tree height at the various sites included in each of these studies). Regardless of this increased variability, the same general pattern is observed between **Figure 2-2** and **Figure 2-1**: Limited shade loss at buffer widths greater than 110 ft and shade loss increases dramatically as the buffer width narrows less than 70 ft.

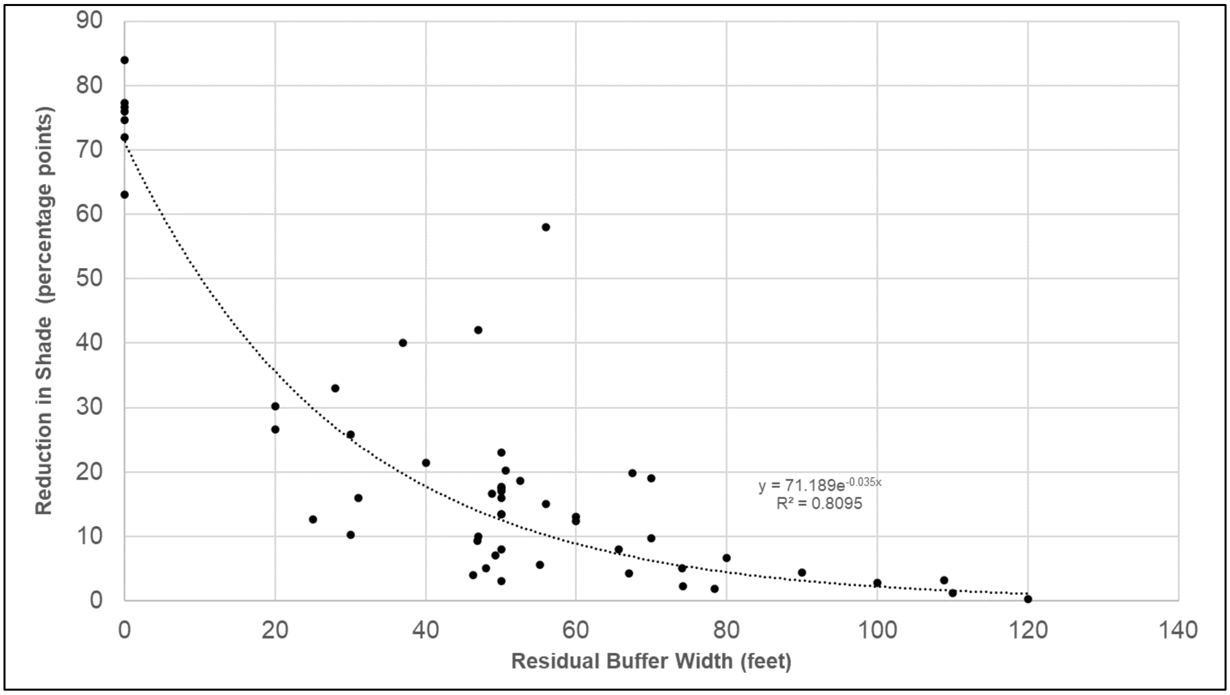

Figure 2-2: Observed stream shade loss at the individual sites associated with "no-cut" riparian buffers with adjacent clearcut harvest.

Barnowe-Meyer et al. (2021) presented the results of a Bayesian model assessing the relationship between horizontal distance buffer width reductions and stream shade loss in Oregon streams (**Figure 2-3**). The plot shows the mean response (black line), and 90% and 95% credible intervals indicated by the colored zones, respectively. Barnowe-Meyer et al. (2021) utilized the same data and approach presented in Groom et al. (2018) but with buffer widths measured using horizontal distance. The results indicate that an approximately 110 ft horizontal distance buffer width is required to ensure mean stream shade loss does not occur. Groom et al. (2018) calculated but did not present in the published article a plot similar to that shown in Barnowe-Meyer et al. (2021) relating slope distance buffer width to shade loss. The authors did provide the results to DEQ and they were incorporated into the plot shown in **Figure 2-2**. As shown in **Figure 2-2**, using slope distance, a 120 ft buffer width corresponds to no mean shade loss. On a similar note, Cristea and Janisch (2007) reported that reference shade conditions were associated with a 120 ft buffer width.

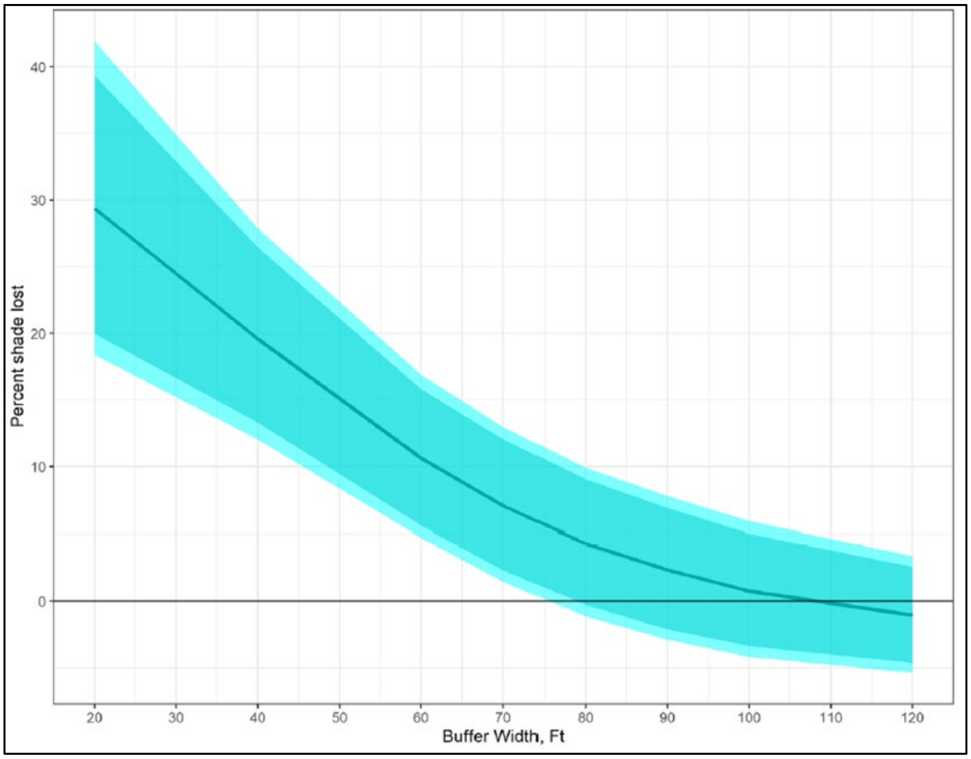

Figure 2-3: Predicted relationship between two-sided horizontal distance buffer width and percent shade lost post-harvest based on the data and analysis approach of Groom et al. (2018). (Figure from Barnowe-Meyer et al., 2021).

These reported relationships between riparian buffer width and stream shade conditions presented above are not unexpected based on how shadow length from a tree is derived. Specifically, the distance of a shadow cast by a tree can be estimated by the following trigonometric equation[2]:

$$Shadow\ Length = \frac{Tree\ Height * \cos(Hillslope\ Angle)}{\tan(Sun\ Angle - Hillslope\ Angle)} - Tree\ Height * \sin(Hillslope\ Angle)$$

Using this equation on a TMDL representative 100 ft tall riparian vegetation condition, it can be determined that the shadow length associated with this tree height condition are at least 120 ft during periods of the day (**Table 2-1**). Although most of the period when a ≥ 120 ft shadow length occurs is when the sun intensity is low (i.e., during early morning and late afternoon hours), these results indicate that some stream shade contributions from the “tall” trees located outside of 100 ft from the stream channel is still possible. In addition, the application of this equation indicated that the shadow length increases as the riparian zone hillslope increases. These results indicate that it would be expected that trees at TMDL targeted height conditions located 100 ft to 120 ft from the stream *could have some impact* on stream shade condition and this result was observed in **Figure 2-1**, **Figure 2-2**, and **Figure 2-3**.

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[2] See Attachment A below for the derivation of this equation.

Table 2-1: Average July 21st and August 21st shadow length (ft) at different times and hillslopes.

Height of Tree (feet)	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm
Flat Hillslope (0°)										
100	181	123	88	67	57	60	74	100	142	217
20° Hillslope										
100	599	239	140	95	78	82	109	169	321	1669

In summary, results presented above indicate that the exact amount of "shade" produced by the particular buffer condition (including the width of the buffer) depends on many attributes associated with the riparian stand being evaluated (i.e., channel width, stream aspect, season (i.e., height of the sun's arc), topography, vegetation height and density). Accordingly, a range of stream shade responses were reported in the field and modeling studies presented above, however these studies also clearly showed that higher stream shade loss was observed at narrower buffer width conditions (i.e., < 60 ft), as compared to wider buffer width conditions (i.e., >100 ft). No decrease in effective shade was observed at buffer distances of 120 ft.

1.4 Impact of riparian buffer density change on stream shade

Thinning riparian buffer vegetation from "below" (i.e., removing small trees) will primarily affect stream shade quality by increasing the transmission of solar radiation through the buffer, whereas thinning from "above" (i.e., removing large/taller trees that cast long shadows) most likely affects both stream shade quality and stream shade duration that is produced by the riparian stand.

Unfortunately, relatively few studies have directly examined the effects of riparian thinning on stream shade conditions, but several studies can give insight into this relationship and are presented below.

Chan et al. (2006) showed that a "light" forest thinning (i.e., 103 trees per acre (TPA)) resulted in limited loss of canopy cover opening (i.e., 12%) and reported that openings mostly recovered to near pretreatment levels 6 years after thinning treatment, while moderate (i.e., 56 TPA) and heavy (i.e., 29 TPA) thinning resulted in much higher levels of canopy opening (i.e., 27% and 42%, respectively) and this impact did not return back to pretreatment levels at eight years following treatment. In addition, this study showed that canopy opening response to various thinning intensities was not a linear response, with higher stream shade loss response observed when tree removal occurs at lower canopy densities. Results of this study, along with results with two similar studies, are illustrated in **Figure 2-4**.

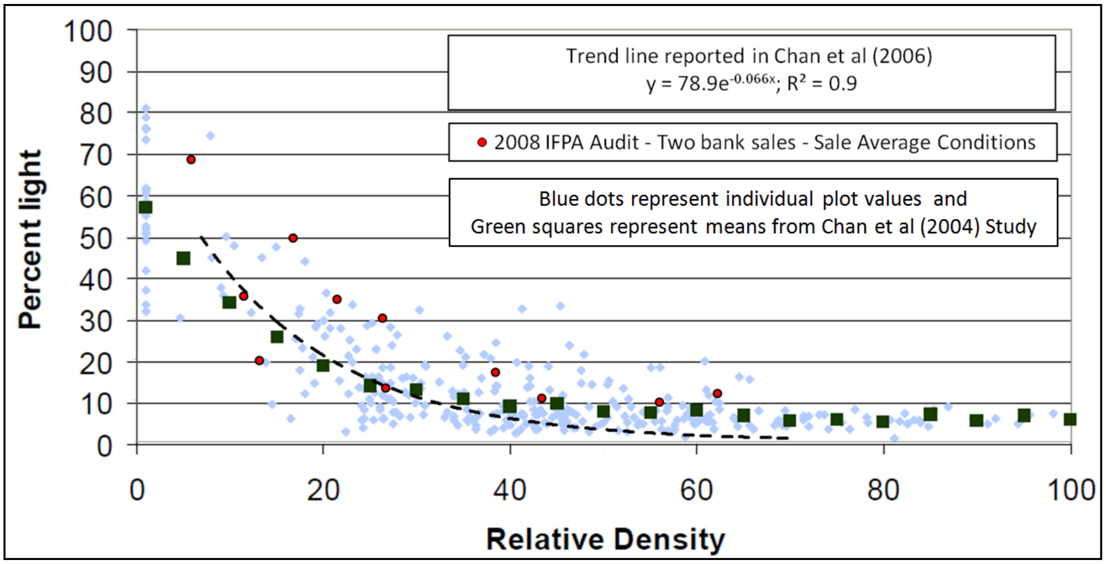

Figure 2-4: The association between relative density and percent skylight in forest stands.

The potential impacts of riparian thinning on stream shade were evaluated as part of the BLM Western Oregon EIS (BLM, 2015) (**Table 2-2**). During this assessment it was determined that minimal shade loss[3] resulting from proposed riparian forest thinning was a function of 1) the width of an “inner no-harvest” buffer, 2) the density of the “inner no-harvest” buffer, and 3) the amount of vegetation retained in the “outer thinned” buffer zone. For example, they reported that a 60 ft wide “inner no-harvest” buffer was required when riparian pre-thinning canopy cover density conditions were ≥ 80%, and that thinning levels within the “outer thinning treatment” buffer zone needed to maintain above 50% canopy cover conditions following thinning activities[4].

Other thinning buffer configurations were modeled as part of this EIS evaluation (USEPA, 2014) but were not presented in the final EIS. For example, a 40 ft wide “inner no-harvest” buffer resulted in excessive stream shade loss at all initial canopy cover densities and modeled thinning levels (i.e., initial canopy cover conditions of 80%, 60%, and 40% thinned to 70%, 50%, 30%) (**Table 2-3**). This effort also showed that thinning outside of an 80 ft wide “inner no-harvest” zone at high initial canopy cover conditions (i.e., 80%) did not result in shade loss levels greater than a targeted change threshold used in the assessment (i.e., ≤ 3%), but values were above this threshold when initial canopy cover levels were moderate (i.e., 60%) or low (i.e., 40%) (**Table 2-4**). Finally, thinning outside of a 100 ft wide “inner no-harvest” zone at high and moderate initial canopy cover conditions did not result in shade loss levels greater than the targeted change threshold used in the assessment (i.e., ≤ 3%) (**Table 2-5**). Groom et al 2011 determined that stream temperatures increased following harvest activities when stream effective shade changes were greater than 6 percentage points (i.e., 6%), otherwise stream

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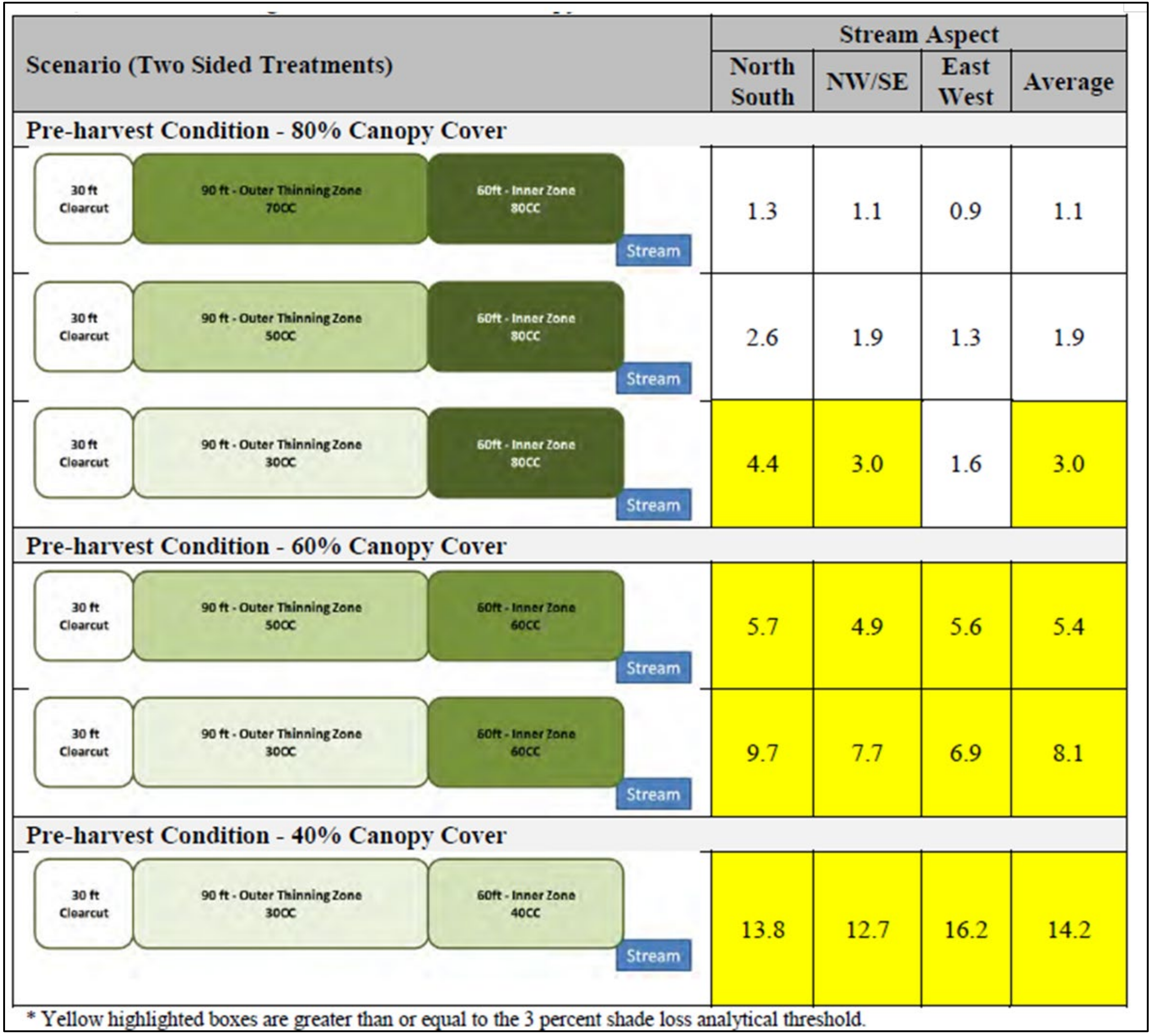
[3] Groom et al. (2011) determined that measurable stream temperature increases (i.e., >0.3°C) were observed when stream shade levels dropped by 6% following riparian harvest activities, and the BLM utilized a 50% margin of safety to estimate a potential non-deleterious shade loss threshold (i.e., 6% * 0.5 = 3%)

[4] In this BLM assessment, the combined width of the “inner no-harvest” and “outer thinned” buffer zones were set at 150 ft (i.e., site potential tree height), however as described in the text at the beginning of this Appendix, this combined distance would likely would have had similar results as observed with a 120 ft combined buffer width.

temperatures directionality fluctuated (i.e., no apparent temperature increase). Accordingly, these shade modeling results indicate that maintaining a sufficiently wide “inner no-harvest zone”, as well as limit the amount of vegetation removal within the “outer thinned” buffer zone, will ensure protection of stream temperature increases from harvest activities.

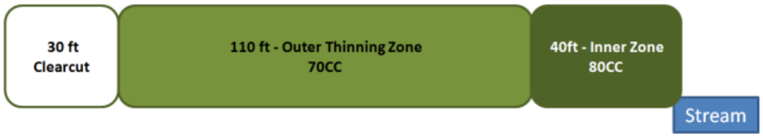
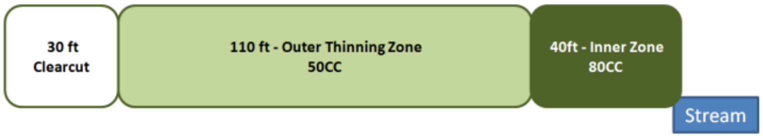
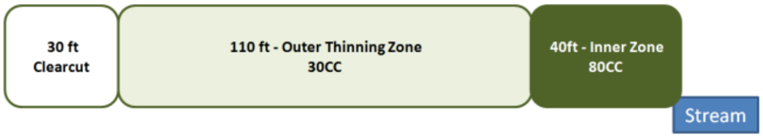
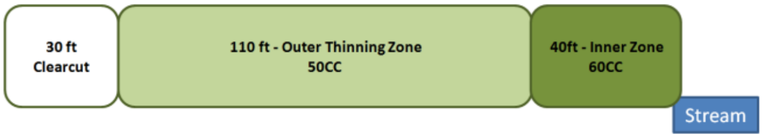
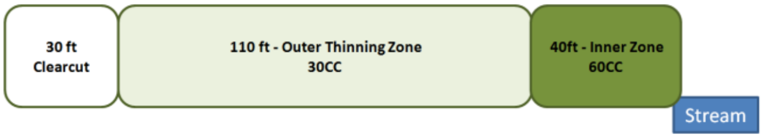
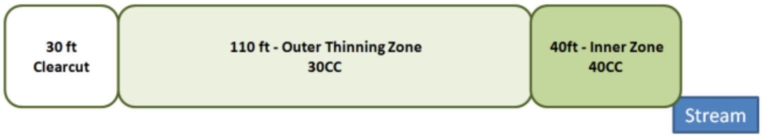
Table 2-2: Modeled percentage point shade loss for a 150 ft wide Riparian Reserve, with a 60 ft inner no harvest zone at various thinning intensities and initial canopy conditions (Source: BLM, 2014, U.S. EPA. 2014).



Scenario (Two Sided Treatments)	Stream Aspect			
	North South	NW/SE	East West	Average
Pre-harvest Condition - 80% Canopy Cover				
30 ft Clearcut 90 ft - Outer Thinning Zone 70CC 60ft - Inner Zone 80CC Stream	1.3	1.1	0.9	1.1
30 ft Clearcut 90 ft - Outer Thinning Zone 50CC 60ft - Inner Zone 80CC Stream	2.6	1.9	1.3	1.9
30 ft Clearcut 90 ft - Outer Thinning Zone 30CC 60ft - Inner Zone 80CC Stream	4.4	3.0	1.6	3.0
Pre-harvest Condition - 60% Canopy Cover				
30 ft Clearcut 90 ft - Outer Thinning Zone 50CC 60ft - Inner Zone 60CC Stream	5.7	4.9	5.6	5.4
30 ft Clearcut 90 ft - Outer Thinning Zone 30CC 60ft - Inner Zone 60CC Stream	9.7	7.7	6.9	8.1
Pre-harvest Condition - 40% Canopy Cover				
30 ft Clearcut 90 ft - Outer Thinning Zone 30CC 60ft - Inner Zone 40CC Stream	13.8	12.7	16.2	14.2

* Yellow highlighted boxes are greater than or equal to the 3 percent shade loss analytical threshold.

Table 2-3: Modeled percentage point shade loss for a 180 ft wide riparian buffer narrowed to 150 ft with a 40 ft Inner “non-thinned” buffer at various thinning intensities and initial canopy cover conditions[5] (Source: USEPA, 2014).

Scenario (Two Sided Treatments)	Stream Aspect			
	North South	NW/SE	East West	Average
Pre-harvest Condition - 80% Canopy Cover				
30 ft Clearcut 110 ft - Outer Thinning Zone 70CC 40ft - Inner Zone 80CC Stream	5.3	4.9	3.3	4.5
30 ft Clearcut 110 ft - Outer Thinning Zone 50CC 40ft - Inner Zone 80CC Stream	7.6	6.5	4.6	6.2
30 ft Clearcut 110 ft - Outer Thinning Zone 30CC 40ft - Inner Zone 80CC Stream	11.0	8.9	6.1	8.6
Pre-harvest Condition - 60% Canopy Cover				
30 ft Clearcut 110 ft - Outer Thinning Zone 50CC 40ft - Inner Zone 60CC Stream	14.3	13.2	12.2	13.3
30 ft Clearcut 110 ft - Outer Thinning Zone 30CC 40ft - Inner Zone 60CC Stream	19.2	16.7	14.8	16.9
Pre-harvest Condition - 40% Canopy Cover				
30 ft Clearcut 110 ft - Outer Thinning Zone 30CC 40ft - Inner Zone 40CC Stream	26.6	25.4	27.6	26.5

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[5] Average shade loss for 1 to 10 meter wide stream channels and highlighted values indicate levels greater than the targeted change threshold used in the assessment (i.e., ≤ 3%).

Table 2-4: Modeled percentage point shade loss for a 180 ft wide riparian buffer narrowed to 150 ft with an 80 ft Inner "non-thinned" buffer at various thinning intensities and initial canopy cover conditions (Source: USEPA 2014).

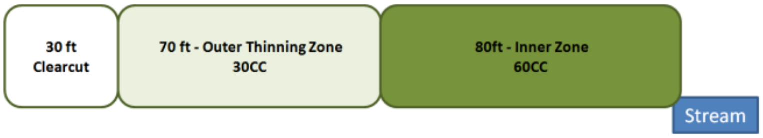
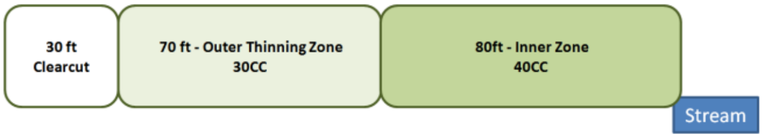
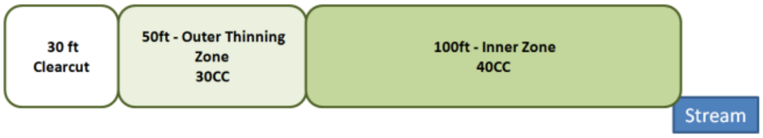
Scenario (Two Sided Treatments)	Stream Aspect			
	North South	NW/SE	East West	Average
Pre-harvest Condition - 80% Canopy Cover				
	0.8	0.6	0.3	0.6
	1.3	0.9	0.3	0.8
	2.2	1.4	0.5	1.4
Pre-harvest Condition - 60% Canopy Cover				
	4.2	3.5	3.0	3.6
	7.7	5.5	3.3	5.5
Pre-harvest Condition - 40% Canopy Cover				
	11.7	10.5	11.5	11.3

Table 2-5: Modeled percentage point shade loss for a 180 ft wide riparian buffer narrowed to 150 ft with a 100 ft Inner “non-thinned” buffer at various thinning intensities and initial canopy cover conditions (Source: USEPA 2014).

Scenario (Two Sided Treatments)	Stream Aspect			
	North South	NW/SE	East West	Average
Pre-harvest Condition - 80% Canopy Cover				
	0.4	0.2	0.1	0.2
	0.7	0.4	0.1	0.4
	1.1	0.6	0.1	0.6
Pre-harvest Condition - 60% Canopy Cover				
	2.3	1.7	1.4	1.8
	3.8	2.6	1.6	2.7
Pre-harvest Condition - 40% Canopy Cover				
	7.3	6.1	7.1	6.9

3. Summary

The studies presented in this literature review agree that riparian buffer width is an important factor for stream shade and temperature. Many studies demonstrated that a lower rate of shade loss occurs when the retained buffer widths were greater than 110 ft. One study (Cristea and Janisch, 2007) reported that reference shade conditions were associated with a 120 ft buffer width. Groom et al. (2018) and Barnowe-Meyer et al. (2021) developed a Bayesian model assessing the relationship between buffer width reductions and stream shade loss in Oregon streams. Their results indicated that a slope distances buffer width of 120 ft (110 ft horizontal distance) is required to ensure mean stream shade loss does not occur. When the reported stream temperature increase following buffer width narrowing was compared across all studies, it was found that a 120 ft buffer width is required to ensure that no stream warming occurs. For these reasons DEQ determined that a vegetation buffer width based on a slope distance of 120 ft would be sufficient in most cases to have no stream warming and attain the TMDL shade targets.

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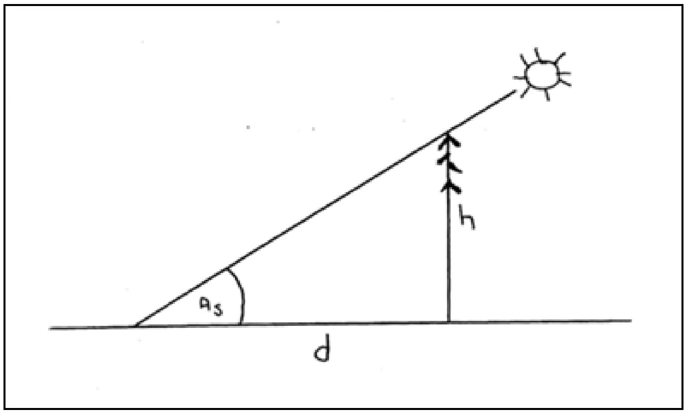
5. Attachment A – Estimating Shadow Distances

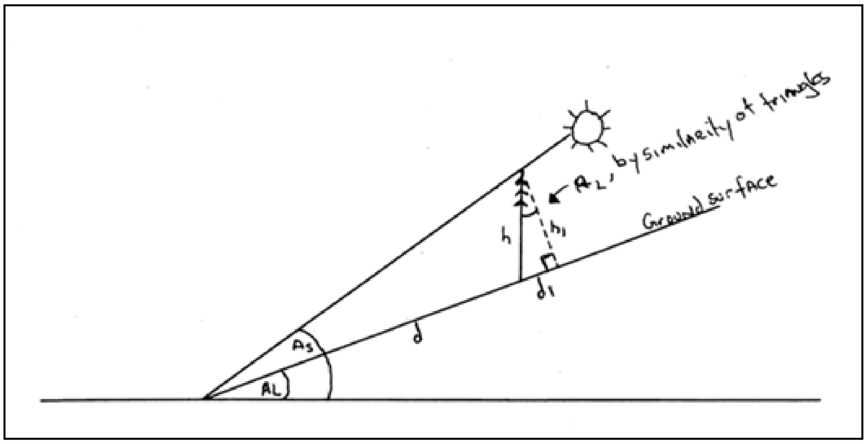
Case 1: *Ground has Zero Slope*



A_S = sun angle, h = tree height, and d = shadow distance

$$\tan(A_S) = \frac{h}{d} \Longrightarrow d = \frac{h}{\tan{(A_S)}}$$

Case 2: *Ground is sloped, with a slope angle = A_L and assume that the tree grows vertically*



A_S = sun angle above the horizon, not the ground surface, h_1 = height of the line drawn from the tree tip, perpendicular to the ground, and d_1 = distance from interception of that line with the ground, to the base of the tree.

Using the same argument as in Case 1,

$$\tan(A_S - A_L) = \frac{h_1}{(d_1 + d)}$$

Solve for d, the shadow distance:

$$d = \frac{h}{\tan{(A_S - A_L)}} - d_1$$

Since,

$$h_1 = h * \cos(A_L)\ and\ d_1 = h * \sin(A_L)$$

Thus,

$$d = \frac{h * \cos(A_L)}{\tan(A_S - A_L)} - h * \sin(A_L)$$

In other words,

$$Shadow\ Length = \frac{Tree\ Height * \cos(Hillslope\ Angle)}{\tan(Sun\ Angle - Hillslope\ Angle)} - Tree\ Height * \sin(Hillslope\ Angle)$$

Note: When $A_L = 0$ (flat ground), this equation reduces to Case 1, because sin(0) = 0, and cos(0) = 1