# Riparian Characteristics and Shade Response Experimental Research Study Scoping Document

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In association with the
The Riparian Science Advisory Committee (RSAG)

Cooperative Monitoring
Evaluation & Research

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Washington State
Cooperative Monitoring, Evaluation, and Research Committee (CMER)
Report

# Riparian Characteristics and Shade Response Experimental Research Study Scoping Document

Prepared by
Upslope Technical Writing Group

Prepared for the
Riparian Science Advisory Committee (RSAG)
of the

Washington State Forest Practices Board
Adaptive Management Program
Washington State Department of Natural Resources
Olympia, Washington

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## Washington State Forest Practices Adaptive Management Program

The Washington Forest Practices Board (FPB) has adopted an adaptive management program in concurrence with the Forests and Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

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

To provide the science needed to support adaptive management, the FPB made the Cooperative Monitoring, Evaluation and Research Committee (CMER) a participant in the program. The FPB empowered CMER to conduct research, effectiveness monitoring, and validation monitoring in accordance with guidelines recommended in the FFR.

## Report Type and Disclaimer

This report was initiated by the Riparian Science Advisory Committee (RSAG**).** The report is intended to inform the Adaptive Management Program and provide information supplemental to the work of the Cooperative Monitoring, Evaluation and Research Committee (CMER) and the Riparian Science Advisory Committee (RSAG).

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

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## Proprietary Statement

This work was developed with public funding, as such it is within the public use domain. However, the concept of this work originated with the Washington State Forest Practices Adaptive Management Program and the authors. As a public resource document, this work should be given proper attribution and be properly cited.

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## Context

This Riparian Characteristics and Shade (RCS) response study is being developed by the Riparian Scientific Advisory Group (RSAG) of the Cooperative Monitoring Evaluation and Research Committee (CMER) as part of the State of Washington's forest practices Adaptive Management Program (AMP). The AMP is funded by the Washington State Legislature to assist the Forest Practices Board (Board) in determining if and when it is necessary or advisable to adjust rules and guidance. CMER is responsible for providing the AMP with the best available science (BAS) through research and monitoring of the effectiveness of forest practice rules at meeting the program's goals.[1]

The RCS study was added to the CMER biennial workplan in 2016. The Timber Fish and Wildlife Policy Committee (Policy) approved limited funding to assist RSAG in developing a study design for Fiscal Year (FY) 2019. No Project Manager has been assigned, and RSAG expects to seek funding to implement the study beginning in FY20 budget period.

## Background

This RCS study would strengthen knowledge on the effectiveness of riparian buffers in protecting aquatic resources by providing a strong analysis of the how changing riparian management prescriptions affect stream shading across the state. The existing CMER research program reflects planning and prioritization decisions made in 1999-2000. Based on a project prioritization process, CMER identified Type Np (non-fish-bearing perennial streams) riparian prescriptions as posing the greatest potential risk to aquatic resources. This was based on the Np rule prescriptions using relatively narrow and discontinuous forested buffers and the general lack of science underpinning those prescriptions. As a result, several CMER riparian rule prescription-effectiveness studies are either complete (Westside Type N Buffer Characteristics Integrity or Function study **(Schuett-Hames, et al. 2012)**) or nearing completion (Effectiveness of Experimental Riparian Buffers on Perennial Non-fish-bearing Streams on Competent Lithologies in Western Washington **(McIntyre et al. 2017)**, Stream-Associated Amphibian Response to Manipulation of Forest Canopy Shading (**MacCracken et al., in review),** and the Westside Type N Soft Rock Effectiveness Study (**CMER1)**). No Type Np stream studies have been implemented on the eastside; although, a study design for an Eastern Washington Riparian Effectiveness Monitoring Project **(CMER2)** has undergone independent scientific peer review (ISPR) and is awaiting approval.

In addition to the ongoing Type Np studies, a set of eastside Type F (fish-bearing waters) stream studies has been completed ((Eastside Solar Shade Effectiveness Study (**McGreer et al. 2011**, and Eastside Bull Trout Overlay Temperature Study (**Cupp and Lofgren 2014)**), a Westside Type F Prescription Monitoring Project **(CMER3)** is in implementation, and a Forested Wetlands Effectiveness Study is ready for ISPR that may examine wetlands both east and west of the Cascades.

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[1] 1. Clean water, 2. Harvestable fish, 3. ESA compliance, 4. Viable timber industry.

Once complete, these effectiveness monitoring studies will provide policy makers with an improved scientific basis to infer how effective the buffer prescriptions tested are in achieving key riparian functions. Even with all these studies, however, many prescriptions in the forest practices rules will remain untested.

The rules that guide forest management along perennial streams and other aquatic features in Washington State are complex, and result in over 90 different potential riparian buffer configurations. Given this complexity, and limited research funds, CMER cannot test the effects on stream temperature for the full suite of potential buffer configurations existing in rule. In addition, if those prescribed buffers tested are found not to meet performance targets, or if new policy goals such as more active management in riparian areas are being considered, there is little in the way of rigorous science to inform adaptive management decision making at Policy and the Board in when considering alternative prescriptions.

Protecting stream temperature is a priority of the state's forest practices rules and is directly related to the Forests and Fish Report and the Forest Practices Habitat Conservation Plan (FPHCP) performance goals of meeting the state water quality standards. Managing stream shading is the primary way the rules were designed to protect stream temperature. The strong relationship between shade and stream temperature provides the AMP with an opportunity. It is significantly quicker and less costly to test how different riparian prescriptions affect stream shading then it is to directly test the effectiveness of prescriptions on stream temperature. For example, this RCS study can provide a very strong test of as many as 13-21 different shade prescription variants within 2 – 3 years, versus the 7 – 9 years commonly needed to complete a single effectiveness monitoring study that would typically examine 2-3 prescription variants. Results from this proposed study could therefore be available in the same time frame as the remaining planned riparian effectiveness monitoring studies described previously. This would allow the RCS study to further validate the findings from the aforementioned studies. Used with the shade-temperature relationships developed in those studies, the RCS shade data would also better inform the extent that untested alternative buffer prescriptions (combinations of no-cut buffer width and thinning of varying intensity) are likely to meet shade and temperature protection targets.

In addition to directly informing how stream shading changes in response to the specific riparian prescriptions assigned for testing, the empirical data being collected could be used to potentially improve existing shade models used in the AMP and by outside cooperators. One of these models, the SHADE.xls model, was developed by the Washington Department of Ecology. This model has been used within the CMER research program (**Cristea and Janisch 2007**), by cooperators to the AMP (**Washington Farm Forestry Association 2015**), and in scientific research trying to determine the effect riparian management prescriptions have on stream shade (**Teply et al. 2012 and 2014**). The SHADE.xls model estimates shade based on user-input data describing riparian conditions and stream and topographic and physiographic characteristics. This model shares underlying algorithms with other shade models used in the region, so information gained to improve the SHADE.xls model can be used to improve other models used in the region. This model was not developed, however, to back-calculate stream buffer widths and management prescriptions, and can produce spurious results. For example, if a user describes a riparian forest as being dense and then extends branches over the stream, the model will be insensitive to the width of the buffer. The model output in such a case will show a one-foot wide buffer to be extremely effective in blocking solar energy. In spite of not being validated or designed to make forest-prescription-level design decisions, cooperators are using it for this purpose. There would be significant value to the AMP to validate the model at a minimum, and to the extent possible, refine the model to allow it to be a more effective tool for evaluating management prescriptions.

## Issue/Problem Statement

Washington's forest practices regulations include riparian prescriptions that include no-harvest buffers of varying width. These no-harvest buffers can be used alone or in some cases be applied in combination with adjacent buffers of varying width within which some level of thinning is allowed. No study has been identified which examines a well replicated range of riparian harvest treatments on stream shade across a broad range of forest types applicable to Washington State. Field research is particularly limited examining how changing the width of no-cut buffers along streams effects the ability to thin the adjacent riparian stands without detrimentally affecting stream shade. In addition to being of direct interest in assessing the effectiveness of the current riparian rules, this is a topic of great interest to policy makers who want to understand the implications to shade of using forest thinning as a tool to promote healthy forests on the Eastside and desired future conditions sooner on the Westside. While other existing and planned CMER research studies will support decisions on the effectiveness of the specific prescriptions tested, they will not inform policy makers of other, untested buffer configurations permitted under forest practices rules, as well as their statewide applicability.

## Purpose Statement

The purpose of this study is to quantify how stream shade responds to a continuum of buffer management treatments of varying intensity across a range of stand types (or geo-physiographic regions)[2] common to commercial forestlands covered under the FPHCP. The results would strengthen the ability of the AMP to interpret and respond to ongoing and future effectiveness monitoring studies that directly test both shade and temperature. The data collected on buffer and stand characteristics would also be used to test and make improvements to Ecology's SHADE.xls model. This would further expand our ability to estimate the response of shade to an even broader range of treatment prescriptions, including alternative prescriptions, over a broader range of riparian forest types and conditions than what we can test directly.

## Objectives

The study has three objectives:

1. To determine the effect of varying buffer width and the intensity of management (i.e., thinning) within the buffer on shade provided to adjacent streams.

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[2] Recommendations on whether to use forest stand types or ecoregions, and which stand types or regions should be tested will be made in the study design phase of this study.

2. To determine relationships between stream shade and common forest-stand metrics (e.g., mean canopy height, crown ratio, relative density, trees per acre, basal area per acre).
3. To refine and calibrate Ecology's stream shade (SHADE.xls) model to improve application across the range of buffer configurations and timber stand types common to commercial forestlands in Washington.

## Critical Questions

The study would address the following critical questions:

1. How does stream shade change in response to a range of no-cut and thinned buffer zones used alone and in combination?
2. How does the shade provided by the tested buffer configurations vary by stand type (e.g., Douglass fir, hemlock-spruce, Ponderosa pine)?
3. What stand metrics (e.g., stand height, relative density, trees per acre, basal area, and crown ratio) alone or in combination, are the best predictor of shade and light attenuation; and how do these predictor variables vary by stand type?
4. What parameter input values and/or changes in the Ecology SHADE.xls model (e.g., canopy density, light extinction, stream overhang) would improve prediction accuracy for timber stand types common to commercial forestlands covered under the FPHCP in Washington?

## SUMMARY OF BEST AVAILABLE SCIENCE

A detailed review of the literature to determine the best available science in support of this study is provided with citations in **Appendix A**.

In summary, the research reviewed suggests moderate thinning can be accomplished with low impact on stream shade and water temperature. However, as the intensity of thinning increases the width of the RMZ will also generally need to increase to provide comparable protection for stream temperature. Thinning more than approximately 25-30% of the standing trees or stand basal area within a riparian buffer is commonly associated with reduced stream shading and increasing stream temperature. As minimum riparian management zones are widened to 75 or 100 feet (22.8 or 30.5 m), or greater, the ability to conduct light to moderate thinning within them without causing streams to warm increases. Adding no-cut buffer zones immediately adjacent to streams increases the confidence that adjacent thinning prescriptions can be conducted with minimal or no loss in stream shading, and allow those thinning treatments to be more intense and thus more likely to be economically and operationally viable. Such a no-cut zone might be adjusted from 25 to 60 feet (7.6 to 18.3 m) depending on whether a light, moderate, or heavy thinning is being conducted.

The above observations apply to harvests which vary greatly in size, from small patch cuts of only tenths of acres in size, to the harvest of small sub-watersheds, and to the harvest of 40-60 acre patches of timber in larger watersheds. They also apply to small to medium size fish-bearing as well as to non-fish-bearing streams. Small streams have been shown to be sensitive to changes in canopy cover, with stream warming often persisting for many years after harvest and extending to the mouth of the watershed. Large streams and rivers, however, respond differently to changes in riparian vegetation. With a larger volume of water that needs to be heated and less ability for adjacent trees and plants to shade a large proportion of the water surface, the temperature of these larger water bodies are more affected by general climatic conditions and the temperature effects of their major tributaries (**Cristea et al., 2010**).

Riparian buffers which are left intact provide the greatest shade, followed by buffers which selectively retain only mature trees. Though buffers of non-merchantable trees and brush can help mitigate temperature increases as compared with clear cuts, the field research examined suggests that they are not as effective in buffering even those very small tributaries sometimes suggested to be effectively shaded by residual brush.

Studies of riparian buffer BMPs indicate their effectiveness for maintaining shade and stream temperature are a function of the riparian stand characteristics (height, density, width) existing immediately after harvest, along with the changes which occur over succeeding seasons. Based on this knowledge, we should expect the effectiveness of the riparian rules for maintaining stream shade will vary in relation to stand characteristics, location, and time after harvest. Further, rule effectiveness in maintaining pre-harvest stream temperatures will likely vary in relation to other key physical characteristics (described above) that contribute to stream sensitivity to thermal loading. Based on the research reviewed, if maintaining stream temperatures across the forested landscape is a goal of the FPHCP (Washington State Department of Natural Resources, 2005), then such prescriptions would be best designed to limit the reduction in stream shade post-harvest to less than 6%.

In addition to variability in temperature or shade responses caused by differences in riparian and physical stream characteristics, the variability observed in the literature is also a foreseeable result of the methods used in the research studies themselves. Few existing studies exert control over the extent of harvest or meter the post-harvest conditions. The studies reviewed predominately tested non-standardized operational applications of state or provincial buffering recommendations. Harvest length and area; harvest block orientation; buffer width, age, and structure; topographic shading; and years since harvest; are all examples of key variables known to affect stream shading and temperature. Yet they are seldom controlled or accounted for in the body of existing research. Shade is often not reported in the riparian buffer literature, instead focusing on temperature responses. Where reported, however, the study may use any of a broad range of metrics and monitoring techniques (light meter, pyranometers, LAI, canopy cover, angular canopy density, effective shade, topographic and canopy shade) and take the measurements from distinctly different positions over and across the streams. Differences in the monitoring methods used in stream temperature studies (distance from cut-block to meter, distance between treatments, uncontrolled harvests in basin, averaging metrics, and frequency of monitoring) further reduce our ability to confidently assess the extent that changes in forest management affect stream temperature. These many sources of variability reduce our ability to confidently use the existing literature to answer the critical questions proposed in this RCS study.

A key objective of this study is to use empirical data to advance the state of our knowledge of how stream shading responds under a common range of riparian management treatments, and to do so under a strictly controlled and standardized set of study conditions. This RCS study is focused on characterizing how variable widths and intensities of buffer management (clearcutting, thinning, and no-cut zones) affect the ability of a riparian stand to intercept solar energy that would otherwise pass through to the stream. Particularly lacking from the existing literature is empirical research examining the added benefit of including no-harvest buffers of a given width adjacent to thinning harvests. This study would substantially address this gap in knowledge and in doing so directly assess a key feature of the state's forest practices riparian buffering prescriptions.

An additional objective of this RCS study, which is complementary to the assessment based on the empirical data, is to identify improvements to the SHADE.xls model. SHADE and SHADE.xls are well established models for estimating the amount of solar energy that will pass through forested canopies and warm streams. The existing literature generally supports the potential to improve the SHADE.xls model. Techniques for running the model that adjust for vertical differences in canopy density (layers), and improved methods for assessing the proportion of a stream shaded by overhanging vegetation, have met with some success. The common thread of the attempts at model improvement reviewed is the use of methods that better characterize the shade patterns created in complex riparian forest stands. The potential for model improvement based on better describing stand characteristics that affect light transmission is further supported by the work of researchers who found that incorporating relative density helped address clumping, that understory density was an important consideration in model accuracy, and that crown depth is a critical variable in light penetration through forest canopies. Although research has demonstrated the potential for model improvements, the work reviewed was restricted in scale and had little or no validation. The existing research also provides a reason to be cautious setting expectations for model improvement. Researchers have found significant variability in light energy extinction coefficients can occur within stands of the same type and age. This documented variability suggests caution is warranted in setting expectations about potential cost effective improvements in model accuracy.

The literature is consistent in finding there is no one best method for measuring shade, canopy cover, or canopy density; and has demonstrated the value of modifying standard field methods where necessary to better isolate the variables of greatest interest. The SHADE model was developed based on overhead canopy cover and overhead canopy density, but the SHADE.xls model allows the extinction coefficient to be turned off and more direct measurements of shade, such as angular canopy cover and effective shade used directly. The effect of these choices and the individual selection of metrics and methods on model results has not been evaluated. Similarly, while more accurately accounting for the shade from branches overhanging streams has been tested with some success, the methods used in the research do not lend themselves well to general use, and the approach has not been more widely validated. The RCS study would therefore need to examine a range of these methods against the modeled and measured results in the effort to identify improvements which are most effective in meaningfully improving model accuracy, and which can be readily applied in field studies.

## Alternative Study Designs

Four options are identified which differ primarily in the extent to which they use an experimental design or inform potential refinements to the SHADE.xls model. RSAG has agreed not to provide a single recommended alternative and to instead rely on Policy to assess the merits without the potential bias of a recommendation.

Alternative 1 and 2 are scoped to meet all of the study objectives and inform all of the critical questions. Alternative 3 and 4 address only a portion of the objectives. Alternative 3 is designed primarily to make improvements to the SHADE.xls model. Alternative 4 provides a least-cost option for providing empirical data describing how effective-shade to streams change with different widths of existing buffers s across the state.

All of the alternatives are scoped as two year field studies that provide statewide information. However, each alternative can be carried out as either an *Eastside-only* or *statewide* study, and can be implemented in pieces separated by time to better fit budget constraints without risking the project goals. As will be discussed later, the RSAG does not recommend a Westside-only scope for any of the alternatives.

### Overview of Alternatives

**The following summarizes the four alternative approaches identified by RSAG (Table 1):**

***Alternative 1*:**

> ***Use a well-controlled and replicated field study to firmly establish relationships between stream shade and the use of no-cut buffers of widths, common to the rules, applied both alone and in combination with adjacent stand-thinning harvests of varying intensity.*** *This alternative would actively harvest experimental plots established in existing un-thinned RMZs to specific target conditions. The plots would be established in experimental blocks representing distinct forest types across the state. SHADE model refinement is not a focus of this alternative, however, the data from this alternative could be used to identify whether the SHADE model has a pattern of bias associated with different stand types, provide more accurate data on stand metrics to use in the model, and provide estimated stand specific shade values and energy extinction coefficients that could be used by modelers to create an updated model.*

***Alternative 2*:**

> ***This alternative would use the same field study design as Alternative 1, but would include more direct measurements of canopy density and light extinction along with a broader range of descriptive stand metrics that affect canopy density throughout a solar path over a single day.*** *In addition to providing the same empirical results as Alternative 1, this study would be designed to: a) examine a greater range of stand characteristics that may correlate with stream shade, and b) include making refinements to the SHADE model that enhance its ability to estimate shade response to prescription scenarios across a range of forest types in Washington.*

*__Alternative 3__*:

***Conduct a two-phased study in which the first phase (described herein) is focused on identifying and making refinements to the shade model using data from existing RMZ's representing a range of forest types and harvest conditions, and the second phase would be to test the validity of the model and any specific prescriptions of policy interest.*** *The primary goal of this alternative would be to refine the SHADE model so it can more accurately estimate shade response to prescription scenarios across a range of forest types in Washington. This alternative would include all of the field metrics in Alternative 2 but would not use replicated treatments, and instead would attempt to find existing harvests that provide a wide range of stand conditions for testing. It would rely on the variability inherent in existing stands when developing regression relationships that try to identify potential improvements to the SHADE.xls model. Based on the revised model created in Phase I, a recommendation would be made for a Phase II follow up study to test the validity of the draft model refinements.*

*__Alternative 4__*:

***Use a rigorous field study to firmly establish relationships between stream shade and existing no-cut buffers widths across a range of forest types.*** *This alternative would examine effective shade provided to streams from un-thinned buffers of varying width retained by landowners after harvest. The plots would be established in experimental blocks representing distinct forest types across the state. SHADE model refinement is not a goal of this alternative, however, the data from this alternative would provide more accurate stand-type-specific buffer conditions to use in modeling.*

## Discussion of Alternatives

*__Alternative 1__:*
***Use a well-controlled and replicated field study to firmly establish relationships between stream shade and the use of no-cut buffers of widths, common to the rules, applied both alone and in combination with adjacent riparian-stand-thinning harvests of varying intensity.*** *This alternative would actively harvest experimental plots established in existing un-thinned RMZs to specific target conditions. The plots would be established in experimental blocks representing distinct forest types across the state. SHADE model refinement would not be a focus of this alternative; however, the data from this alternative could be used to identify whether the SHADE model has a pattern of bias associated with different stand types, provide more accurate data on stand metrics to use in the model, and provide estimated stand specific shade values and energy extinction coefficients that could be used by modelers to create an updated model.*

This alternative would use a well-controlled and strongly replicated field study inspired by the work of Park et al. (2008). The following is intended to provide a general road map for understanding the likely structure, scale, and cost of this study. Final recommendations would be provided in a detailed study design.

At the conclusion of this study policy makers would, at a minimum, have robust information describing:

- The relationship between the change in stream shade and the change in no-cut buffer widths used alone and in combination with two to three intensities of adjacent thinning in the RMZ (see Figure 2 below).
- The statistical strength of these relationships within and between forest types across the study area (state or eastside).
- A data set that could be used to validate the SHADE.xls model, and tables of stand conditions that could be used to more accurately parameterize the existing model.

It is recommended this study:

1) Use a before-after-impact design.

2) Include five sites within each of four statistical blocks comprised of different stand types (e.g., hemlock, Douglas fir, silver fir, ponderosa pine) or physiographic areas (e.g., coast, inland west, eastern cascades, and northeast) across Washington; for a total of 20 sites.

3) , Establish three study plots within each of the 20 sites. Within each plot, two thinning treatments[3] and a clear-cut treatment would be applied sequentially **(see Figure 1)**:

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[3] Practical limitations related to harvesting and monitoring efficiency are expected to restrict the number of thinning treatments to two, but the feasibility of including three intensities of thinning will be considered in developing a study design.

    - Plot 1. Thin moderately, then heavily, then clear-cut - to the edge of a 30-ft no-cut zone[4]
    - Plot 2. Thin moderately, then heavily, then clear-cut - to the edge of a 50-ft no-cut zone
    - Plot 3. Thin moderately, then heavily, then clear-cut - to the edge of a 75-ft no-cut zone

    Using the proposed sequential thinning strategy, the manipulation of three plots within a single site allows 9 prescription variants to be tested, in addition to the pre-treatment prescription. It is recommended the harvest zone be progressively thinned from below to a target level of tree density (e.g., 100, 50, and then 0 trees per acre) or basal area (e.g., 100, 70, and then 0 basal area per acre)[5]. It is further recommended that shade be measured at the upland-edge of the no-cut buffer towards the thinning zones (which would be 45, 70, and 90 feet in width). This would provide supporting information on the shade contributed by the various widths and intensities of thinning without no-cut buffers and effectively test 6 additional prescription variants for a total of 16 variants.

4) Stream shade would be measured using HemiView photographic analysis using the Sunmap method for measuring shade. The treatment bank would be assigned to the south regardless of its actual positon in order to reduce stream-orientation variability and standardize the results.

Buffer widths and stand metrics would ultimately be chosen to best inform the range of no-cut and thinning prescriptions in regulation. Thinning-targets would be selected that allow for sequential thinning through a series of harvests. Stand metrics which lend themselves to this purpose are trees per acre and basal area per acre. These metrics can be effectively used to set harvest targets that can be consistently replicated between treatments and provide information on regulatory threshold metrics often used to restrict the extent of harvest. While a single target metric (i.e., trees per acre or basal area per acre) would be used to standardize the intensity of the thinning harvest, additional stand metrics would be collected to assess buffer shade performance (e.g., basal area, relative density, crown ratio, canopy cover, tree species, height, topographic shade).

Analyses would compare treatments within and across stand types. These comparisons would be made at both the prescription and plot level (considering the response curve created by imposing a graduated range of treatments).

**Some benefits of the recommended approach include:**

- Informative:
    - Directly tests shade for a range of no-cut and buffer widths in rule.

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[4] During study design development it will be considered if the study can increase the number of buffers tested without significantly increasing the cost or reducing the power of the study, and will assess if it would be better to test a narrower no-cut buffer instead of the 30-ft treatment to create greater difference from the 50-ft treatment.

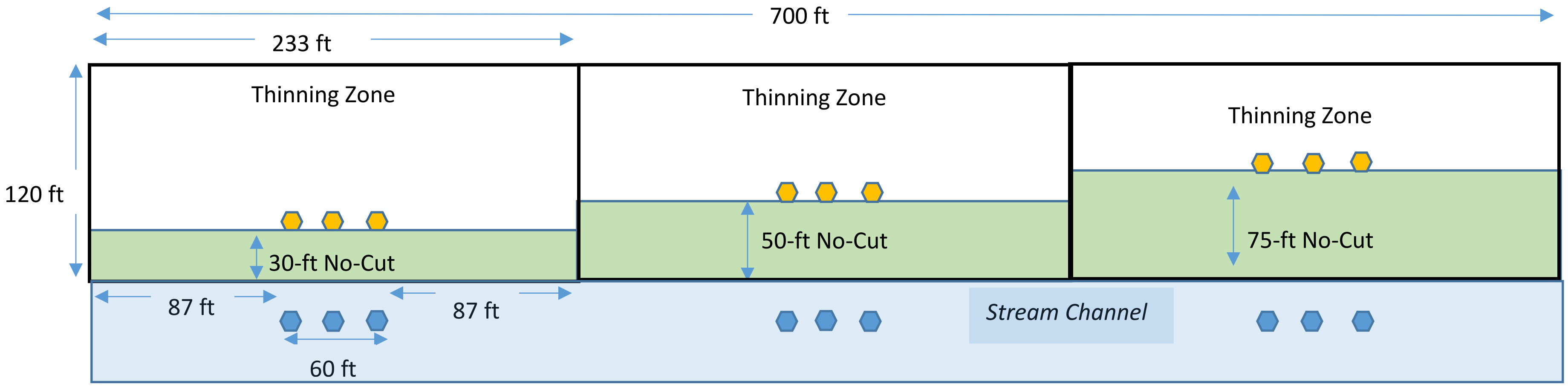
[5] It is important that the same form of thinning be used throughout; however, other levels, or metrics (basal area vs trees per acre), may be used to guide thinning if they are of policy interest or refined in the study design process.

  - Informs policy makers on the consistency of the shade response to riparian management across stand types and geographic regions in Washington.
  - Produces a series of tables and associated predictive equations within which current rule effectiveness for shade preservation can be generally assessed across a range of prescriptions (both within rule and alternatives of policy interest) **(Figure 2).**
  - Tests the accuracy of the SHADE model for industrial forest lands in Washington.
  - Examines a range of stand characteristics by stand-type to identify potential improvements to the SHADE.xls model.
  - Produces stand-type-specific characterization data that can be used to more accurately parameterize shade models.
- Flexible:
  - Can be done on one-sided no-entry RMZs left after an upland harvest.
  - Small footprint and few site screening criteria increase candidate sites.
  - Treatments can be spaced out across years to fit budget and logistic limits.
- Timely/Efficient:
  - A block of three plots can be completed in a five-day period.
  - Sites can be marked for the entire sequential harvest in advance; allowing site marking and harvesting/sampling (field work) to proceed separately.
  - A contract harvester could work in tandem with the monitoring crew(s).
  - The straight forward dataset would streamline analysis and report writing.
- Minimal Landowner Commitment/Cost:
  - Does not require landowners to alter harvest plans, set aside control sites, or provide long-term access.
  - Landowners can market the treatment-trees harvested in the study.

**Some limitations of the recommended approach include:**

- The standardized experimental design would result in some sites having prescriptions applied that do not match what would otherwise be required in WAC 222-30.
- The study only examines shade in relation to changing harvest conditions, and thus informs only one of the five riparian functions, and not how shade changes over time.
- May have less potential to inform model improvements then Alternative 2 by excluding stand vertical structural assessments and not directly measuring light energy extinction.
- Attempts to develop statistical models (relationships) between stand structures and conditions may not be successful.
- Relies on Ecology modelers, or a secondary process, to change the model.

Figure 1. Draft Plan View of Site Layout for Alternative 1 and Alternative 2. Symbols represent locations for shade measurement (blue hexagons capture the shade from the no-cut buffers alone and in combination with the thinning zones; yellow hexagons capture the shade from only the thinning zones). Plots and sampling sites are spaced to minimize interference of plots on each other.[6][7][8]



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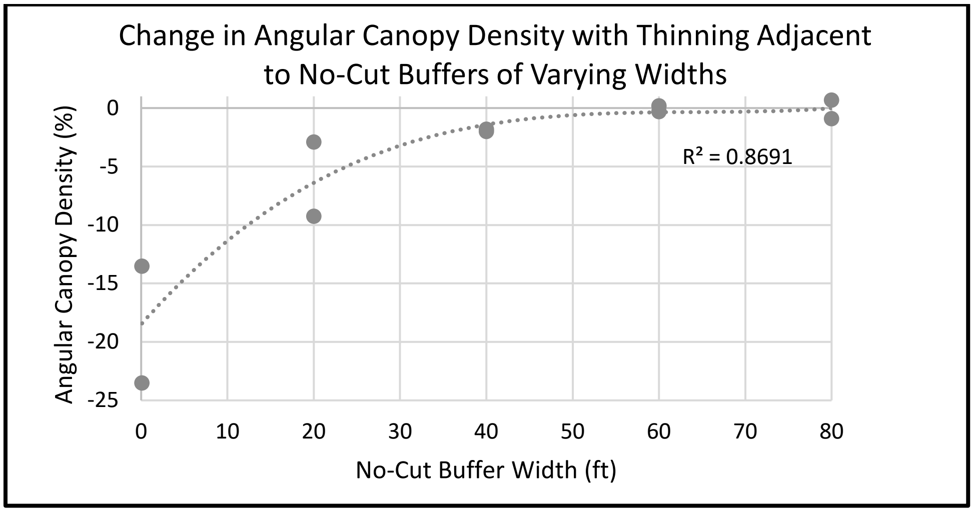
[6] The specific number and positions for monitoring shade may be adjusted based on the alternative selected and the need to quantify the increment of shade produced by vegetation overhanging the stream.

[7] The specific choices of no-cut buffer widths and thinning intensities to include in testing may be adjusted in the study design process. This could allow for adjustments based on operational limitations to thinning or to allow new comparisons.

[8] While not scoped in this study proposal, the final harvested condition of the three no-cut buffer widths left at each site could be re-measured over longer time periods to assess recovery/response patterns.

Figure 2. Example of the type of empirical results provided by Alternative 1 and Alternative 2. Figure shows how shade changes with alterations in the width of a no-cut buffer left along a stream adjacent to an overstocked riparian forest after thinning it to a target condition (adapted from Park et al. 2008).



***<u>Alternative 2</u>:***

***This alternative would use the same field study design as Alternative 1, but would include more direct measurements of canopy density and light extinction along with a broader range of descriptive stand metrics that affect canopy density throughout a solar path over a single day.*** *In addition to providing the same empirical results as Alternative 1, this study would be designed to: a) examine a greater range of stand characteristics that may correlate with stream shade, and b) includes making refinements to the SHADE model that enhance its ability to estimate shade response to prescription scenarios across a range of forest types in Washington.*

This alternative would include all of the field metrics in Alternative 1 plus examine vertical layering, and directly measure effects on radiant energy over the course of the day. This added information would be used to support a more extensive analyses designed to identify and make refinements to the SHADE model. It would also enhance our ability to classify treatment responses on light attenuation based on differences in crown shape and understory vegetation. Statistical models would be explored to help identify which stand characteristics can be used to effectively predict stream shading. In addition, the model would be run in an exploratory fashion to examine the effect of using different measures of canopy density (with extinction-on and off) and to assess the best approach for accounting for overhanging branches on stream shade. If stand type or other stand characteristics are found to predict riparian extinction coefficients, recommendations for model refinement would be made.

Some benefits of the recommended approach include:

- All of the benefits of Alternative 1 plus:
    - Examines a greater range of stand characteristics and stand-model relationships which may be used to refine the SHADE model.

- Makes any refinements identified to the SHADE.xls model.

Some limitations of the recommended approach include:

- All of the limitations of Alternative 1 plus:
  - Higher costs due to the added complexity associated with the additional metrics, analyses, and model refinement.
  - No greater confidence that meaningful model refinements would be identified.

***<u>Alternative 3</u>:***

***Conduct a two-phased study in which the first phase (described herein) would be focused on identifying and making refinements to the shade model using data from existing RMZ's representing a range of forest types and harvest conditions, and the second phase would be to test the validity of the model and any specific prescriptions of policy interest.*** *The primary goal of this alternative would be to refine the SHADE model so it can more accurately estimate shade response to prescription scenarios across a range of forest types in Washington. This alternative would include all of the field metrics in Alternative 2 but would not use replicated treatments, and instead would attempt to find existing harvests that provide a wide range of stand conditions for testing. We would be relying on the variability inherent in existing stands when developing regression relationships that try to identify potential improvements to the SHADE.xls model. Based on the revised model created in Phase I, a recommendation would be made for a Phase II follow-up study to test the validity of the draft model refinements.*

The primary goal of this alternative would be to identify potential refinements to the SHADE model to increase its accuracy for estimating how shade responds to prescription scenarios. This alternative would include all of the field metrics in Alternative 2. It would not, however, use replicated treatments, and instead relies on the variability inherent in existing stands to help with developing meaningful regression relationships for use in identifying potential improvements to the SHADE.xls model. Rather than selecting and testing buffer and thinning prescriptions directly and using those experimental prescriptions to improve the SHADE.xls model, this alternative postpones (or potentially eliminates) model and prescription performance validation work until after the SHADE.xls model is refined using data collected across Washington. Once the model is revised, it could then be used to test specific prescriptions policy-makers have interest in, and which could be the focus of direct testing in a follow-up experimental field validation study.

Some benefits of the recommended approach include:

- It does not require working with landowners to conduct coordinated harvests.
- A revised model may be more useful in allowing policy makers to identify prescriptions of interest to test using experimental replication in the Phase II field study.

Some limitations of the recommended approach include:

- As proposed this alternative would test fewer sites than the other alternatives, and would have less ability to characterize within-stand variability, and would not directly assess any specific treatment prescriptions.

- Study would not produce an empirical data set that can directly inform policy makers on buffer effectiveness. Instead, the benefits depend on identifying and making significant improvements to the SHADE.xls model.
- Estimated costs are only for Phase I, and to be of full value a second field study (Phase II) is expected to be needed to validate model revisions for the range of any alternative prescriptions of policy interest.

***Alternative 4*:**

***Use a rigorous field study to firmly establish relationships between stream shade and existing no-cut buffers widths across a range of forest types.*** *This alternative would examine effective shade provided to streams from un-thinned buffers of varying width retained by landowners after harvest. The plots would be established in experimental blocks representing distinct forest types across the state. SHADE model refinement is not a goal of this alternative, however, the data from this alternative would provide more accurate stand-type-specific buffer conditions to use in modeling.*

Effective shade is a key variable which accounts for the portion of the sun's energy that contributes most to stream heating. This study is designed to provide a bare bones approach to characterizing how effective shade varies across stand types and physiographic regions. By collecting a minimal data set and using sites retained by landowners, this study would be less costly than the other alternatives. The tradeoff is that it would provide less information on how differences in stand structure affect shading, and less potential information to use to improve the use of the SHADE.xls model.

This study would use a stratified semi-random after-harvest design to sample a moderately large number of sites across the state. Stream shade would be measured using HemiView photographic analysis using the Sunmap method for measuring shade. The treatment bank would be assigned a southerly aspect to reduce stream-orientation variability and standardize the result.

At the conclusion of this study policy makers would, at a minimum, have information describing:

- The relationship between the change in stream shade and changes across a range of no-cut buffer widths.
- The statistical strength of these relationships within and between forest types across the study area (state or eastside).
- A table of values of tree height and effective shade that can be used as default stand-type-explicit values for parameterizing the SHADE.xls model.

**Some benefits of the recommended approach include:**

- Informative:
  - Directly tests a key shade metric across a range of existing no-cut buffer widths.
  - Informs policy makers on the consistency of the shade response to riparian management across stand types and geographic regions in Washington.

    - Produces a table of forest-type specific riparian buffer characteristics that can be used to parameterize the existing SHADE.xls model.
- Flexible:
    - Can be done on one-sided no-entry RMZs left after an upland harvest.
    - Small footprint and few site-screening criteria increase candidate sites.
    - Treatments can be spaced out across years to fit budget and logistic limits.
- Timely/Efficient:
    - Least costly of the alternatives.
    - Two sites can be monitored in a full day allowing 4-5 sites to be sampled each week.
    - Sites do not need to be surveyed and marked prior to the study.
    - The straight forward dataset would streamline analysis and report writing.
- Minimal Landowner Commitment/Cost:
    - Does not require landowners to alter harvest plans, set aside control sites, or provide long-term access.

**Some limitations of the recommended approach include:**

- The study would only examine shade in relation to changing harvest conditions, and thus informs only one of the five riparian functions, and not how shade will change over time.
- The study would not include most of the forest stand and shade metrics included with the other alternatives.
- May have less potential to inform model improvements then any of the other alternatives and does not include the step of making such refinements.

**Table 1**. Comparison of the Four Alternatives for the RCS Study Design.[9]

| Characteristics | Alternative 1 | Alternative 2 | Alternative 3 | Alternative 4 |
|---|---|---|---|---|
| **Stream & Topography** | • Topographic shade angle<br>○ Bank full width<br>○ Bank slope & incision<br>• Disturbance zone<br>• RMZ hill slope<br>• Stream Azimuth and elevation | • Same as Alternative 1 | • Same as Alternative 1 | • Same as Alternative 1 |
| **Riparian Vegetation** | • TPA<br>• BA<br>• RD<br>• QMD<br>• Height<br>• Live canopy ratio<br>• Stand structure<br>• Dominant Species | • Same as Alternative 1 | • Same as Alternative 1 | • Dominant Species<br>• Height<br>• Coarse structure (visual assessment) |
| **Shade & Cover** | • Effective Shade (stream only)<br>• Overhead canopy cover and canopy closure (stream and riparian zones)<br>• Estimated leaf area index | • Same as Alternative 1 plus:<br>• Direct measurement of solar energy extinction (radiometric)<br>• Ground, mid layer, and upper canopy overhead cover and solar energy. | • Same as Alternative 2 | • Effective Shade (stream only) |
| **Model Revision** | • Existing SHADE model validation by block and stand type using measured overhead canopy closure and height values by RMZ zone. | • Same as Alternative 1 plus:<br>• Make model refinement based on study results. | • Same as Alternative 2 | • Existing SHADE model validation by block and stand type effective shade over stream. |

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[9] This comparison provides general expectations of the scale and scope of this study. Specific sample sizes, sample parameters and study costs will be determined in the study design phase.

| | | | | |
|---|---|---|---|---|
| | • Identify key characteristics affecting shade within each forest type (e.g., height, density, width, zones of disturbance, overhang) | | | |
| **Outcome Products** | • Empirically derived stream shade values associated with a range of no-cut buffers widths and RMZ thinning intensities (presented in tabular and equation form).<br>• And evaluation of differences in stream shade by stand type across region.<br>• Identification of key vegetation parameters affecting shade<br>• Field derived values of overhead closure and cover by zone (including stream overhang) and tree height that can be used to more accurately parameterize the existing SHADE.xls model by stand type.<br>• LAI measured by stand type, and converted to estimates of light extinction coefficient to use in refining the SHADE.xls model. | • Same as Alternative 1 | • Refined SHADE model and/or model application guidance.<br>• Prescription set and revised SHADE.xls model to validate in a follow-up field study. | • Empirically derived effective shade values associated with a range of no-cut buffer widths as implemented by landowners with assessment of the effects of stream width, orientation, and stand type. |

| | | | | |
|---|---|---|---|---|
| **Pre-harvest Monitoring** | Yes | Yes | No | No |
| **Prescriptions Replication** | Yes | Yes | No | No |
| **Empirical analysis of prescriptions** | Yes | Yes | No | No |
| **Extent of model improvement** | Moderately High | High | Moderate | Low |
| **Stand types (S.T.)** | 4 | 4 | 4 | 4 |
| **Samples/S.T.** | 50 | 50 | 10 | 20 |
| **Prescription variants tested** | 10 - 16 | 10 - 16 | NA | NA |
| **Samples/ prescription** | 20 | 20 | NA | NA |
| **Total samples** | 200 - 380 | 200 - 380 | 40 | 80 |
| **Field Time** | 2 years | 2 years | 2 years | 2 years |
| **Meets <u>all</u> objectives & CQs** | Yes | Yes | No | No |
| **Cost Statewide**<br>**Cost Eastside** | **$433,125**<br>**$258,875** | **$621,055**<br>**$344,500** | **$436,777**[10]<br>**NA** | **$237,000**<br>**$142,750** |

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[10] Alternative three is the first phase of a two phase study. The second phase would include validation and testing of specific prescriptions of Policy interest. Costs and time frames for conducting the second phase have not been determined.

### Limiting Geographic Scope of the RCS Study to the Eastside

As noted previously, each of the three alternatives can be carried out as either an *Eastside-only* or *statewide* study.

Because of the higher practical importance of examining the effects of thinning on the Eastside where the practice and environmental value is viewed as more prominent, RSAG does not recommend a Westside-only alternative be pursued for this study.

Restricting the study to only forest lands on the eastside of the Cascades:

- Reduces the cost and potentially the time needed for the study (if only two rather than four stand types or physiographic regions are sampled); or alternatively, it would allow for increased replication or a greater number of stand types to be sampled at same cost.
- Focuses research on thinning to the eastside where forest health and fire resiliency are greater concerns.
- Would not inform policy makers on untested Westside rules and potential alternate plans and templates.

## Data Requirements

Sampling parameters and data needs are described above for each of the four alternatives presented (Table 1). The data needs are substantially different between the alternatives and will be finalized in the study design phase, but broadly they include:

- Multiple metrics of stream shade and overhead cover.
- Stand metrics collected within the forest stand which characterize the trees and vegetation in each of the buffer zones.
- Physical stream measurements (e.g., bankfull width, wetted width, incision depth, and side-bank slope) describing the range of conditions included in the study plots, and where applicable used to run the SHADE.xls model.

## Level of Effort and Estimated Budget

Preliminary annual budget projections for each alternative are provided below with the basis described in detail in Appendix B:

***Alternative 1:***
***Use a well-controlled and replicated field study to firmly establish relationships between stream shade and the use of no-cut buffers of widths common to the rules applied both alone and in combination with adjacent stand-thinning harvests of varying intensity.***

| **Alternative 1** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | $210,875 | $174,250 | $48,000 | $433,125 |
| **Eastside only** | $210,875 | $48,000 | | $258,875 |

***Alternative 2:***
***This alternative would use the same field study design as Alternative 1, but would include more direct measurements of canopy density and light extinction along with a broader range of descriptive stand metrics that affect canopy density throughout a solar path over a single day.***

| **Alternative 2** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | $276,555 | 248,500 | $96,000 | $621,055 |
| **Eastside only** | $248,500 | $96,000 | | $344,500 |

***Alternative 3:***
***Conduct a two-phased study in which the first phase (described herein) is focused on identifying and making refinements to the shade model using data from existing RMZ's representing a range of forest types and harvest conditions.***

| **Alternative 3** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | $204,405 | $136,370 | 96,000 | $436,777 |

***Alternative 4:***
***Use a rigorous field study to firmly establish relationships between stream shade and existing no-cut buffers widths across a range of forest types.***

| **Alternative 4** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | $99,250 | $94,250 | $48,000 | $241,500 |
| ***Eastside Only*** | $99,250 | $48,000 | | $147,250 |

## Proposal Initiation

This study would follow the process of interaction established in the CMER Protocols and Standards Manual. The SAG/Project Team would develop a draft recommendation for a study scope (this document), solicit comments and obtain approval of a final version by the Board approved CMER members, then take the recommended project to Policy for approval for any funds necessary to develop the study design and for potential placeholder funds to implement the study. The Project Team would then develop a study design which would go to RSAG and CMER for review and approval. The study design would then be sent to ISPR and revised based on their feedback. Once a study design is developed and approved, CMER would request prioritization and funding from the Policy Committee as part of the biennial budget prioritization process.

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## Appendix A – Best Available Science Review

### THERMAL PROCESSES IN THE FORESTED ENVIRONMENT

**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. Therefore, riparian vegetation that blocks direct solar radiation along the sun's pathway across the sky is most effective at reducing the amount of radiant energy available for stream heating (**Moore et al. 2005**). Research shows that the attenuation of direct beam radiation by riparian vegetation is a function of canopy height, vegetation density, buffer width (**Beschta et al. 1987**; **Sridhar et al. 2004**; **DeWalle 2010**) and stream azimuth **(DeWalle 2010)**. Increases in canopy height and buffer width both act to increase the solar path length through the vegetation. This acts in combination with vegetation density to increase the amount of solar energy extinguished before that energy reaches the stream. This helps explain why studies examining the effect of buffer width within a population of riparian stands having differences in stand height, density, and buffer orientation produce only moderate predictive relationships (**Brazier and Brown 1973; Steinblums et al. 1984**).

**Shade from riparian vegetation is not the only factor affecting stream temperature.** Research shows the temperature response from timber harvest of riparian vegetation is variable and can be highly dependent on the depth and volume of stream flow, substrate type, groundwater inflow, and surface/subsurface water exchange (i.e., hyporheic exchange) (**Moore et al. 2005**). In general, stream sensitivity to shade loss is a function of reach-scale physical characteristics and geomorphic setting. As an example of contrasting conditions, streams at lower elevations (i.e., warmer air temperature), with no topographic shading, with shallow-wide channels (i.e., high width to depth ratio), or with bedrock substrate (i.e., hyporheic exchange limited) are more sensitive to heating due to shade loss than are streams at higher elevations, with topographic shading, with deep-narrow channels, or with alluvial substrate.

**Summer stream temperatures vary both within stream reaches and across the landscape. This is due to variation in physical, hydrologic, and climatic conditions that drive thermal processes**. Stream temperature also varies as a result of differences in past riparian management practices and disturbance (**Brown and Krygier 1970**; **Brosofske et al. 1997**; **Wilkerson et al. 2006**; **Dent et al. 2008**; **Pollock et al. 2009**; **Kibler et al. 2013**). Much of the scientific uncertainty in the effectiveness of riparian management practices is likely caused by the complexity of heating and cooling processes in streams (**Poole and Berman 2001**; **Moore *et al.* 2005a**; **Johnson, 2004**).

In order to understand the components that drive stream temperature change, it is useful to consider a one-dimensional energy model for well mixed streams without inflows or outflows (per **Caissie *et al.* 2007**):

$$\frac{\partial T_w}{\partial t} + v\frac{\partial T_w}{\partial x} - \frac{1}{A}\frac{\partial}{\partial x}\left(AD_L\frac{\partial Tw}{\partial x}\right) = \frac{W}{\theta\rho A}H_n \qquad (1)$$

where, $T_w$ represents the water temperature*,* $t$ is the time*,* $v$ is the mean water velocity*,* $x$ is the distance traveled, $A$ is the cross-sectional area, $W$ is the river width, $D_L$ is the dispersion coefficient in the direction of flow, $\theta$ is the specific heat of water, $\rho$ is the water density, $H_n$ is the net heat flux, and $\partial$ preceding a parameter denotes its partial differential. For a given point in time, and excluding the effect of longitudinal dispersion, the equation can be simplified to:

$$\frac{dT_w}{dx} = \frac{1}{v}\frac{H_n}{\theta\rho D} \qquad (2)$$

where $D$ is depth and $d$ preceding the parameter denotes its differential. The model indicates that as water travels through the reach its temperature changes as a function of $H_n$, which is the sum of the heat exchange processes including net solar radiation, net long wave radiation, sensible and latent heat exchange, and bed heat conduction (**Johnson, 2004**; **Moore *et al.* 2005a**). For a given net heat flux in equation 2, the change in water temperature is proportional to the surface residence time ($x/v$) and inversely proportional to water depth. Thus a stream reach with a lower flow or shallower depth would warm at a greater rate as it moves through a reach exposed to solar energy.

Tributaries can also modulate stream temperatures (**Cristea et al. 2010; Lynch et al. 1984; Hetrick et al. 1998; Beschta et al. 1987**). The effect of tributaries depends on the temperature difference between the inflow and receiving stream temperatures and on their relative contribution to discharge, which can be modeled according to a simple mixing equation (**Moore *et al.* 2005a**):

$$dT_w = \frac{Q_{trib}}{Q_{main}}\left(T_{trib} - T_{main}\right) \qquad (3)$$

where, $Q$ is discharge. This model can be extended to account for the effects of other discrete inflows (e.g., springs). When changes in flow are not discrete, the model becomes:

$$\frac{dT_w}{dx} = \frac{Q_{in}}{Q_{sw}}\left(T_{in} - T_{sw}\right) \qquad (4)$$

where, $Q_{in}$ / $Q_{sw}$ is the functional relationship between the diffuse inflow and surface water flow along the reach, and $T_{in}$ and $T_{sw}$ are, respectively, the diffuse inflow and surface water flow temperatures. This equation can be used to model the effects of diffuse groundwater inputs and direct precipitation to the channel.

Hyporheic exchange occurs along a subsurface flow path where surface water mixes with subsurface water and then returns to the stream (**Gooseff et al. 2003**). Water in the hyporheic zone is sheltered from exchanges along the air-water interface so it directly affects the spatial/temporal distribution, rather than the magnitude, of stream heat energy, and is often viewed as an important temperature buffer (Poole and Berman, 2001). Hyporheic water temperature ($T_{hyp}$) can be modeled in terms of the residence time (**Gooseff *et al.* 2003**):

$$\frac{\partial T_{hyp}}{dt} = \int_0^t \frac{\partial T_w(t-\tau)}{\partial t} g^*(t)dt \tag{5}$$

where, $\tau$ is a lag time and $g^*(t)$ is a function of the distribution of exchange rates.

Thermal processes can be accounted for using an additive effects model (**Moore *et al.* 2005a**) in which the rate of change in water temperature over a reach length ($x$) is a function of the incoming water temperature, net energy exchange across the air-water surface, and change in temperature associated with inflows, including the desynchronizing effect of hyporheic exchange (Figure 1).

Riparian timber harvest can affect stream temperatures through effects on shade, logging debris recruitment, and discharge. In forested environments with perennial streams, shade provided by riparian vegetation is generally the single most important variable influencing summer stream temperature (**Brown 1969**; **Johnson and Jones 2000**; **Danehy *et al.* 2005**; **Groom *et al.* 2011**). Harvest of riparian trees can reduce canopy cover and shade, thereby increasing the amount of solar radiation reaching the stream (**Brazier and Brown 1973**; **Moore *et al.* 2005b**). The retention of riparian tree buffers ameliorates some of the loss of shade from adjacent timber harvest, though effectiveness of the buffer varies with buffer width, tree height, and tree density (**DeWalle 2010**).

Harvest adjacent to the stream can result in delivery of logging debris to the channel which can provide short-term stream cover and temporarily offset some of the loss of forest canopy shade (**Jackson et al. 2001; Kibler et al. 2013**). Logging debris also increases hyporheic exchange capacity through the creation of debris jams and channel steps (**Wondzell 2006**). Changes in discharge also affect temperature by diluting or concentrating the incoming heat load into a larger or smaller volume of water (**Poole and Berman 2001**).

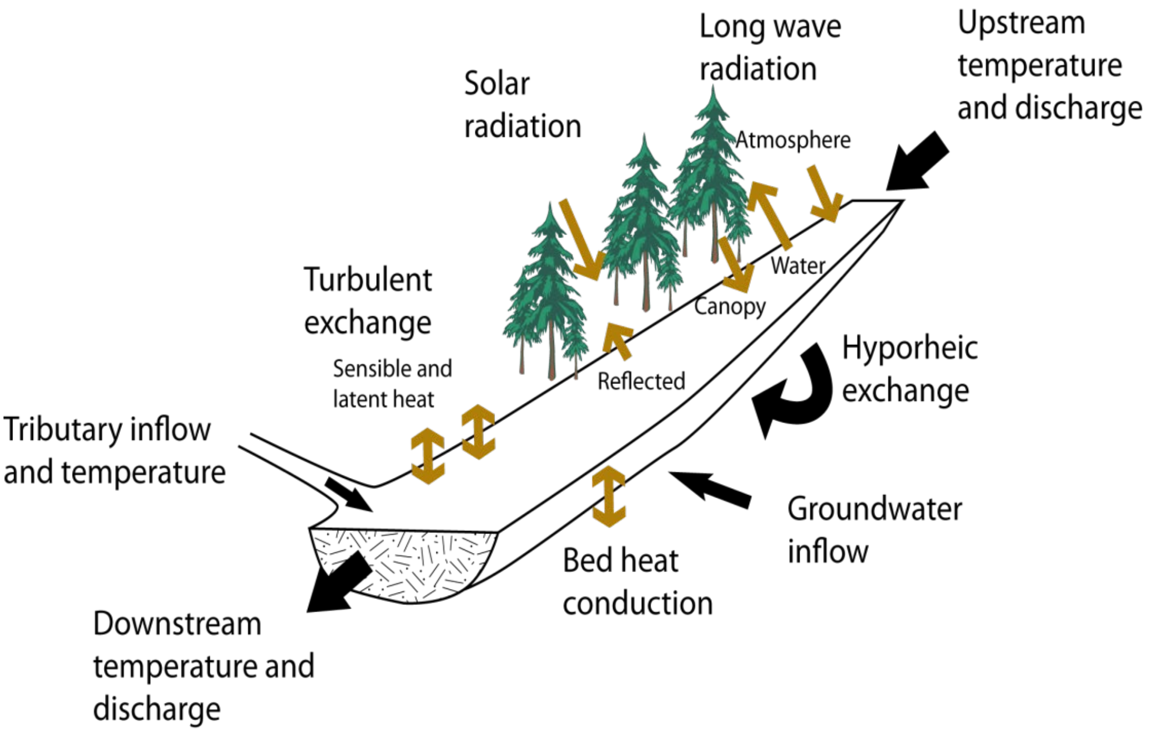


Figure 1: Conceptual model of stream heating and cooling processes (Moore *et al.* 2005a). Black arrows indicate energy fluxes associated with water exchanges.

## SHADE AND TEMPERATURE RESEARCH APPLICABLE TO RIPARIAN BUFFERS

### Limitations to Comparing Results from Different Studies

**Some of the variability in temperature and shade responses observed in the existing research may be due to differences in the actual level of vegetation removal rather than the planned treatments.** Many researcher do not describe the level of post-harvest removal of vegetation; instead simply describing the treatments as clear-cut or explaining the sites were cut in compliance with the local rules. Without post-harvest assessments, it is uncertain, what intensity of vegetative removal actually occurred in response to the harvest **(Groom et al. 2018**). Temperature and shade responses associated with these studies vary from a summer average daily maximum of 3.3°C (**Swift 1982**) to over 9°C as a summer maximum (**Lee and Samuel 1976**), and reductions in Angular Canopy Density from 75% to 47% (**Teti 2006**).

**Comparing studies is further complicated by the differences in the averaging periods associated with measuring and reporting the temperature response**. Potentially affecting comparisons are differences in the frequency of temperature samples which may range from instantaneous to 0.5-3 hour intervals (**DeGroot et al, 2007; Hetrick et al. 1998; Brown et al 1971; Burton and Likens 1973**). Additionally, researchers choose different averaging periods to conduct and present their analyses such as: seasonal average of the daily average (**Hetrick et**

**al. 1998**); annual average of daily maximum (Young et al 1999); seasonal and multi-month average maximum (**Kibler and Skaugset 2007; DeGroot et al. 2007: Swift 1982; Simmons et al. 2014; Janisch et al. 2012**); 40-day average maximum (**Groom et al 2011b**); monthly average maximum (**Levno and Rothacher 1969; Lynch et al. 1984; Harris 1977**); seven-day moving average maximum (**Dent 1995; McIntyre et al. 2017; Bladon et al. 2016; CMER 2 in Review**); annual maximum (**Brown and Krygier 1970**); and instantaneous or daily maximum (**Brown et al. 1971; Herunter et al. 2003; Cole and Newton 2013**).

**Not all of the studies use references to adjust results to account for changes in climatic conditions over their study, and as a result some of the variability in responses observed in the literature are likely influenced by seasonal differences in both stream flow and weather**. Helping to illustrate this point is the work by **Hetrick et al. (1998)**. **Hetrick et al. (1998)** alternated removal and retention of 40 m to 70 m (131 ft to 229.7 ft) patches of deciduous (red alder), riparian vegetation along two small (1-3 m) (3.3-9.8 ft) anadromous salmon streams on Prince of Wales Island in southeast Alaska. Seasonal average daily water temperature and diel fluctuations were similar in the two canopy types in 1988 when the weather was predominantly overcast and rainy was but was significantly higher in the open canopy section in 1989 when the summer weather was mostly sunny with infrequent rain. Periphyton biomass was significantly higher in open-canopy sections of the two streams in the summer of 1988 and in the one stream sampled in 1989. Using a model (from **Beschta et al. 1987**), and setting 11°C as a baseline, they predicted no increase in seasonal average water temperature under any weather condition at high flows (0.020 $m^3/s$) in a 160 m (525 ft) open reach, a 3°C increase in seasonal average stream temperature during moderate flows (0.010 $m^3/s$) over a 150 m (492 ft) reach, under sunny weather, and 3°C to 15°C in about 50 m (164 ft) of open canopy at low flows (0.001 $m^3/s$) during overcast and sunny weather, respectively.

### Clear-Cut-Only Treatments

**Clearcutting done in conjunction with wood removal from streams, scarification, or broadcast burning has been shown to increase the effect on the temperature of the adjacent streams (Young et al. 1999; Feller 1981; Levno and Rothacher 1969; Brown and Krygier 1970; Harris 1977; Lynch et al 1984; Bladon et al. 2016).** Daily maximum stream temperatures in response to such intensive treatments has been noted to be 15°C or greater (**Young et al. 1999; Brown and Krygier 1970**) with average maximum temperatures increasing by 5.5°C to 9°C (**Harris 1977; Levno and Rothatcher 1969; and Lynch et al 1984**).

**Contemporary clear-cut harvesting of merchantable trees along streams without broadcast burning, scarification, or herbicide treatments have generally found more muted affects to temperature**. **Kibler et al. (2013)** found mean daily maximum temperatures increased from 0.6 to 1.1°C when only merchantable trees were removed and high levels of slash was assumed to have aided in mitigating warming, as water surface shade was reduced on average by only 20%. **Levno and Rothacher (1969)** found clearcut logging increased maximum water temperature by 2.2°C when only merchantable trees were removed. **De Groot (2007)** carefully logged only merchantable trees (excluding machines from within 5 m of stream and leaving all shrubs behind and large wood left in the streams) and found mean daily maximum summer temperatures increased between 1°C to 2°C at the bottom of 381 m to 509 m treatments. Kiffney et al. 2003 and **Gomi et al. 2006** found clearcut treatments without buffers at study sites in coastal British Columbia experienced average summer maximum temperature increases of up to 2-8°C. **McIntyre et al. (2017)** used a replicated BACI study design to examine warming associated clear-cutting along four perennial non-fish-bearing streams in western Washington. Significant post-harvest increases in the 7-Day Average Daily Maximum Temperature Treatment Response (7-DMax) of 3.4°C and 3°C were estimated for the two years post-harvest. **Bladon et al. (2018)** used data from 3 paired watershed studies (29 sites) in western Oregon to examine headwater and downstream temperature effects associated with contemporary forest harvesting. They found the <u>median July through September</u> 7-day moving average of daily maximum stream temperature ($T_{7DAYMAX}$) was greater during the post-harvest period at 7 of the 8 harvested upstream study sites. The four-year post-harvest average of the treatment effects ranged from 1.2°C to 3.3°C among these seven sites. The largest increases occurred within the Trask paired watershed study where the median $T_{7DAYMAX}$ had warmed from 2.4 to 3.9 C at the three clearcut study sites.

**Removing the vegetation from even small sections of stream can result in substantial warming where the water is shallow or moving slowly.** **Burton and Likens (1973)** found that temperature in a small stream could rise by 4-5ºC as it passed through 25 m (82 ft) wide clear-cuts during the month of July in a hardwood forest in New Hampshire. **Herunter et al. (2003)** found that low flow streams draining under 50 m (164 ft) road right of ways commonly increased 1.0°C (maximum 2.2°C), with increases of 0.5°C and 0.2°C (maximums of 1.5°C and 0.4°C) detected with 30 (98.4 ft.) and 20 m (65.6 ft) right of ways, respectively. **Clinton et al. (2010)** found 60 m (196.9 ft) patch cuts along one side of a Georgia stream resulted in a 2°C increase in the monthly maximum stream temperature within the cut area following harvest. **MacCracken et al. (in review)** examined the effect of reducing canopy density along 50 meter (164 ft) test reaches in small non-fish bearing streams in Western Washington. Canopy density was reduced from 92-97% pretreatment to 77, 61 and 40% post-treatment in the three strata examined. The maximum seven-day moving average increased 0.5, 2.0, and 2.5°C, respectively, for the three shade levels examined. **Brown et al. (1971)** assessed the change in temperature associated with clear-cutting for harvests and roads, and found a 150 foot (45.7m) gap in vegetation during road construction resulted in a 7.2°C increase in stream temperature. A 60 foot (18.3 m) fire line and skid trail was associated with a 2.2°C increase. **Simmons et al. (2014)** found that clearcutting in 80 m to 130 m (262.5 to 426.5 ft) long reaches during the summer at 11 sites in the USA and Canada increased daily maximum temperatures by an average of 1.0ºC. **Dent (1995)** found that the typical instantaneous temperature increase within a 600 foot (182m) harvest block ranged from 2.0 to 3.75°C, while across 300 foot (91.4m) openings ranged from 0.11 to 0.86ºC; with a 10 foot wide untreated brush strip left along the streams edge. **Cole and Newton (2013)** examined three types of buffer retention treatments within small (257 to 371 feet) (78.3 m to 113 m) stream-adjacent harvests on four small streams in Western Oregon. In the no-merchantable tree retention treatment where herbicide was applied beyond 3 m (9.8 ft) daily maximum stream temperatures increased up to 3.8°C. **Lynch et al. (1984)** estimated that flows from an unbuffered stream that became perennial after harvest created 500 m (1640 ft) of exposed stream which raised the temperature of the downstream perennial stream by 3.9-4.5°C.

## Buffer Width Comparison Studies

It is common for stream buffers to be established as regulatory zones within which no-harvest is permitted. While the use of buffers is common, there is a surprising lack of available research comparing the effectiveness of different widths and configurations in maintaining either stream shade or water temperature.

The studies found for this review include buffers of widths ranging from approximately 20 to 140 feet, but most of the work is focused on buffers of three general widths of 33, 49 and 98 feet (10, 15, and 30 meters).

**Research comparing buffers of 98 feet (30 m) and wider generally find these buffers perform better for maintaining shade and stream temperature than narrower buffers.** However, 98 ft (30 m) no-harvest buffers have sometimes been associated with treatment responses **(Rishel et al. 1982; Kiffney et al. 2003; Gomi et al. 2006)**, and narrower buffers have been found by some researchers to be fully effective (**Brown et al. 1971; Wilkerson et al. 2006; Cupp and Lofgren 2014)** . These somewhat conflicting results, need to be considered in the full context of which the test prescriptions were applied on the landscape, and as part of the collective consideration of the scientific weight provided by all the buffer studies presented in this review. **Cole and Newton (2013)** found no significant warming associated with the one 98 ft (30 m) buffer they tested in Western Oregon; compared with warming up to 5.3ºC for the 49 ft (15 m) buffers tested. **Kiffney et al. (2003)** found an average treatment response of 1.7ºC for 98 ft (30 m) buffers using a BACI replicated treatment design in British Columbia. This compared with the 3ºC increase they found associated with 49 ft (15 m) buffers. **Gomi et al. (2006)** used a subset of the data from **Kiffney et al. (2003)** to demonstrate a new method for analyzing seasonal temperature response data and similarly found a statistically significant but lower increases in temperature with the 98 ft (30 m) buffers. **Rishel et al. (1982)** found monthly average maximum temperatures (Feb – Oct) increased from 0.6 to 2.2ºC in the one watershed they included in their study having a 98 ft (30 m) buffer. They further separated this response seasonally with spring treatment effects of 0.7, 2.2, and 2.2ºC and summer treatment effects of 1.1 and 1.8ºC, for the treatment streams where data sets were complete enough for their study design. The **Kiffney et al. (2003)** treatment response for the 98 ft (30 m) buffers was further supported by their findings of an increase in both photosynthetic active radiation (PAR) and periphyton growth. **Erman et al. (1977)**, however, surveyed 62 northern California streams and found no measurable biologic responses with buffers of 98 ft (30 m) or greater in width. **Groom et al. (2018)** used previously collected field data from Oregon streams to develop a Bayesian statistical model to simulate prescribed harvests. The model predicted that employing a no-cut slope-distance riparian zone of 27.4 m (89.9 ft) would result in average warming below 0.3°C of unharvested conditions, with the range of distances that contain 0.3°C in their 95% credible interval ranging from 22.8 m (74.8 ft) to 33.5 m (114.8 ft).

While other research testing stream temperature responses to buffers of this 98 ft (30 m) width category were not identified, authors were found who provide shade response data. **Steinblums et al. (1984)** measured angular canopy density associated with buffer strips of varying widths in forests dominated by Douglas-fir, western hemlock, and western red cedar and found a significant relationship between buffer width and ACD; which when plotted out shows the percent of cumulative ACD continuing to increase, but at a diminishing rate, as buffer width increases beyond about 100 ft **Brazier and Brown (1973)** examined shade associated with buffers along nine steep v-shaped small mountain streams in western Oregon and concluded maximum angular canopy density was reached within 80 feet (24.4 m).

**Cupp and Lofgren (2014)** used a replicated BACI study to test effectiveness an eastern Washington riparian prescriptions requiring all available shade (ASR) be retained within 75 feet of the stream in riparian management zones of 75 to 110 feet in width (depending on stream size and site class). As operationally applied the ASR rule limited the mean decrease in effective shade to 1%, with a maximum decrease of 4%. Mean daily maximum stream temperature increased on average by 0.02°C in both the ASR sites and the no-harvest reference reaches. **McGreer et al. (2012)** conducted a companion study to Cupp and Lofgren (2014) and found average pyranometer responses at the 16 sites supported the conclusion that the all available shade rule did not significantly alter the amount of solar radiation reaching the stream.

The cause for some authors finding a measurable increase in water temperature using 98 ft (30 m) buffers is not clear, but **Rishel et al. (1982),** and **Lynch et al. (1984)** in a companion paper, note that their buffers were placed alongside only perennial streams in the watershed, and in one intermittent stream that became perennial after harvest very warm water was being delivered to the perennial stream. They estimated this warm water was sufficient to cause or contribute to the measurable increase in temperature to the perennial stream downstream of the 98 ft (30 m) buffer test reach. Increasing flows in stream channels after harvest due to reduced evapotranspiration as a result of tree removal and brush control is a well know response to forest harvesting. If this activates flows in clear-cut reaches without adequate buffers those flows would contribute to downstream warming. **Harris (1977)** examined the effect of multiple clear cut patch cuts at a watershed scale. The author found that three clear-cuts covering 25% of a 750 acres watershed with 100 ft buffers placed only on the perennial stream reaches (2 of the three patch cuts) resulted in a 2.0°C increase in the monthly mean maximum temperature at the bottom of the watershed. Similarly, **Bourque and Pomeroy (2001)** examined stream temperatures collected in five neighboring streams (sub-catchments) in New Brunswick, Canada, over a period of five years. The purpose was to determine if land cover changes from clear cutting in areas outside forest buffer (applied to streams >0.5 m (1.6 ft) wide) might contribute to an increase in summer mean stream temperatures in buffered streams down slope by infusion of warmed surface and sub-surface water into the streams. Mean temperatures down slope of harvest areas increased by 0.3 to 0.7°C. No clear relationship was found between forest buffer strip width used in the study (ranging from 30-60 m) and the level of stream warming observed. However, the authors found the increase in mean stream temperatures coincided with forest harvesting activities outside forest buffers, where conditions promoting stream warming were greatest. Near perfect linear relationship between stream temperature change and modeled insolation levels.

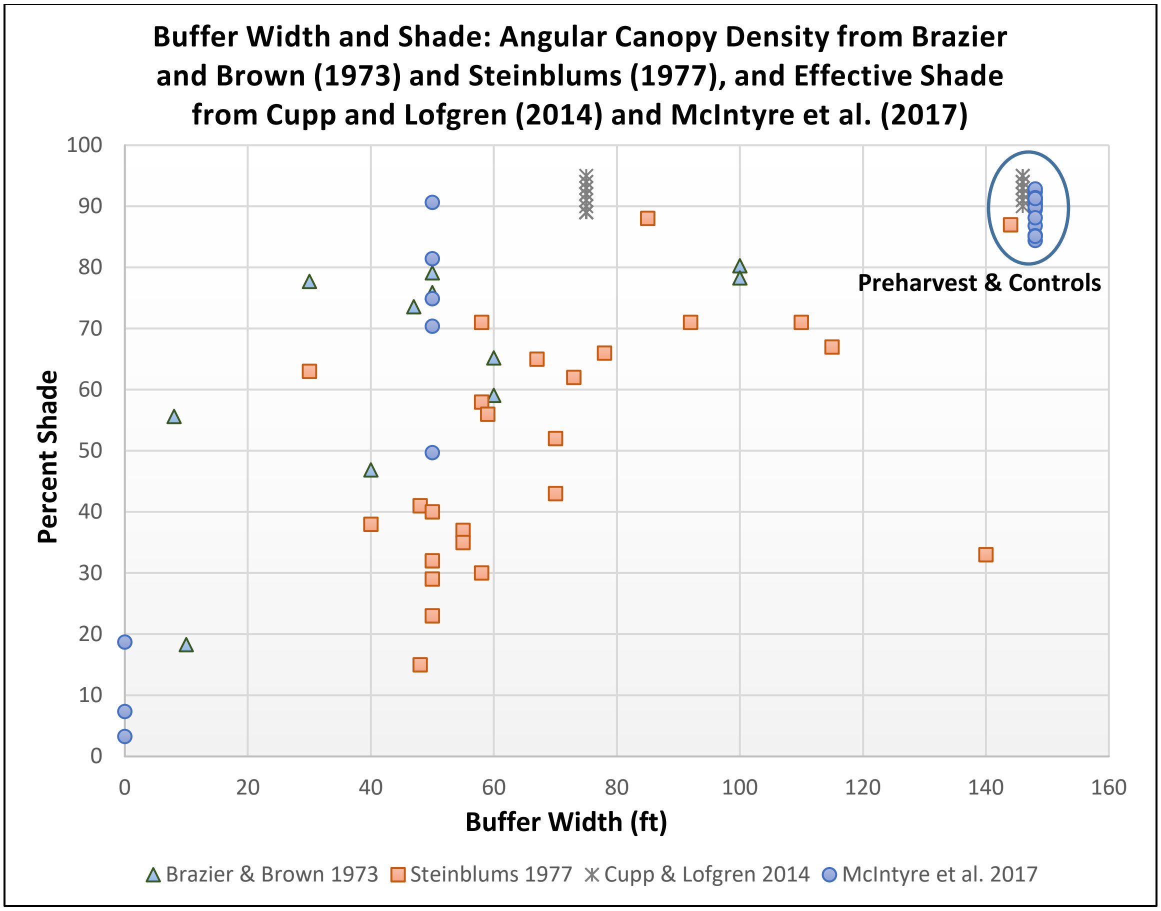
**No-harvest buffers of widths less than 69 feet (15-21 m) have generally been shown to be less successful in preventing the measurable warming of streams than wider buffers (e.g., 98 ft, 30 m). Veldhuisen and Couvelier (2006)** examined shade against buffer width at 14 sites over a three year period in northwestern Washington and concluded that buffers 66 ft (20 m) or wider are needed to be equivalent to an uncut standing forest. **Jackson et al. (2001)** studied first- or second-order (*non-fishbearing*) streams in the Coast range of Washington. Three streams were cut to widths ranging from 49-69 ft (15-21 m) (*one side of one buffer was 2.3 m*). Summer average maximum temperature changed in the three buffered streams varied with two becoming warmer (1.6°C and 2.4°C) and one slightly cooler (-0.3°C). Temperatures within the two monitoring stations located in the one non-merchantable buffer site increased 3.7°C and 6.6°C. The authors opined that the non-merchantable trees left appeared to have prevented shading from slash burial in addition to providing less overhead canopy. It should be noted that, while stream lengths were not generally provided, some were described as being less than 100 meters. In three test streams examined by **Cole and Newton (2013)** that were tested with 49 ft (15 m) buffers in Western Oregon, each reportedly experienced a 5.3°C increase in the daily maximum temperature. **Brown et al. (1971)**, however, in a single season upstream-minus-downstream comparison study was unable to detect any temperature change in two test streams with buffers of 47 to 50 feet (14.3-15.2 m) (one reach 550 feet in length and the other 2,150 feet). **Janisch et al. (2012)** used a BACI design to examine stream temperature response to forest harvest in small (<9 ha) forested headwater catchments (*from 2.2 to 21 acres*) with 33-49 ft (10-15 m) wide buffers. In the first year after logging, daily maximum temperatures during July and August increased in these catchments on average by 1.1°C (range 0.0 to 2.8°C). Temperature responses after logging were found to increase in direct proportion to the area of exposed water surface area and saturated soils (wetlands) upstream of monitoring stations. Length of continuously wetted stream channel above the stream-temperature monitoring stations ranged from as little as 34 meters to as much as 203 meters (111 to 666 ft). **McIntyre et al. (2017)** used a replicated BACI study design to examine warming associated with continuous 50-foot (15.2 m) wide buffers along four perennial non-fish-bearing streams in western Washington. Significant post-harvest increases in the 7-Day Average Daily Maximum Temperature Treatment Response (7-DMax) of 1.2°C were estimated for each of the two post-harvest years. The authors concluded based on their work that even small (less than 10%) decreases in shade were noted as causing measurable increases in summer maximum stream temperature.

Several studies were found that examined the temperature responses of using no-harvest buffers of 20-33 ft (6-10 m) wide. **Kiffney et al. (2003)** found an average treatment response of 3°C for three replicate 33 ft (10 m) buffers, using a BACI replicated treatment design in British Columbia. **Gomi et al. (2006)** used a subset of the data from **Kiffney et al. (2003)** to demonstrate a new method for analyzing seasonal temperature response data. In their 2006 study, **Gomi et al. (2006)** found that for the one stream they tested having a 33 ft (10 m) buffer, the seasonal average maximum temperature increased by 2.2°C in the spring and 4.1°C in the summer.

In addition to the research on temperature responses, **Veldhuisen and Couvelier (2006)** examined stream temperature and shade against buffer width at 14 sites over a three year period in northwestern Washington and estimated that a 10 m (33 ft) buffer (on each side) provided about 70% of the shade of a mature forest. In the work of **Steinblums et al. (1984)** buffers of approximately 49 ft (10 m) are estimated to provide 27.4% less Angular Canopy Density than would a 100 ft buffer (30.5 m). **Schuett-Hames et al. (2012)** examined the operational application of the state of Washington forestry prescriptions to non-fish-bearing streams in western Washington. Eight sites were clear-cut to the edge of the stream, and thirteen had 50-foot wide no-cut buffers on both sides of the stream. Comparisons with local reference sites found that one year after harvest, mean overhead shade was lower in the 50-foot buffer streams (76%) than in the reference patches (89%). Mean overhead shade in the clear-cut streams was 12% one year after harvest, but increased to 37% five years after harvest in response to growth of shrubs and saplings. The mean density of live trees in the 50-foot buffers experienced 3.5 times the mortality of that of the reference patches in the first three years. Wind was the dominant mortality agent in the 50-foot buffers, while suppression mortality exceeded wind mortality in the reference reaches. The cumulative percentage of live trees that died over the entire five year period was 27.3% in the 50-foot buffers compared to 13.6% in the reference reaches.

In Figure 2 below, four studies which use comparable shade metrics are shown together to illustrate study-specific variability. The studies by **Cupp and Lofgren (2014)** and **McIntyre et al. (2017)** were conducted on harvest age stands of commercial forest lands in Washington State. The work of **Brazier and Brown (1973)** and **Steinblums et al. (1984)** targeted small steep v-shaped valleys and included a much wider range of stand ages (from young to old growth) and recovery times prior to measurement (1-15 years). In the figure, preharvest and control stand results are placed just beyond the tested maximum cut buffer width to allow for comparison. In addition to buffer width, these shade results would be affected by site differences in buffer orientation to the sun, topographic shade, stand height, and density.

**Figure 2**. Angular Canopy Density and Effective Shade data from four studies examining buffer width effects on shade in the Pacific Northwest.



## Buffer Thinning Studies

Studies examining the effect on water temperature in response to forest thinning prescriptions are not easily summarized. The studies obtained for this review generally test the operational expression of minimum requirements and commonly do not provide the actual pre- and post-harvest metrics to allow the results to be converted to comparable expressions of the actual harvest or the level of buffer retention. Few authors tested similar buffer widths and levels of harvest within those buffers, and only one limited pilot study specifically examined the mitigating effect of including or not including no-harvest zones immediately adjacent to the stream **(Park et al. 2008)**. While these conditions restrict the strength of the existing information to inform decision makers about the effectiveness of specific prescriptions, there are general results which are common enough to the literature citations to be helpful in guiding the development of future research or interim management decisions (to be validated or adjusted using adaptive management).

**Evidence suggests wider Riparian Management Zones (RMZs) provide more opportunity to thin within them without causing a significant increase in stream temperature or loss of canopy cover. Groom et al. (2011b)** using a well replicated BACI design examined and compared the State of Oregon's forestry rules for harvesting along on small to medium fish bearing streams on private versus state lands. With average retained buffers of 31.0 m (101.7 ft) and thinning within those buffers allowed outside of a 6 m (19.7 ft) immediately adjacent to the stream down to 10.0 $m^2$/ha (small streams) and 22.9 (medium streams) $m^2$/ha (**43.6-99.8 $ft^2$/ac**.) basal area, the authors found a mean increase in the 40-day average summer maximum temperature (July 23-August 15) of 0.7°C (range -0.9-2.5°C). In a follow-up up study **Groom et al. (2011a)** found the harvest rules as applied to these privately owned treatment sites exhibited a 40% probability of exceedance of Oregon's water quality temperature antidegradation standard (i.e., >0.3°C increase in the 7-day average daily maximum temperature). Under the Private Forest regulations, the riparian management areas (RMAs) are 15 m and 21 m (49.2 and 68.9 ft) wide around small and medium fish-bearing streams, respectively. Both small and medium streams have a 6 m (19.7 ft) no-cut zone immediately adjacent to the stream. Harvesting is allowed in the remaining RMA to a minimum basal area of 3.7 $m^2$/ha (small streams) and 11.1 $m^2$/ha (medium streams) (16.12 and 48.35 $ft^2$/ac, respectively). No increase in temperature or increase in the probability of exceedance were detected in streams buffered using the greater state lands prescription. Sites on state lands retained wider 52 m (170.6 ft) buffers on all fish-bearing streams, an 8 m (26.2 ft) no cut zone, and limited harvest within 30 m (98.4 ft) of the stream and only when it was determined needed to create mature forest conditions. Harvest operations in this zone must maintain 124 trees per hectare (50 TPA) and a 25% Stand Density Index. **Groom et al. (2011b)** further noted their best supported shade models indicated that the lowest observed shade value of 50% is associated with a predicted increase in the maximum stream temperatures by as much as 2ºC. In a draft predictive modeling study, **Groom et al. (2018)** used their previously collected field data from Oregon streams to develop a statistical model to simulate prescribed harvests. The authors combined two earlier stream temperature and shade models from Groom et al (2011a and 2011b) into a Bayesian hierarchical model. The model predicted that harvest according to a full implementation of the state forest harvest plan would on average result in a 0.19C increase, while the model predicted that a similarly-scaled harvest to current private forest regulation specifications would lead to an average increase of 1.45°C. [The range of distances that contain 0.3°C in their 95% credible interval range from 22.8 to 33.5 m (75 ft to 110 ft)]. This is useful in comparing against the treatment responses observed in other research. **Bladon et al. 2016** conducted a BACI study of a watershed in western Oregon harvested under the current forest practices rules. The authors did not report the actual buffer widths or tree retention levels, but the state rules would have allowed clear cut harvest down to a 15 m (49.2 ft) riparian management zone with no harvest within 6 m (19.7 ft) of the stream and harvesting allowed in the remaining RMA down to a minimum basal area of 3.7 $m^2$/ha (small streams) (16.12 $ft^2$/ac) (no buffer was required for non-fish bearing tributaries). The authors found that only the summer period analysis showed a statistically significant increase in temperature, which was reported as 0.6° C across sites. The authors acknowledged the north to south orientation of the stream and the steep catchment and channel slopes (39°) may have minimized the temperature response and so the results should be extrapolated with caution. **Wilkerson et al. (2006)** tested three replicates of two sided patch (6 ha, 14.8 ac.) cuts along (300 m, 984 ft) 1st order tributaries in Maine. Clearcutting adjacent to 11 m (36 ft) partially harvested buffers (31% reduction in basal area) resulted in an 11% reduction in canopy cover and an increase in the seasonal average maximum temperature of 1.4-2.5°C. While clearcutting with 23 m (75.5 ft) partially harvested buffers (21% reduction in basal area) resulted in only a 4% reduction in canopy cover and no increases in either the 7DADMax or summer average maximum stream temperature. **Witt et al. (2016)** evaluated two-replicate buffer treatments in first-order perennial watersheds in Kentucky. Watersheds with 55-ft perennial-stream RMZs and 50% canopy retention resulted in a 3.4°F (1.9°C) increase in mean maximum daily temperature. While watersheds with 55-ft and 110 ft perennial RMZ's requiring 100% canopy retention were not associated with a significant temperature increase. **Cupp and Lofgren (2014)** used a replicated BACI study to test two riparian prescriptions applied to 1,000 ft test reaches along 30 small fish-bearing streams in eastern Washington. The first prescription required that all available shade (ASR) be retained within 75 feet of the stream (applied within an RMZ of 100 feet for large streams (≥15 ft) and 75 feet for small streams (<15 ft)). The second prescription is the standard rule (SR), which conditionally allows harvest within 75 feet or 100 feet (small versus large streams) of the stream to reduce basal area to 70, 90, or 110 $ft^2$/acre basal area and a minimum 50 TPA; depending on the elevation and pre-harvest density and basal area (the actual average basal area retained was 122 $ft^2$/ac, and TPA retained was 109). As operationally applied using a densiometer to identify harvest-eligible trees, the ASR resulted in median reductions in BA and TPA of 5% (0-27%) and 13% (2-19%), respectively. This resulted in a mean decrease in shade of 1%, with a maximum decrease of 4% (n=16). The limited response in shade was supported in a separate study performed in **McGreer et al. (2012)** who found no significant harvest related changes in solar energy reaching the ASR treatment streams. Under the SR treatment, median reductions in BA of 26% (5-56%) and TPA of 39% (10-62%) occurred. This resulted in a mean decrease in shade of 4%, with a maximum reduction of 10% (n=14). Mean daily maximum stream temperature increased 0.16°C in the SR harvest reaches, whereas stream temperatures in both the ASR sites and in the no-harvest reference reaches increased on average by only 0.02°C. **Gravelle and Link (2007)** selectively cut first order tributary headwaters to a small stream (0.2 to 0.5 m, 0.66-1.6 ft wide) in northern Idaho. Approximately 50 percent of the treatment watershed was harvested using a 50% canopy removal target (actual level of retention not provided), with a 9 m (30 ft) equipment limitation zone. Based on densiometer measurements taken 5 to 10 cm above the water surface, the treatment resulted in an average initial 2% decrease in stream canopy cover, followed by three years where canopy cover increased above pre-harvest and control levels. One of two monitoring sites located within or just below the selective-cutting treatments had a significant increase in temperature (0.4°C) with the other showing a non-significant heating effect of 0.6°C in the first year post-harvest (2002-2005). **Moore (2007)** used a paired-catchment BACI design to examine the effects of harvesting on stream temperature in western British Columbia, Canada. Removing 50% of the basal area over 40% of the catchment of three treatment streams increased the seasonal average daily maximum temperature of two creeks over 4°C, while that of a third stream increased 2°C (though daily maximum temperature increases reached 6°C on a few days during an unusually low flow period). Significant increases (>1°C) in summer maximum temperatures were equally great through spring and summer, and the daily minimum temperatures of two of the three streams experienced significant warming of 1 to 2°C.

**Macdonald et al. (2003)** used a BACI design to investigate three variable-retention harvest prescriptions on the temperature of 8 first-order streams (BFW=0.6-3.2 m, 2-10.5 ft) in the interior sub-boreal forests of northern British Columbia: 1) A 20 m (66 ft) riparian management zone comprised only of non-merchantable trees and a 5 m (16 ft) equipment exclusion zone resulted in summer maximum mean weekly temperature increases of 3°C to >5°C. The stream with greatest temperature impact extended 185 m (607 ft) through the cut-block in a small (25 ha., 61.8 ac.) watershed experiencing a 90 percent harvest (treatments ranged from 40-90 percent harvest) (2 treatment streams). 2) A 20-30 m (66-98 ft) riparian management zone comprised of only large merchantable timber >30 cm DBH and a 5 m (16 ft) equipment exclusion zone resulted in summer maximum mean weekly temperature increases from <1°C to approximately 2°C (2 treatments). Initially this treatment mitigated the temperature effects, but 3 years of wind-throw reduced canopy density and caused temperature impacts. The authors noted the stream having the lowest temperature response was the largest in the study (2.8 m, 9.2 ft), had a deeply incised channel, less stream length in the cut-block, and had the least amount 6% of watershed harvested (the other treatment had 38% of watershed harvested). 3) A 20-30 m (66-98 ft) riparian management zone comprised of only large merchantable timber >30 cm DBH and a 5 m equipment exclusion zone and applied only to the lower 60% of the stream with removal of all riparian vegetation in the upper 40% of the watershed resulted in a summer maximum mean weekly temperature increase of nearly 4°C (one treatment stream). The actual percent of watershed harvested was noted to be 89%. Five years after harvest, temperatures remained 4°C to 6°C degrees warmer, and diurnal variation remained higher than in the control streams regardless of treatment. The authors credit wind-throw as impacting the thermal recovery of streams in their study.

**Herunter et al. (2004)** used a subset of the study sites examined in **Macdonald et al. (2003)** in a follow-up study and found after seven years, none of the treatments showed full recovery of stream temperature. **Kreutzweiser et al. 2009** evaluated the effect of partial-harvest logging in riparian buffers along boreal mixed-wood forest streams (stream BFW 2.6–6.4 m, 8.5-21 ft) near Ontario, Canada. Partial-harvest logging in 30-100 m (98-328 ft) wide riparian buffers) resulted in an average removal of 10.8%, 20.4%, and 28.6% of the basal area from riparian buffers (550-600 m in length) at the three logged sites. At the two more intensively logged sites, there were small (<10%) reductions in canopy cover (P=0.024) but no significant changes in light (PAR) at stream surfaces (P>0.18). There were no measurable impacts on stream temperatures at two of the three logged sites. At the most intensively logged site, daily maximum temperatures were significantly higher (approx. 4°C) for about 6 weeks in the first summer after logging (P<0.001) but the authors thought this was due to a temporary logging-induced disruption in cool water inputs from a lateral-input seep area. **Boggs et al. (2016)**, however, tested 15.2 m (50 ft) buffers of non-high-value trees (27% and 48% of basal area removed; consisting of high value merchantable trees) and noted that temperatures spiked after harvest, although provided no temperature data. **Hewlett and Fortson (1982)** used a paired watershed design to examine the effect of clear cutting a 50 year old Loblolly pine plantation on water temperature in Georgia. A 20 foot (6.1 m) wide buffer was left on each side of a small (6-10 feet wide) (1.8-3 m) entrenched stream draining 80 acres wherein mature pines were removed and non-merchantable hardwoods retained. A small tornado took about one quarter of the remaining over-story in the buffer strip, covering about 50 percent of the stream with deciduous hardwoods. The authors found that monthly mean daily maximum water temperatures increased 12°F (6.7°C) degrees during June and July for the first four years after clearcutting; rising to 14°F (7.8°C) in the hottest summer. The authors also found that temperatures remained elevated even though the lower channel was almost completely covered by low shrubs and brush. The authors opined that this may have been a consequence of the still air under the shrub layer not facilitating a compensatory evaporative cooling response. They also provided evidence to support the hypothesis that clear cutting was elevating ground water temperature, and therefore, elevated stream temperature was linked to the period of time needed for the seedlings and other vegetation to shade the uplands.

**There appears to be a disproportionate benefit to stream shading and temperature protection created by including a no-harvest zone immediately next to a stream as part of a thinning prescription.** In an unpublished draft study **Park et al. (2008**) conducted a field study in the Rogue River Siskiyou National Forest in Western Oregon to examine the effect of varying widths of no-harvest riparian buffers before and after thinning on angular canopy density (ACD). The study was conducted on 40 years old Douglas fir stands with 90 foot tall, 10 to 12 inch diameter trees on slopes less than 10 percent with a north-south intermittent stream flowing through the middle of the study area. Stands were described as "over dense" (220 tpa) and needing treatment.

The study design consisted of 5 plots (3 on one bank and 2 on the opposing bank) that received equal levels of thinning treatments but varied in the width of no-harvest zone adjacent to the stream. Each plot was 100 feet wide and 180 feet in depth. Zero, 20, 40, 60, and 80 foot (6.1, 12.2, 18.3, 24.4 m) no-harvest zones were assigned to the five plots, without replication. ACD was measured at two points in each plot using a digital camera placed on the bank opposite the treatment and canted 40° towards the treatment of interest. ACD was measured before and after treatment. A light histogram was generated to assess the portion of the photograph that represented the color and lightness of open sky.

The study found that thinning (removing 80-100 tpa and leaving approximately 120-140 tpa) to the stream without leaving a no-harvest buffer reduced ACD by 14% to 24%. As the width of the no-harvest buffer increased, the loss of ACD decreased. ACD loss reduced to 6% ACD with use of a 20-foot no-harvest buffer, 0.9% with a 40-foot (12.2 m) no-harvest buffer, 0.05% with a 60-foot (18.3 m) no-harvest buffer, and +0.1% with an 80-foot (24.4 m) no-harvest buffer. The authors concluded that retaining a 50-foot no-harvest buffer adjacent to thinning to the level in their study should prevent shade loss. However, the work of **Park et al. (2008)** cannot stand on its own due to a number of factors: 1) treatments were not replicated, 2) study was not published or peer reviewed, 3) the study tested only one level of relatively light thinning, and, 4) the study used a novel method to assess ACD. However, the general approach of setting up the plots and the overall pattern in the post-harvest response was used to inform the design of our RCS study.

**Teply et al. (2014)** developed a model to simulate prescriptions for the state of Idaho which allow management within 75 foot (22.9 m) RMZs without causing more than a 1.8°C increase in stream temperature or a greater than 10% loss in shade. The authors found that thinning throughout the buffer (i.e., up to the stream bank) and narrow buffers (e.g., 50 feet or less (≤15.2 m)) led to an unacceptable decrease in shade (pre-defined as >10%). Based on their simulations, it was determined they could not limit shade loss to 10% except with very light thinning in these

75 foot (22.9 m) RMZs, and that maintaining “an inner no-harvest zone is an important consideration for formulating effective riparian management prescriptions.”

**The effectiveness of narrower buffers may be more easily compromised by post-harvest tree losses due to wind events. Rex et al. (2012)** found that tree retention decreased from 16, 20 and 14 stems of merchantable trees per 100 m (328 ft) of buffer length to 6, 16, and 10 stems, respectively (36% reduction on average) from blow down along small fish-bearing streams (0.9-1.48 m, 3-4.9 ft wide). The combined effect was a harvest related 30-50% decrease in shade (ACD) as well as an increase in air and stream temperature at all treatment sites which persisted for the two years of post-harvest monitoring. **Macdonald et al. (2003)** in a study in the interior sub-boreal forests of northern British Columbia found that one of their three treatments, a 20-30 m (66-98 ft) riparian management zone comprised of only large merchantable timber >30 cm DBH initially mitigated temperature effects, but 3 years of wind-throw-reduced canopy density summer maximum mean weekly temperatures increased from <1°C to approximately 1-2°C. **Herunter et al. (2004)** used a subset of the study sites examined in **Macdonald et al. (2003)** and concluded that after seven years, the treatment streams still had not reached full recovery of temperatures. **Schuett-Hames et al. (2012)** examined thirteen sites with 50-foot (15.2 m) wide no-cut buffers on both sides of the stream. The mean density of live trees in the 50-foot buffers experienced 3.5 times the mortality of that of the reference patches in the first three years. Wind was the dominant mortality agent in the 50-foot buffers, while suppression mortality exceeded wind mortality in the reference reaches. The cumulative percentage of live trees that died over the entire five year period was 27.3% in the 50-foot buffers compared to 13.6% in the reference reaches.

**Shading produced from an over-story of mature trees may be more effective in general than that provided by low-lying vegetation in preventing harvest related stream warming. Rex et al. (2012)** found water temperature in their study streams continued to experience heating by 1–2°C rather than decreasing with increasing understory shade recovery. With an observed increase in air temperature 0.5 m (1.6 ft) above the streams, the authors suggested higher cut block wind speeds was facilitating greater energy exchange by long wave, conductive, and advective heat transfer mechanisms. **Macdonald et al. (2003)** tested a 20 m (66 ft) riparian management zone comprised only of non-merchantable trees and found summer maximum mean weekly temperature increases of 3 to >5°C. However, a 20-30 m (66-98 ft) riparian management zone comprised of only large merchantable timber >30 cm DBH resulted in temperature increases from <1°C to approximately 2°C. **Allen and Dent (2001)** examined riparian structure, buffer width, and stream shade at 30 sites in the northwest coast range and 31 sites in the Blue Mountains of northeastern Oregon. Data were collected on both harvested stream reaches and those with no recent history of harvest. There was no distinct trend between percent of shade contribution from shrubs and bankfull width with narrow channels. However, shrub contribution to shade was less than 8% on channels wider than 25 ft in both geo-regions. Shade over streams in the Blue Mountains appears to be more sensitive to having additional trees farther away from the stream than the Coast Range. Authors concluded that if the objective is to maximize shade, this would suggest promoting stands in the stem exclusion stage. **Hewlett and Fortson (1982)** used a paired watershed design to examine the effect of clear cutting a 50 year old Loblolly pine plantation on water temperature in Georgia. The authors found that temperatures remained elevated even though the lower channel was almost completely covered by low shrubs and brush. The authors opined that this may have been a consequence of the still air under the shrub layer not facilitating a compensatory evaporative cooling response. They also provided evidence to support the hypothesis that clear cutting was elevating ground water temperature and therefore, elevated stream temperature was linked to the period of time needed for the seedlings and other vegetation to shade the uplands. **Klos and Link (2018)** examined the radiative heating of small streams having 5-year old riparian buffers that differed substantially in their structure but had similar levels of shade (radiative energy). In spite of providing similar shade at the water surface, buffers composed of shrubs were not as effective at preventing heating as those composed of trees. The authors concluded having the warmer air closer to the stream allowed for greater turbulent transfer of sensible heat to the stream.

**Changes in canopy shading of more than 6-10% has been associated with measurable (>0.2°C) warming of streams in well replicated studies. Allen and Dent (2001)** examined riparian structure, buffer width, and stream shade at 30 sites in the northwest coast range and 31 sites in the Blue Mountains of northeastern Oregon. Data were collected on both harvested stream reaches and those with no recent history of harvest. Average stream shade in harvested stands was 15% and 11% less than unharvested stands in the Blue Mountain and Coast Range regions, respectively. **McIntyre et al. (2017)** used a replicated BACI study design to examine three levels of harvest treatments in Western Washington and observed a significant increase in stream temperature (1.2 – 3.4°C) with a mean decrease in angular canopy density greater than 10% or the decrease in canopy closure greater than 5%. **Groom et al. (2011b)** used a well replicated BACI study to examine temperature changes associated with riparian harvests in the coastal Douglass fir forests of western Oregon. The authors reported generally observing an increase in maximum temperatures post-harvest for sites that exhibited an absolute change in shade of greater than 6%. **Bladon et al. (2016)** in testing the state of Oregon's forestry regulations found a 7% decrease in canopy closure resulted in a statistically significant 0.6°C increase the average summer 7-day average daily maximum temperature. **Wilkerson et al. (2006)** tested three harvest replicates in 1st order tributaries in Maine and found an 11% reduction in canopy cover resulted in an increase in the seasonal average maximum temperature of 1.4-2.5°C. The treatment having only a 4% reduction in canopy cover was not associated with an increase in stream temperature. **Cupp and Lofgren (2014)** found that a mean decrease in shade of 4% (10% maximum, n=14) along their 1,000 ft test reaches on small fish-bearing streams was associated with an estimated increase of 0.16°C in mean daily maximum stream temperature, whereas no significant difference (+0.02°C) with control streams was found in sites where a prescription to leave all available shade within 75 ft of the stream resulted in an average decrease in shade of 1% (4% maximum, n=16). **Guenther (2007)** and **Guenther et al. (2014)** examined the effect of bottom-up removal of 50% of the basal area within small (12 ha) catchments in southwest British Columbia. The authors found a 13-14.5% decrease in canopy closure associated with an increase in maximum stream temperatures from 5°C to 7°C during the summer, and increases in the average daily maximum temperatures for July and August from 1.64°C to 3.0°C across sites. The authors also identified temperature increases in both bed and shallow groundwater following harvest despite generally cooler weather in the post-harvest period. **Kreutzweiser et al. 2009** evaluated the effect of partial-harvest logging in riparian buffers along boreal mixed-wood forest streams (stream BFW 2.6–6.4 m, 8.5-21 ft) near Ontario, Canada. At the two more intensively logged sites, there were small (<10%) reductions in canopy cover (P=0.024) but no significant changes in light (PAR) at stream surfaces (P>0.18) and no significant impacts on stream temperatures. **Gravelle and Link (2007)** selectively cut first order tributary headwaters to a small stream (0.2 to 0.5 m, 1.6 ft wide) in northern Idaho. Based on densiometer measurements taken 5 to 10 cm above the water surface, the treatment resulted in only an average initial 2% decrease in stream canopy cover, followed by three years where canopy cover increased above pre-harvest and control levels. In spite of this low level of shade loss, one of two monitoring sites located within or just below the selective-cutting treatments had a significant increase in temperature (0.4°C) with the other showing a non-significant heating effect of 0.6°C in the first year post-harvest (2002-2005).

## MODELING SHADE AND SOLAR ENERGY ATTENUATION

Environmental simulation models are simplified mathematical representations of complex real-world systems. Models cannot fully depict the multitude of processes occurring at all physical and temporal scales. As generally cautioned by **Boyd and Kasper** (**2007**), measured values are more accurate than modeled values and as a general rule models should not be used where data can be measured directly. Models can, however, make use of known interrelationships among variables to predict how one variable would change in response to a change in another interdependent variable. In this way, models can serve as a useful and cost effective tool that provides a framework for investigating how a system would likely respond to a perturbation from its current state.

To provide a credible basis for predicting and evaluating options for mitigation, the ability of a model to represent real-world conditions should be demonstrated through a process of model calibration and validation. The purpose of the following discussion is to establish a foundation for examining key relationships used to predict stream shading in the SHADE.xls model, which is commonly used for both scientific inquiry and regulatory evaluations in the state of Washington.

### The Role of Beer's Law in Modeling Shade

Direct beam solar energy is the dominant source energy causing the warming of streams and rivers. Direct radiation is attenuated (lessened) when the sun's energy is reflected or absorbed in vegetative canopies or blocked by topographic barriers. As the density of the vegetation increases, and as the length of travel through that vegetation increases, fewer direct paths exist for the photons to reach the stream surface, thus increasing attenuation.

**The Beer-Lambert law establishes a relationship between canopy density and light transmission through the canopy which is commonly used in modeling both stand densities and their effect on stream shading**. Attenuation of light as it moves through vegetative canopies is commonly modeled using equations based on the Beer-Lambert law. The Beer-

Lambert law was originally developed to explain the passage of light through a solution. While it can be presented in different forms, the Beer Lambert Law is described by the following:

$$A = a(\lambda) * b * c \qquad (1)$$

where A is the measured absorbance of the solution, a(λ) is a wavelength dependent absorptivity coefficient, b is the path length, and c is the analyte concentration.

Researchers recognized Beer's equation could be modified and used to explain the attenuation and absorption of light passing through vegetative canopies. This has been done by rearranging the terms and replacing the absorptivity coefficient with a coefficient of extinction, and using the density of plant leaves to represent the analyte concentration:

$$I = I_0\, e^{-\lambda L} \qquad (2)$$

where $I$ is average short-wave radiation (light intensity) at a given height; and $I_o$ is short-wave radiation received above the canopy, $e$ is the base of natural logarithm, $-\lambda$ is the light extinction coefficient, and $L$ represents the leaf area index (LAI) accumulated from the top of the canopy down to the level $z$ (**Oke 1987; Monsi and Saeki 2005; Richardson et al. 2009**).

Additionally, transmissivity **is defined by** $T = I\,/I_0$ and can be substituted into the equation and LAI (L) replaced with other measures of vegetative density. For example, **Perot et al. (2017**) replaced leaf area index with basal area to give the following:

$$Ti = e^{(-\lambda G_i)} + \varepsilon i \qquad (3)$$

where $Ti$ is the transmittance at point $i$, $Gi$ is the local basal area per hectare at point $i$, $\lambda$ is the light extinction coefficient and $\varepsilon i$ is the residual part of the model. Tested in sessile oak and Scot pine stands in France this model explained up to 77% of the variation in light transmittance through the canopy of both mono-specific and mixed stands.

Beer's Law and its modifications has also been rearranged to solve for leaf area index, which is a valuable index of canopy density and energy absorption used in both agricultural and forestry applications. Since directly measuring LAI is both complex and time consuming, resource managers and researchers often use indirect methods such as making use of the relationships in the Beer-Lambert Law **(Pierce and Running 1988; Smith et al. 1991; Smith 1993; Aubin et al. 2000; Breda 2003; Link et al. 2004; Richardson et al. 2009)**.

Researchers have used established hemispherical photographic-based predictive models, as well as direct measures of above to below canopy light (**Lindroth and Perttu, 1981**) or energy to derive transmissivity factors. These transmissivity factors may then be paired with default light extinction coefficients from the literature to estimate LAI **(Dignam and Bren 2003, Canham et al. 1994)** based on the relationships established in the Beer-Lambert Law.

### Making Improvements to SHADE.xls

**SHADE.xls is a publicly available model developed by the Washington State Department of Ecology (Ecology, http://www.ecy.wa.gov/programs/eap/models.html). The SHADE.xls**

**model uses stream centerlines, wetted widths, and near-stream disturbance zone widths to spatially describe the physical stream, and assess solar loading in consideration of stream aspect, topographic shade, elevation and vegetative buffer characteristics. These characteristics include canopy height and density, the width of the vegetative zone, and the extent that vegetation overhangs the modeled stream segment.**

Modeled effective shade is the fraction of shortwave solar radiation that does not reach the stream surface because it is intercepted by vegetative cover and topography. Effective shade is influenced by latitude/longitude, time of year, stream geometry, topography, and vegetative buffer characteristics. SHADE.xls produces estimates of the reach-averaged hourly effective shade and potential solar energy load and is commonly used to develop Total Maximum Daily Load (TMDL) assessments by Ecology which can be applied to forest lands. The SHADE.xls model has also been used in the Washington State Forest Practices Adaptive Management Program (**Cristea and Janisch 2007**) to evaluate potential harvest options, and used to develop riparian buffer configuration recommendations for the State of Idaho (**Teply et al. 2012; and Teply et al. 2014**), as well as to propose alternative harvest prescriptions for small forest landowners in Washington (**Washington Farm Forestry Association, 2015**). Because of its common use, there is interest in further validating and increasing the accuracy of the SHADE.xls model in estimating the shade response to forest practice treatments in Washington.

SHADE.xls allows users to calculate shade using one of two optional methods: 1) the **Chen et al. (1998)** method, or 2) the original method from the ODEQ Heat Source model version 6 (see **Boyd and Kasper 2007**). Ecology recommends use of the Chen method in its stream shade analyses because it represents a published peer reviewed method that is broadly cited in other published research. Regardless of the method selected, however, they both use similar methods to estimate light absorption and transmission through vegetative canopies.

As described in **Chen et al. (1998),** the SHADE model which underlies the Ecology SHADE.xls model incorporates a series of computational procedures involving the sun position, stream location and orientation, and riparian characteristics to calculate the amount of solar radiation reaching a stream. By accounting for the dynamic shading effects of riparian vegetation and topography, SHADE computes the actual amount of solar radiation absorbed by stream water in modeled stream reaches. Input required by SHADE are the characteristics of stream channel, hillslope topography, and riparian vegetation buffers (i.e., watershed location, daily global solar radiation, stream location, stream width, topographic shading angles, vegetation shading (based on distance from edge of stream wetted perimeter to the near stream polygon boundary, width of the polygon, average height of the polygon in absolute value, average height of the polygon in reference to the elevation of the stream surface, and average canopy density of the polygon). Stream shading dynamics are controlled by the spatial relationships among sun position, location and orientation of stream reach, hillslope topography, and riparian vegetation buffers. The changing position of the sun is quantified in one-hour time steps using the two angles of solar zenith and azimuth. The model disaggregates global solar radiation into two components: direct beam and diffuse because they are reduced differently by topographic and vegetation shading effects. The reduction of direct beam radiation is controlled by the geometric relationship among the solar path, valley topography, and riparian vegetation buffers. The amount of diffuse radiation that reaches the stream surface mainly depends on the sky openness at the stream sample point used in the modeled stream reaches.

Two factors control the amount of solar radiation that enters streams. These are the shading effects of topography and vegetation buffers, and the albedo of the moving water surface. When the solar altitude is greater than the topographic shade angle, the vegetation buffer (if existent) provides the only obstruction to the sunbeam. The amount of direct beam radiation that reaches the stream surface is estimated through the following four steps. First, the solar azimuth and stream orientation is used to determine the stream bank direction from which the sunbeam comes. Second, for each vegetation polygon on the sunward bank at a stream sample point, two critical height values are estimated (minimum height a polygon can produce shade (**HMIN**), and the height required to generate a shadow fully covering the stream surface (**HFCV**)). Because the solar altitude increases and decreased during the day, a vegetation polygon that contributes shade in the morning or afternoon may not generate as much or any shade around solar noon. For each contributing buffer, the shadow width measured perpendicularly to the stream by:

$$SHDWID = \frac{(\mathrm{HDEM})\sin|\mathrm{AZ} - \mathrm{SO}|}{\tan ALT} - DIS \tag{4}$$

Where **SHDWID** is the contributing shadow width of a buffer polygon, **HDEM** is the average height of the buffer in relation to the stream surface, and **DIS** is the distance from the edge of the stream to the near-stream polygon boundary (near stream disturbance zone).

**After accounting for topographic shading, SHADE estimates effective shade density using Beer's law** (as modified by **Oke 1978**) through three steps **(Chen et al. 1998)**: 1) the extinction coefficient (**λ**) is computed using the average canopy density (**DEN**) and the average height of the vegetative polygon (**HABS**) by (5*a*); 2) the average path length of a sunbeam through the buffer (**$PL_{avg}$**) is assumed to be equal to the average of the maximum and minimum path lengths using (5*b*-4*e*); and 3) the effective shade density (**SHDDEN**) is derived (see 5*f*).

$$\lambda = \frac{\ln(1 - \mathrm{DEN})}{\mathrm{HABS}} \tag{5a}$$

$$PLmax = \frac{\min(\mathrm{SHDWID}, \mathrm{WID})}{\sin|AZ - SO|\cos ALT} \tag{5$b$}$$

$$PLmin\ = 0\ if\ HDEM\ \leq HFCV \tag{5c}$$

$$PLmin = \frac{\mathrm{TWID}}{\sin|AZ - SO|\cos ALT}\ if\ HDEM > HFCV \tag{5$d$}$$

$$PLavg = \frac{\mathrm{PLmax} + \mathrm{PLmin}}{2} \tag{5$e$}$$

$$SHDDEN = 1 - \exp(-\lambda \mathrm{PLavg}) \tag{5f}$$

The accumulated effective width of the shadow formed by the non-overhanging portion of single or multiple vegetation polygons of set width **(WID)** is then computed. The shadows of all contributing buffers are sorted and renumbered based on shadow width (**SHDWID**) in increasing order. The accumulated effective shade of the shadows can be considered as an aggregate of the shade segments. Each shade segment has an accumulated density that is assumed to be equal to the maximum SHDDEN of the contributing buffer polygons to that segment plus 20% of the SHDDEN from other contributing buffers (the accumulated density never exceeds 1). The effective width of each shade segment is equal to the actual width multiplied by the accumulated density. The sum of all overlapping effective widths of the shade segments is vegetative shade (**VEGSHD**) **(Chen et al 1998)**.

Where a vegetation polygon on the sunward bank is located very close to the stream, the overhanging canopy right above the stream surface may contribute shade (**OVHSHD**). While Ecology's SHADE.xls model allows the user sets the specific width of overhang, the Chen et al. (1998) model establishes overhang as 10% of the tree height (HABS). Therefore, when (0.1 X HABS – DIS) is greater than zero, the effective width (OVHSHD) of the stream surface shaded directly by the overhanging canopy can be computed approximately by **(Chen et al 1998)**:

$$OVHSHD = (-.1HABS - DIS)DEN \tag{6a}$$

if (0.1HABS – DIS) < TWID

$$OVHSHD = (TWID)DEN \tag{6b}$$

if (0.1HABS – DIS) ≥ TWID

Finally, VEGSHD + OVHSHD is divided by the stream surface stream width (TWID) to approximate the fraction of stream surface covered by the composite shade. This ratio then is used to estimate the amount of incoming direct beam radiation that actually reaches the water surface as expressed by (7). This ratio must be set to be one when VEGSHD + OVHSHD is greater than TWID.

Thus direct beam radiation (RADB) with shade is then derived from direct beam radiation above the buffer (RADB) by **(Chen et al 1998)**:

$$RADB\ (with\ shade) = \left(1 - \frac{\mathrm{VEGSHD} + \mathrm{OVHSHD}}{\mathrm{TWID}}\right) RADB\ (without\ shade) \tag{7}$$

The equation (5a) for estimating a light extinction coefficient used in the shade model establishes a logarithmic decay using vegetation density and canopy height. As such, the SHADE model is designed to use an extinction coefficient in association with the use of overhead shade measurements (e.g., densiometer readings or 1-visSky from Hemiview) for each of the modeled vegetative zones comprising the stream buffer. This is consistent with the conceptual foundation which was discussed previously regarding the incorporation of leaf area index as a canopy density metric in Beer's Law.

The Ecology SHADE.xls model includes the option to use overhead cover with extinction on (e.g., same as Chen's SHADE model method as described above), or to use an input value of effective shade density or angular canopy density with the extinction calculation routine turned off. If the option to turn off extinction is selected in SHADE.xls, then the following equation is used to estimate the effective shade density (SHDDEN) directly as the input of the canopy density metric (DEN):

$$SHDDEN = DEN \tag{8}$$

**The existing literature reveals the potential to improve the SHADE.xls model. Teply (2012)** and **Teply et al. (2012, 2014)** demonstrated techniques for running the model that adjust for vertical differences in canopy density (layers), and that of **Li et al. (2012)** focused on improving methods for assessing the proportion of a stream shaded especially shaded by overhanging vegetation. The common thread of these attempts at model improvement are better characterization the shade patterns created in complex riparian forest stands. The potential for model improvement is supported by the work of **Smith (1993)** who found incorporating relative density helped address clumping, **Aubin et al. (2000)** who found that understory density was an important consideration in model accuracy, and **Canham et al. (1994)** who identified crown depth as critical variable in light penetration through forest canopies.

**Teply (2012)** and **Teply et al. (2012)** used a shade model to assess the change in effective shade resulting from a 75-foot (22.9 m) RMZ thinned proportionally to 88 trees per acre greater than 8 inches diameter breast height (dbh) adjacent to a 25-ft no-harvest buffer. Average tree heights of 69 feet (21 m) and average canopy cover of 81% were used in their analysis. They found the effects of forest management increased with increased clearing of riparian buffers and with increased thinning intensity. **Teply et al. (2014)** modelled simulated changes in effective shade to a 10-foot (3 m) wide stream oriented at 45 degrees using two-sided stream harvest scenarios for five forest stand types. In this study, 50-ft (15.2 m) and 75-ft (22.9 m) wide Riparian Management Zones were thinned in simulations to four relative stocking intensities (RS 60, 50, 40, and 30) adjacent to a 25-ft (7.6 m) no-harvest zones; and a 75-ft (22.9 m) RMZ was thinned at those same four intensities but in association with a lightly thinned 25-foot (7.6 m) streamside buffer.

Based on their simulation, less than 50% of the total available shadow is cast by trees beyond 25 feet (7.6 m) from the edge of their simulated 10-foot stream. All of the tested prescriptions provided less shade than a simulated 100-ft no-harvest buffer. Declines in shade ranged from 2% to 6% due to reducing the unharvested buffer from 100 to 75 feet (30.5 to 22.9 m) (the maximum RMZ width used in the thinning treatment simulations). Effective shade steadily declined with increased thinning intensity when a no-harvest buffer was not included (approximately a 10% reduction in effective shade for each RS increment), with only slightly greater shade retained in association with a 75-ft (22.9 m) RMZ than a 50-ft (15.2 m) RMZ. Including a 25-ft no-harvest zone muted the relative effect of increasing the intensity of adjacent thinning with both the 50-ft and 75-ft (15.2 and 22.9 m) RMZ; however, the 75-ft (22.9 m) RMZ with a 25-ft (7.6 m) no-cut zone retained the greatest amount of shade and appeared to keep shade loss to approximately 7%. Lightly thinning the 25-ft (7.6 m) zone increased shade loss by approximately 10%. This simulation work suggested a disproportional benefit of including a 25-ft (7.6 m) no-harvest zone in allowing more active thinning in the adjacent RMZ. The authors also examined the relationship between model errors and 13 stand metrics. Overall, the strongest correlation with prediction errors occurs with average live crown ratio of trees.

**This RCS study proposes to treat forest stand type as a strata for analysis of variation in attenuation and for potential refinement of the light extinction coefficients in the SHADE.xls model. While there is some basis to assert that this may result in a meaningful refinement to the model, there is some acknowledged risk that the site level variation in density and extinction factors may reduce the benefits of establishing models for broad stand types.** The strong effect of stand level characteristics on light extinction has been identified by numerous researchers. **Aubin et al. (2000)** used light availability and understory vegetation to estimate light extinction coefficients (*k*) in six different forest types in Abitibi, Quebec, Canada. The Authors found that extinction coefficients varied significantly among strata and according to types of understory vegetation. **Saitoh et al. (2012)**, however, compared stand derived extinction coefficients to that of default constant k for the purpose of estimating LAI. These authors concluded the assumed k was a useful second-best alternative when applications are constrained to the fully-leaved out period.

**Canham et al. (1994)** determined that variation in light extinction was more closely related to differences in crown depth than to differences in light extinction per unit depth of crown. While understory vegetation has been found important to light transmission, **Dignam and Bren (2003)** examined overstory and understory basal area and density and found these not to be significant in their light extinction model once distance had been included. The authors opine that this may be at least in part due to the homogeneity of the study area in terms of forest type and general topography. The homogeneity of the stand was also found to be important to **Perot et al. (2017)** who found extinction coefficients did not differ between mono-specific and mixed stands of sessile oak and Scots pine; indicating modifications in crown structure and leaf distribution are likely only slight, or even nonexistent, when the two species grow in homogeneous mixtures. **Cole and Newton (2015)** found that basal area produced a lower correlation with solar radiation reaching their test streams due in part to its inability to account for differences in the spatial arrangement of the trees. **Smith et al. (1991)** concluded the extinction coefficient varied with canopy architecture and associated differences in stand structure for the lodge pole pine stands they examined in southeastern Wyoming. And **Smith (1993)** found stand level patterns of clumping prevent a single extinction coefficient from governing the attenuation of PAR for even-aged Douglas-fir stands on Vancouver Island, British Columbia, Canada. This observation was shared by **Pierce and Running (1988**) and **Breda (2003)** who both found canopy transmittance was influenced by LAI being less random and more clumped in coniferous stands. Such variation in light extinction coefficients within species has also been demonstrated other forms of agricultural crops besides forestry (**Costa and Dennett, 1992**).

Critical questions being asked in this study would inform if improvements can be made to the Ecology SHADE.xls model so it can be used more effectively in estimating stream shading under a wide variety of riparian stand management prescriptions.

Two key elements of the SHADE.xls model stand out as potentially benefiting the most from refinement and validation, and thus aid in the model's use in timber stands common to managed forest lands covered by the FPHCP in Washington. These are the light extinction coefficient used in processing canopy density effects (**Link et al. 2004**) and the canopy overhang function which creates an additive-extinction algorithm within the model (**personal communication with SHADE.xls developer Greg Pelletier, Department of Ecology**).

## METHODS FOR MEASURING SOLAR ENERGY AND CANOPY DENSITY

**Changes in canopy density and light and energy transmission through vegetative canopies can be measured directly or indirectly. The choice of a method or combination of methods needs to match the purpose of the investigation (Fiala et al. 2006). Tradeoffs occur between cost, accuracy, speed, and simplicity that must be considered; and the choice of instruments needs to be based on the forest resource issue that is of greatest interest** (**Brunnel and Vales 1990; OWEB 1999; Teti and Pike 2005**). The purpose of this discussion is not to provide a detailed review these methods but instead to provide a general framework for understanding some of the general limitations and uses as they may apply to this RCS study.

Photometric, radiometric and quantum (such as PAR) techniques may all be used to directly measure the transmission of light and energy through a canopy (**Jennings et al. 1999).** Canopy density, which affects that transmission, may be examined through both direct and indirect means. Indirect estimates are typically used to substitute for otherwise complicated and expensive direct measurements (**Jennings et al. 1999**). For example, leaf area index can be measured directly by extensive destructive field sampling, or it can be modeled using established relationships (**Breda 2003, Richardson et al. 2009**) or estimated using monitoring instruments that make the calculation based on measured conduct gap fraction **(Welles and Cohen 1996)**.

**Methods and instruments used to characterize forest canopy density typically fall into one of two main areas of emphasis. The first is canopy cover, which is the percent of forest area occupied by the vertical projection of tree crowns on the ground (or other height of interest). The second is canopy closure, or canopy density, which is the proportion of sky hemisphere obscured by vegetation as viewed from a single sample point (Korhonen et al. 2006)**. The difference in instruments is related to the relative angles of view, where instruments giving a narrow angle of view are more suited for canopy cover estimation, and instruments providing a wider angle of review (>30°) are more suited to estimating canopy closure (**Paletto and Tosi 2009; MacCracken et al. In review**).

**In general, canopy cover is more suited to forest planning and management surveys, and canopy closure is more suited to assessments of light regimes and solar energy penetration** (**Paletto and Tosi 2009**). However, in water temperature modeling both direct beam and diffuse beam radiation may be modeled as they affect water temperature responses through different mechanisms and exposure pathways (**Chen et al. 1998**). Where accurate modeling and accounting of stream heat budgets are desired both canopy cover and canopy closure may therefore be of interest. As noted by **Jennings et al. (1999),** canopy cover is an important variable required in estimating stand statistics from remotely sensed images. As such it also remains relevant to the parameterization of common forestry and stream shade models. Canopy cover may be measured using techniques such as the moosehorn, line intercept, GRS densiometer, visual estimation, and hemispherical photos when assessed using a narrow angle of view (**Fiala et al 2006**). **Korhonen et al. (2006)** compared five methods for measuring canopy cover: Cajanus tube, line intersect sampling (LIS), modified spherical densiometer, digital photographs using standard lens, and ocular estimation. Controls were developed using the Cajanus tube measured at 195 points within a circular 12.52 m plot. The authors modified the use of the spherical densiometer by using only the four out of the 24 squares that were located closest to the observer. This was done to reduce the angle of view from the original 60 degrees to about 20 degrees. The Cajanus tube became imprecise with a sample size less than 102. The LIS method proved to be another accurate method for measuring canopy cover with the average difference between the LIS and the control 2.5% and never more than 5%. The modified spherical densiometer method using 49 measurement points was considered to be a compromise between measurement speed and accuracy, with decreasing the sample size to 23 or only nine points weakening the results.

**Measurements of canopy closure are typically of greatest applicability in research seeking to understand the effect of buffer shading on stream temperature**. This is because solar insolation contributed from a relatively wide range of azimuth angles is known to affect stream temperature. Two common methods used to assess exposure to solar energy are the use of the spherical densiometer and hemispherical photographic analysis. These two methods present some tradeoffs which should be understood when choosing between them for stream temperature research.

Hemispherical photographic analysis produces high quality permanent canopy cover records and is less prone to user error than other methods. The ability to use computer analysis allows more complex data manipulation, analysis, and storage; and can be as a direct measure of shade. **Kelly and Kruger (2005)** note that hemispherical imaging collects the maximum amount of potential information and is therefore regarded as the de facto reference method for quantifying percent cover and shade. But it is also expensive, heavy, delicate, and not simple to use so it tends to be reserved for situations where the number of sample sites is limited such as with research experiments. **Englund et al. (2000)** found digital photography was effective and more convenient and inexpensive than film cameras, with film photographs less effective in recording light coming through small holes in the canopy.

The spherical densiometer includes both convex (Model A) and concave (Model B) mirrors. **Lemon (1957)** reported that experienced users can produce tight replication of canopy readings, with the spherical densiometer having demonstrated a variation in replicated overstory density within 1.3, 2.4, and 3.1 percent at probability levels of 70, 95, and 99 percent, respectively at the forest level. Variation was cited as being only slightly larger at the site level (2, 3, and 4% respectively). However, other authors have reported estimates being further apart at more intermediate levels of canopy cover than within either heavy or sparse cover conditions (**OWEB 1999; Jennings et al. 1999**).

**Kelly and Kruger (2005)** compared the sampling efficiency of hemispherical photographic analysis and spherical densiometers. They concluded larger sample sizes may be required to produce the same level of accuracy at a given statistical confidence when using the spherical densiometer. In their comparison, hemispherical imaging was more precise and required lower sample sizes (1 to 68 samples to sample within 10 percent of the mean at a 95% confidence); while the densiometer was the least efficient (requiring from 10 to 2,045 samples). In addition, while the two methods are correlated, the reduced angle of view of the spherical densiometer has been shown to produce lower mean estimates in canopy closure (**Paletto and Tosi 2009; Kelly and Kruger 2005; Englund et al. 2000). Englund et al. (2000)** determined the view angle of the densiometer to be 48.4° in front of the observer and 9° behind the observer. This smaller angle of view means that the area observed with this instrument is more overhead **(Kelly and Kruger 2005)**. Consequently, the cover at wider angles is not included, and when measured from the center of a stream, the area measured typically overstates open sky relative to the other instruments. Moreover, modification of the densiometer as specified in the Oregon Plan **(OWEB 1999; Strickler 1959)**, where 3 of the 4 quadrants are masked off, results in an even smaller view angle than the standard densiometer, presumably producing even larger differences between the instruments.

In addition to simple modification of the Lemmon spherical densiometer, researchers interested primarily in the amount of solar insolation reaching streams use methods which attempt to better quantify the ability of direct beam solar energy to pass through vegetative canopies. These methods share the common trait of using the date the sample was taken and the sites geographic position to plot the course of the sun. Methods vary from relatively simple variations on the spherical densiometer**,** such as the angular canopy densiometer developed by Patrick Teti **(Teti and Pike 2005; Pike 2003)** which measures the extent of canopy closure along the suns path, to software algorithms (used in hemispherical photographic analysis) or mathematical adjustments (used in solar pathfinder analysis) to estimate the solar energy reaching a sample site. **Cole and Newton (2015)** examined the relationship between several canopy closure estimates on four stream sites in western Oregon under varying riparian buffer configurations. Solar radiation estimated using hemispherical photographs was compared to canopy closure estimated visually, based on basal area, and using a hand-held densitometer pointing south. While the use of spherical densitometer oriented south (following **Strickler 1959**) resulted in the highest correlation the authors suggested better results would be likely using an angular canopy densiometer that samples only along a specified sun track (see **Beschta et al. 1987**, and **Teti 2001**).

## Summary of Best Available Science

In summary, the research reviewed suggests moderate thinning can be accomplished with low impact on stream shade and water temperature. However, as the intensity of thinning increases the width of the RMZ will also generally need to increase to provide comparable protection for stream temperature. Thinning more than approximately 25-30% of the standing trees or stand basal area within a riparian buffer is commonly associated with reduced stream shading and increasing stream temperature. As minimum riparian management zones are widened to 75 or 100 feet (22.8 or 30.5 m), or greater, the ability to conduct light to moderate thinning within them without causing streams to warm increases. Adding no-cut buffer zones immediately adjacent to streams increases the confidence that adjacent thinning prescriptions can be conducted with minimal or no loss in stream shading, and allow those thinning treatments to be more intense and thus more likely to be economically and operationally viable. Such a no-cut zone might be adjusted from 25 to 60 feet (7.6 to 18.3 m) depending on whether a light, moderate, or heavy thinning is being conducted.

The above observations apply to harvests which vary greatly in size, from small patch cuts of only tenths of acres in size, to the harvest of small sub-watersheds, and to the harvest of 40-60 acre patches of timber in larger watersheds. They also apply to small to medium size fish-bearing as well as to non-fish-bearing streams. Small streams have been shown to be sensitive to changes in canopy cover, with stream warming often persisting for many years after harvest and extending to the mouth of the watershed. Large streams and rivers, however, respond differently to changes in riparian vegetation. With a larger volume of water that needs to be heated and less ability for adjacent trees and plants to shade a large proportion of the water surface, the temperature of these larger water bodies are more affected by general climatic conditions and the temperature effects of their major tributaries (**Cristea et al., 2010**).

Riparian buffers which are left intact provide the greatest shade, followed by buffers which selectively retain only mature trees. Though buffers of non-merchantable trees and brush can help mitigate temperature increases as compared with clear cuts, the field research examined suggests that they are not as effective in buffering even those very small tributaries sometimes suggested to be effectively shaded by residual brush.

Studies of riparian buffer BMPs indicate their effectiveness for maintaining shade and stream temperature are a function of the riparian stand characteristics (height, density, width) existing immediately after harvest, along with the changes which occur over succeeding seasons. Based on this knowledge, we should expect the effectiveness of the riparian rules for maintaining stream shade will vary in relation to stand characteristics, location, and time after harvest. Further, rule effectiveness in maintaining pre-harvest stream temperatures will likely vary in relation to other key physical characteristics (described above) that contribute to stream sensitivity to thermal loading. Based on the research reviewed, if maintaining stream temperatures across the forested landscape is a goal of the FPHCP (Washington State Department of Natural Resources, 2005), then such prescriptions would be best designed to limit the reduction in stream shade post-harvest to less than 6%.

In addition to variability in temperature or shade responses caused by differences in riparian and physical stream characteristics, the variability observed in the literature is also a foreseeable result of the methods used in the research studies themselves. Few existing studies exert control over the extent of harvest or meter the post-harvest conditions. The studies reviewed predominately tested non-standardized operational applications of state or provincial buffering recommendations. Harvest length and area; harvest block orientation; buffer width, age, and structure; topographic shading; and years since harvest; are all examples of key variables known to affect stream shading and temperature. Yet they are seldom controlled or accounted for in the body of existing research. Shade is often not reported in the riparian buffer literature, instead focusing on temperature responses. Where reported, however, the study may use any of a broad range of metrics and monitoring techniques (light meter, pyranometers, LAI, canopy cover, angular canopy density, effective shade, topographic and canopy shade) and take the measurements from distinctly different positions over and across the streams. Differences in the monitoring methods used in stream temperature studies (distance from cut-block to meter, distance between treatments, uncontrolled harvests in basin, averaging metrics, and frequency of monitoring) further reduce our ability to confidently assess the extent that changes in forest management affect stream temperature. These many sources of variability reduce our ability to confidently use the existing literature to answer the critical questions proposed in this RCS study.

A key objective of this study is to use empirical data to advance the state of our knowledge of how stream shading responds under a common range of riparian management treatments, and to do so under a strictly controlled and standardized set of study conditions. This RCS study is focused on characterizing how variable widths and intensities of buffer management (clearcutting, thinning, and no-cut zones) affect the ability of a riparian stand to intercept solar energy that would otherwise pass through to the stream. Particularly lacking from the existing literature is empirical research examining the added benefit of including no-harvest buffers of a given width adjacent to thinning harvests. This study would substantially address this gap in knowledge and in doing so directly assess a key feature of the state's forest practices riparian buffering prescriptions.

An additional objective of this RCS study, which is complementary to the assessment based on the empirical data, is to identify improvements to the SHADE.xls model. SHADE and SHADE.xls are well established models for estimating the amount of solar energy that will pass through forested canopies and warm streams. The existing literature generally supports the potential to improve the SHADE.xls model. Techniques for running the model that adjust for vertical differences in canopy density (layers), and improved methods for assessing the proportion of a stream shaded by overhanging vegetation, have met with some success. The common thread of the attempts at model improvement reviewed is the use of methods that better characterize the shade patterns created in complex riparian forest stands. The potential for model improvement based on better describing stand characteristics that affect light transmission is further supported by the work of researchers who found that incorporating relative density helped address clumping, that understory density was an important consideration in model accuracy, and that crown depth is a critical variable in light penetration through forest canopies. Although research has demonstrated the potential for model improvements, the work reviewed was restricted in scale and had little or no validation. The existing research also provides a reason to be cautious setting expectations for model improvement. Researchers have found significant variability in light energy extinction coefficients can occur within stands of the same type and age. This documented variability suggests caution is warranted in setting expectations about potential cost effective improvements in model accuracy.

The literature is consistent in finding there is no one best method for measuring shade, canopy cover, or canopy density; and has demonstrated the value of modifying standard field methods where necessary to better isolate the variables of greatest interest. The SHADE model was developed based on overhead canopy cover and overhead canopy density, but the SHADE.xls model allows the extinction coefficient to be turned off and more direct measurements of shade, such as angular canopy cover and effective shade used directly. The effect of these choices and the individual selection of metrics and methods on model results has not been evaluated. Similarly, while more accurately accounting for the shade from branches overhanging streams has been tested with some success, the methods used in the research do not lend themselves well to general use, and the approach has not been more widely validated. The RCS study would therefore need to examine a range of these methods against the modeled and measured results in the effort to identify improvements which are most effective in meaningfully improving model accuracy, and which can be readily applied in field studies.

## Appendix B – Level of Effort and Estimated Budget

**Alternative 1:** [11]

Alternative 1 monitors 3 plots within five sites in each of four stand types or physiographic regions (statistical blocks). Each of the three plots would be sequentially thinned two times followed with clearcutting down to a predetermined no-harvest buffer width. Layout would consist of field teams working in advance to color-mark trees to indicate which trees would be removed during each harvest entry. Shade and select stand measurements would be taken both pre-treatment and after each harvest. Using this approach monitoring and harvest teams can complete 10 blocks over a 10 week field season (June –August). **Thus a single field team would require two 10-week field seasons to implement this study statewide (20 blocks). The following cost assumptions cover the full statewide study unless stated otherwise**:

**Project Coordinator: $60,000.** Based on one person working half-time for 10 weeks (200 hours) at $100/hour to conduct site-acquisition ($20,000) and working half-time to coordinate harvests and monitoring over two 10-week field seasons ($40,000)**.**

**Marking Stands for Harvest, and Shade and Stand Monitoring**: **$148,500.** Based on a 2 two-person field team working full time at $6,750 per week (with wages, overhead, travel, and lodging) over two field seasons (20 weeks) would be ($135,000), plus two weeks (13,500) to cover pre-field preparation.

**Harvesting to Prescriptions**: **$160,000.** Based on assuming a two person per day level of effort at $100/hour would be $8,000 per week continuously over two field seasons (20 weeks)**.**[12]

**Data Analysis and Report Writing**: The simple study design should limit the time needed to analyze the data and develop a study report to 3 months, working half-time and at $100/hour this would be **$48,000.**[13]

**Special Equipment Costs**: **$16,625-$26,175.**

- Fish Eye Camera and Hemi-view software (or equivalent) to measure overhead cover and effective shade. Cost can vary substantially. If over-counter camera ($375.00) and leveling tripod ($125) and freeware are used, compared to a dedicated HEMI-DC camera system ($6,800) and HemiView Software ($3,250) purchased from vendor.
- Li-Cor LAI 2200TC at $16,125 to measure leaf area index for calculating light extinction coefficients.

**Alternative 1 Preliminary Budget Estimate: $433,125** statewide, or **$258,875** eastside.

Table 2: Project costs estimated by year and expenditure type.

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[11] Cost estimates assume no in-kind assistance by landowners in the harvest of the timber, and no assistance from CMER staff in study coordination or data analysis. This eliminates likely areas of substantial cost savings.

[12] Costs for harvest may be reduced if landowners rather than contractors agree to harvest their own lands.

[13] Costs for analysis and report writing may be reduced if this task is conducted by CMER staff or cooperators.

| **Alternative 1** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | **$210,875** | **$174,250** | **$48,000** | **$433,125** |
| *Equipment* | *$16,625* | | | |
| *Site Acquisition* | *20,000* | | | |
| *Harvest Coordination* | *20,000* | *20,000* | | |
| *Harvesting* | *80,000* | *80,000* | | |
| *Field Work* | *74,250* | *74,250* | | |
| *Analysis-Reporting* | | | *48,000* | |
| **Eastside only** | **$210,875** | **$48,000** | | **$258,875** |
| *Equipment* | *16,625* | | | |
| *Site Acquisition* | *20,000* | | | |
| *Harvest Coordination* | *20,000* | | | |
| *Harvesting* | *80,000* | | | |
| *Field Work* | *74,250* | | | |
| *Analysis-Reporting* | | *48,000* | | |

*Note: Both the Statewide and Eastside-only alternatives can have the field work spread out over additional years or with gap years without a loss in study value.*

### Special Project Risks and Considerations

- **Board Approval**: Study would need to be approved as a pilot rule by the Forest Practices Board since harvest treatments would go below current forest practices rule standards.
- **Contractor Coordination**: Study requires substantial coordination and a dedicated coordinator may be needed. Having consultants dedicated to the harvest may increase efficiency but substantially increases the cost over landowners harvesting their own timber.
- **Landowner Coordination**: Coordination would be needed with landowners on getting the harvested trees decked at an acceptable landing/location to facilitate hauling to log yards, and to ensure operations can remain on schedule without conflict with other landowner.
- **Operational Risk**: The use of progressing harvests, while efficient, creates some risk of accidental losses of unmarked trees during harvest.
- **Site Selection**: Study requires identifying and working with willing landowners who would allow harvest of RMZs that are in relatively good condition and are at least 120' wide along streams that meet the stream width and RMZ length (700') requirements.

### Alternative 2:

Alternative 2 follows the design and includes all of the measurements and outcomes of Alternative 1, but also: a) increases the number of stand, shade, and solar energy metrics monitored, b) collects these measurements at three heights over the stream and within the riparian management zones to reflect potential differences in vegetative structure, c) increases model refinement analyses, and d) revises the SHADE.xls model based on the study results. The effect of adding the additional field metrics is to double of the field personnel crew from 2 to 4 persons and to increase the costs of monitoring equipment. The addition in field metrics will also require a more extensive analysis of the metrics and their effect on shade/energy. The analyses in Alternative 2 would be kept relatively straightforward, but including exploratory modeling using multi-factor regression and step wise model refinement would warrant consulting with an independent statistician along with the cost of adding a modeler to test and capture any potential improvements in a revised SHADE.xls model. This is expected to add two months to the time needed for analysis, report writing, and model revision. The following cost assumptions cover the full statewide study (16 blocks) unless stated otherwise:

**Project Coordinator: $60,000.** Based on one person working half-time for 10 weeks (200 hours) at $100/hour to conduct site-acquisition ($20,000) and working half-time to coordinate harvests and monitoring over two 10-week field seasons ($40,000)**.**

**Marking Stands for Harvest and Shade Monitoring**: **$297,500.** Based on a 4-person field team working full time at $13,500 per week (with wages, overhead, travel, and lodging) over two field seasons (20 weeks) would be $270,000 plus two weeks (27,000) to cover pre-field preparation.

**Harvesting to Prescriptions**: **$160,000.** Based on assuming a two person per day level of effort at $100/hour would be $8,000 per week continuously over two field seasons (20 weeks)**.**[14]

**Data Analysis and Report Writing**: **$96,000.** Based on assuming the added exploratory analyses is expected to increase the time needed to analyze the data and develop a study report by one month compared with Alternative 1. Four months at $100/hour would be $64,000. The additional modeling and model revision and documentation work is expected to require two months at $100/hour ($32,000).

**Alternative 2 Preliminary Budget Estimate: $621,055** statewide or **$344,500 eastside**.

**Special Equipment Costs**: **$28,055-$42,705.**

- Fish Eye Camera and Hemi-view software (or equivalent) to measure overhead cover and effective shade **$500-$10,550**. Cost can vary substantially. If over-counter camera ($375.00) and leveling tripod ($125) and freeware are used, compared to a dedicated HEMI-DC camera system ($6,800) and HemiView Software ($3,250) purchased from vendor.
- Li-Cor LAI 2200TC at **$16,125** to measure leaf area index for calculating light extinction coefficients.
- Thermopile Pyranometer arrays to measure global solar radiation. **$11,030 min**. [(Apogee SP-510 $295.00 each sensor or Campbell Scientific CS320 or Kipp and Zonen SP) and minimum array of 9 per treatment site plus offsite open-view control (min 27 units), and leveling base plates (AL-100 $35.00 ea) and stands (?) and 2-4 data meters (LI-1500 $355.00 each or CR300 for LOGBOX SE by Kipp and Zonen with allows for up to 8 radiometers)].

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[14] Costs for harvest may be reduced if landowners rather than contractors agree to harvest their own lands.

- Towers to collect shade/energy samples as an array at multiple heights off the ground. **$400 to $5,000**. Price varies substantially from each with decision based on final height required in final study design and whether sequential sampling can be used an enable a single portable tower to be used in.

Table 3: Project costs estimated by year and expenditure type.

| **Alternative 2** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | **$276,555** | **248,500** | **$96,000** | **$621,055** |
| *Equipment* | *28,055* | | | |
| *Site Acquisition* | *20,000* | | | |
| *Harvest Coordination* | *20,000* | *20,000* | | |
| *Harvesting* | *80,000* | *80,000* | | |
| *Field Work* | *148,500* | *148,500* | | |
| *Analysis-Reporting* | | | *96,000* | |
| **Eastside only** | **$248,500** | **$96,000** | | **$344,500** |
| *Equipment* | *28,055* | | | |
| *Site Acquisition* | *20,000* | | | |
| *Harvest Coordination* | *20,000* | | | |
| *Harvesting* | *80,000* | | | |
| *Field Work* | *148,500* | | | |
| *Analysis-Reporting* | | *96,000* | | |

### Special Project Risks and Considerations

Same as those listed for Alternative 2 above.

### Alternative 3:

Alternative 3 includes all of the measurements in Alternative 2, but eliminates the use of replicated treatments. The focus of this alternative is model refinement and as such it takes more of an exploratory approach; using regression analysis to try and distinguish stand characteristics most affecting shade. This approach reduces overall cost per site as compared with the Alternative 2 but it also reduces the ability to recognize significant differences between stand types and prescription categories. The stands would still need to be measured, but rather than remaining at the same site for a week conducting coordinated harvests and monitoring of three plots, this alternative allows a 4 person crew to monitor 2 sites per week over a 10 week field season, with two years needed to obtain sufficient samples to complete the study.

**Project Coordinator: $60,000.** Based on one person working half-time for 3 months at $100/hour to conduct site-acquisition (10 weeks @ $20,000) and working half time to coordinate field work over two field seasons (20 weeks)($40,000)**.**

**Stand and Shade Monitoring**: **$272,700.** Based on a 4-person field team working full time at $13,500 per week (with wages, overhead, travel, and lodging) over one field season (10 weeks @ $135,000) and adding 1 week to cover pre-field preparation ($13,500) is $136,350 per field season. Of note, this alternative does not have the requirement of marking stands pre harvest, but retains the need to inventory the stands. This may reduce total time by not requiring marking the trees, but not expected to result in less paid days in the field or smaller field crews.

**Harvesting to Prescriptions**: **NA**

**Data Analysis and Report Writing**: **$96,000.** Based on assuming the added exploratory analyses is expected to increase the time needed to analyze the data and develop a study report by one month compared with Alternative 1. Four months at $100/hour would be $64,000. The additional modeling and model revision and documentation work is expected to require two months at $100/hour ($32,000).

**Alternative 3 Preliminary Budget Estimate): $436,777** statewide for Phase I.

**Special Equipment Costs**: **$28,055-$42,705.**

- Fish Eye Camera and Hemi-view software (or equivalent) to measure overhead cover and effective shade **$500-$10,550**. Cost can vary substantially. If over-counter camera ($375.00) and leveling tripod ($125) and freeware are used, compared to a dedicated HEMI-DC camera system ($6,800) and HemiView Software ($3,250) purchased from vendor.
- Li-Cor LAI 2200TC at **$16,125** to measure leaf area index for calculating light extinction coefficients.
- Thermopile Pyranometer arrays to measure global solar radiation. **$11,030 min**. [(Apogee SP-510 $295.00 each sensor or Campbell Scientific CS320 or Kipp and Zonen SP) and minimum array of 9 per treatment site plus offsite open-view control (min 27 units), and leveling base plates (AL-100 $35.00 ea) and stands (?) and 2-4 data meters (LI-1500 $355.00 each or CR300 for LOGBOX SE by Kipp and Zonen with allows for up to 8 radiometers)].
- Towers to collect shade/energy samples as an array at multiple heights off the ground. **$400 to $5,000**. Price varies substantially from each with decision based on final height required in final study design and whether sequential sampling can be used an enable a single portable tower to be used in.

Table 4: Project costs estimated by year and expenditure type.

| **Alternative 3** | **Year 1** | **Year 2** | **Year 3** | **Total Cost** |
|---|---|---|---|---|
| **Statewide** | **$204,405** | **$136,370** | **96,000** | **$436,777** |
| *Equipment* | *$28,055* | | | |
| *Site Acquisition* | *20,000* | | | |
| *Field Coordination* | *20,000* | *20,000* | | |
| *Harvesting* | *NA* | | | |
| *Field Work* | *136,350* | *136,350* | | **Unknown** |
| *Analysis-Reporting* | | | *96,000* | *Scoping Phase II* |

*Only a statewide study is proposed for this option since it is focused only on collecting sufficient variation in stand conditions to allow improvements to the SHADE.xls model to be identified. A follow-up study is expected to be needed to validate the model and to test specific prescriptions identified by policy makers using the revised model.*

### Special Project Risks and Considerations

- **Board Approval**: The second field phase may need to be approved as a pilot rule by the Forest Practices Board to allow prescription variants that go below current rules.
- **Weather**: Use of radiometers and pyranometers requires control and treatment sites be measured during clear sky periods, thus affecting the efficiency of the field schedules.
- **Operational Risk**: Project success depends on meaningful model refinements being identified in Phase 1.
- **Site Selection**: Study requires treatment sites have local hilltop or large areas with a clear view of sky in order to set up control sites for determining radiative energy using pyranometers.

### Alternative 4:

Alternative 4 focuses on characterizing effective shade reaching streams and how that varies across stand types or physiographic regions. Sample sites would be chosen to represent a range of buffer widths left by landowners post-harvest within each stand type. This narrower focus allows two proximate locations to be monitored on each field day allowing 4 to 5 sites to be monitored each week during the field season (June –August). **Using this design, a single 2-person field team could sample 20-30 sites during one 10-week field season.**

**Project Coordinator: $20,000.** Based on one person working half-time for 10 weeks (200 hours) at $100/hour to conduct site-acquisition ($20,000) and establish agreements on access for the 10-week field seasons**.**

**Shade and Stand Monitoring**: **$74,250.** Based on a 2 two-person field team working full time at $6,750 per week (with wages, overhead, travel, and lodging) over one field seasons (10 weeks) would be ($67,500), plus one week ($6,750) to cover pre-field preparation.

**Harvesting to Prescriptions**: **NA**

**Data Analysis and Report Writing**: The simple study design should limit the time needed to analyze the data and develop a study report to 3 months, working half-time and at $100/hour this would be **$48,000.**[15]

**Special Equipment Costs**: **$500 – $10,005.**

- Fish Eye Camera and Hemi-view software (or equivalent) to measure overhead cover and effective shade. Cost can vary substantially. If over-counter camera ($375.00) and leveling tripod ($125) and freeware are used, compared to a dedicated HEMI-DC camera system ($6,800) and HemiView Software ($3,250) purchased from vendor.

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[15] Costs for analysis and report writing may be reduced if this task is conducted by CMER staff or cooperators.

**Alternative 4 Preliminary Budget Estimate: $241,500 statewide or $147,250 eastside only**.

Table 5: Project costs estimated by year and expenditure type.

| Alternative 4 | Year 1 | Year 2 | Year 3 | Total Cost |
|---|---|---|---|---|
| **Statewide** | **$99,250** | **$94,250** | **$48,000** | **$241,500** |
| *Equipment* | *$500* | | | |
| *Site Acquisition* | *20,000* | *20,000* | | |
| *Harvest Coordination* | *NA* | *NA* | | |
| *Harvesting* | *NA* | *NA* | | |
| *Field Work* | *74,250* | *74,250* | | |
| *Analysis-Reporting* | | | *48,000* | |
| ***Eastside Only*** | **$99,250** | **$48,000** | | **$147,250** |
| *Equipment* | *$500* | | | |
| *Site Acquisition* | *20,000* | | | |
| *Harvest Coordination* | *NA* | | | |
| *Harvesting* | *NA* | | | |
| *Field Work* | *74,250* | | | |
| *Analysis-Reporting* | | *48,000* | | |

### Special Project Risks and Considerations

- **Board Approval**: Study would need to be approved as a pilot rule by the Forest Practices Board since harvest treatments would go below current forest practices rule standards.
- **Contractor Coordination**: Study requires substantial coordination and a dedicated coordinator may be needed. Having consultants dedicated to the harvest may increase efficiency but substantially increases the cost over landowners harvesting their own timber.
- **Landowner Coordination**: Coordination would be needed with landowners on getting the harvested trees decked at an acceptable landing/location to facilitate hauling to log yards, and to ensure operations can remain on schedule without conflict with other landowner.
- **Operational Risk**: The use of progressing harvests, while efficient, creates some risk of accidental losses of unmarked trees during harvest.
- **Site Selection**: Study requires identifying and working with willing landowners who would allow harvest of RMZs that are in relatively good condition and are at least 120’ wide along streams that meet the stream width and RMZ length (700’) requirements.