Riparian Characteristics and Shade Response Experimental Research Study
Draft Study Design

INTRODUCTION

The effect of timber harvest on stream temperature is a key issue for meeting water quality standards in Washington State. Increases in stream temperature following timber harvest can alter stream ecosystem processes and trophic dynamics, and cause stress and mortality of aquatic species, including threatened and endangered fish species (Beschta et al. 1987, Bryant and Lynch 1996, Myers and Bryant 1998). Protecting stream temperature is a priority of the Washington Forest Practices Rules and is directly related to the Forests and Fish Report (FFR 1999) and Forest Practices Habitat Conservation Plan (Schedule L-1, Appendix N; FPHCP 2005) performance goals for meeting state water quality standards. Removal of shade is strongly associated with increases in stream temperature (Brown 1969, Johnson and Jones 2000, Danehy et al. 2005, Moore et al. 2005).

Washington's forest practices rules include requirements for retention of riparian buffers along streams to help maintain stream shade following timber harvest in adjacent uplands. The regulations include no-harvest buffers of varying width. In some cases, these no-harvest buffers can be combined with adjacent riparian buffers in which some amount of timber harvest (thinning) is allowed. In total, the forest practices rules allow for over 90 different riparian buffer configurations, the majority of which remain untested regarding their effects on stream shade. This study will conduct a field experiment to examine stream shade response to a range of riparian harvest treatments similar to those permitted under Washington's forest practices rules.

Problem Statement

Washington's forest practices regulations include riparian prescriptions that incorporate stream-adjacent no-harvest buffers of varying width. The rules include no-harvest buffers that can be used alone or in some cases applied in combination with adjacent buffers of varying width within which some amount of harvest (thinning) is allowed. Field research is particularly limited examining the combined effect of stream-adjacent no-harvest zone width and adjacent-stand harvest intensity (i.e., thinning density) on stream shade. This study will address a key question about how shade could be affected by using forest thinning as a riparian management tool.

Purpose

The purpose of this study is to evaluate how stream shade responds to a range of riparian harvest treatments of varying intensity within multiple environments common to commercial forestlands covered under the Forest Practices Habitat Conservation Plan (FPHCP 2005).

For the purposes of this study, stream shade (effective shade, *ES*) is defined as the fraction of total possible solar radiation blocked from reaching the stream surface for the period 1 June to 1 September for solar altitudes 40° or greater. Note that solar altitude refers to the sun angle relative to the horizon. This experimental design is intended to isolate the effects of the riparian harvest treatments on stream shade assuming a common stream azimuth (east-west and north-south), latitude/longitude, and portion of the solar cycle. Thus, this study is not intended to evaluate the mean treatment response across all possible scenarios. Rather, stream azimuth, latitude/longitude, time of year, and time of day will be standardized across all the study sites (described in more detail in the Methods section).

Objectives

1. Estimate stream shade response to a range of riparian harvest treatments that combine different stream-adjacent no-harvest zone widths and adjacent-stand harvest intensities (i.e., thinning treatments or clear-cut).
2. Examine how stand composition and structure characteristics influence stream shade response to the riparian harvest treatments.

Critical Questions

1. How does stream shade respond to riparian harvest treatments with different stream-adjacent no-harvest zone widths and adjacent-stand harvest intensities?
2. How does stream shade response to the riparian harvest treatments vary among ecoregions where commercial timber harvest commonly occurs?
3. What are the important patterns, trends, and relationships between stand characteristics and stream shade response to the riparian harvest treatments?

LITERATURE SUMMARY

A full literature review was completed within the approved scoping document (Hicks 2018) for this project. The following section provides a brief summary of that literature review, including references for relevant, recently completed Cooperative, Monitoring, Evaluation, and Research committee (CMER) research projects.

Shade provided by riparian vegetation is generally the single most important variable influencing summer water temperature for perennial streams in forested environments (Brown 1969, Johnson and Jones 2000, Danehy et al. 2005, Moore et al. 2005). 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. 2005, Ehinger et al. 2018). Reductions in canopy shading of more than 6-10% have been associated with measurable increases in stream temperature (>0.2 °C; Wilkerson et al. 2006, Groom et al. 2011b, Guenther et al. 2014, Bladon et al. 2016, Witt et al. 2016, Ehinger et al. 2018, Raulerson et al. 2020, Roon et al. 2021). Forestry regulations commonly establish riparian buffer zones along streams in which harvest is restricted to minimize shade loss and other adverse environmental effects.

The amount of stream shade provided by a riparian buffer is related to the width, tree density, and height of the trees in the buffer (DeWalle 2010) and the intensity and configuration of tree harvest (thinning) within the buffer. Understory vegetation, standing dead trees, and topography can also be important contributors to stream shade. Removal of more than about 25-30% of standing trees or basal area within a riparian buffer is associated with reduced stream shading and increased stream temperature (Wilkerson et al. 2006, Boggs et al. 2016, Roon et al. 2021).

Evidence suggests that wider riparian buffers provide more opportunity for thinning within the buffer without causing a significant loss of canopy cover or increase in stream temperature (Wilkerson et al. 2006, Groom et al. 2011a, Groom et al. 2011b, Groom et al. 2018). Adding a stream-adjacent no-harvest zone within the buffer may increase the ability to thin adjacent stands at higher intensities with minimal or no loss in stream shading (Park et al. 2008, Teply et al. 2014). The no-harvest zone width necessary to prevent shade loss depends on the intensity of the adjacent harvest zone thinning treatment. The effectiveness of riparian buffers for maintaining shade and stream temperature is also a function of riparian stand characteristics immediately following harvest, along with the changes that occur over succeeding seasons. Stand characteristics, including species composition, basal area, tree density, tree height, and live crown ratio can influence stream shading (Allen and Dent 2001, Dent et al. 2008, DeWalle 2010, Groom et al. 2011b). In general, stream shading is positively correlated with basal area, tree density, and tree height, but the importance of individual variables depends on site conditions, such as stream orientation (DeWalle 2010, Groom et al. 2011b). Therefore, the effectiveness of riparian harvest rules for maintaining stream shade varies based on stand characteristics, location, and time since harvest.

METHODS

Study Area and Site Selection

The study area includes riparian forest stands along Type Np (non-fish-bearing perennial) and Type F (fish-bearing) streams occurring on non-federal lands managed under the FPHCP within the Northwest Coast, West Cascades, Okanogan, and Canadian Rocky Mountains ecoregions in Washington State (Figure 1; WADNR 2007). Specifically, field study sites will be selected according to the following criteria:

1) Within the Northwest Coast, West Cascades, Okanogan, or Canadian Rocky Mountains ecoregions in Washington State (Figure 1).
2) Riparian stands of harvest age.
3) Washington Department of Natural Resources (WADNR) Site Classes II and III (FFR 1999; Table 1).
4) Type Np or Type F streams with bankfull widths from 5 to 25 feet.
5) Local topography does not completely obscure solar radiation penetration to the stream for more than 10% of the solar period that will be evaluated in this study (the solar period evaluated in this study is described later).

The first four criteria represent the geographic regions, stand age range, and site conditions where timber harvest most commonly occurs on non-federal forest lands in Washington state (Forest Practices Application Review System, FPARS).

The ecoregion boundaries were initially developed by the U.S. Environmental Protection Agency and refined by Washington Natural Heritage Program scientists (WADNR 2007). Each ecoregion is characterized by a distinct biophysical environment, including climate, landform, soils, hydrology, and vegetation. Ecoregions provide a useful framework for distributing study sites across a range of geographic regions and environments in western and eastern Washington.

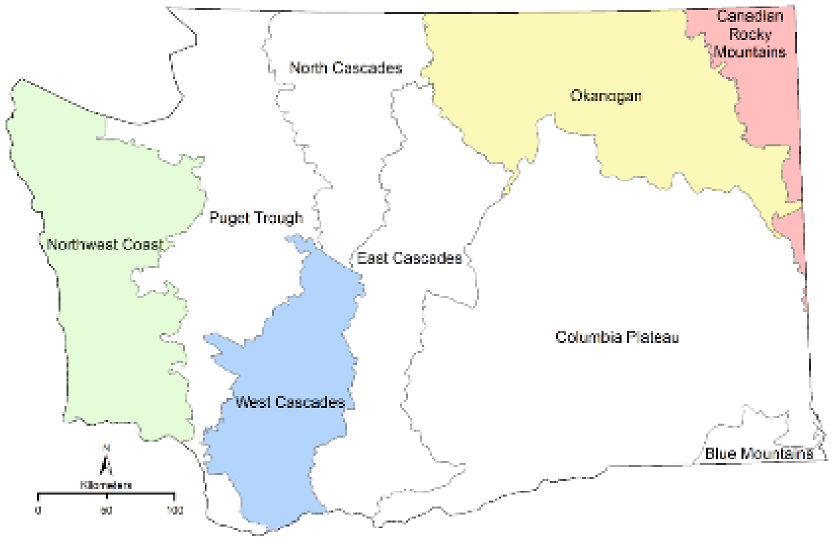


Figure 1. [Ecoregions of the Pacific Northwest in Washington State] (WADNR 2007). Study sites will be located in the Northwest Coast, West Cascades, Okanogan, and Canadian Rocky Mountains ecoregions. Site classes (FFR 1999; Table 1) provide an indication of site productivity and tree growth. The average total tree height that has been or will be attained at a given age is known as the "site index" (McArdle 1961). Site indices are grouped into five broad site classes: Site Class I, Site Class II, Site Class III, Site Class IV, and Site Class V. Study sites will be located within Site Classes II and III, where the majority of commercial timber harvest occurs in Washington (Forest Practices Application Review System, FPARS).

Table 1. Washington Department of Natural Resources site class definitions based on site potential tree height (FFR 1999). Study sites will be located within Site Classes II and III (in bold).

Region	**Site Class**	**Site Potential Tree Height (feet)**
Western Washington	I	200
	II	**170**
	III	**140**
	IV	110
	V	90
Eastern Washington	I	130
	II	**110**
	III	**90**
	IV	70
	V	60

Five study sites will be established in each of the four selected ecoregions, for a total of 20 study sites statewide. Potential study sites will be initially identified in a GIS platform. Potential study sites also may be identified by querying the Washington Department of Natural Resources Forest Practices Application Review System (FPARS) for approved Forest Practices Applications (FPAs) for stands that meet the selection criteria and will be harvested during the timeframe of the study. Based on this screening, landowners with potential study sites will be contacted to solicit participation in the study.

The GIS screening will produce a site visitation list for each of the four ecoregions. The site list order will be randomized and sites will be visited sequentially. Sites will be disqualified if field inspections conclude that they do not meet the selection criteria. Site visitations will continue in random order until five qualifying sites have been identified within an ecoregion.

During inspection of potential study sites, a subset of the two most dominant tree species will be sampled for height and age. Tree age may be derived from tree cores or stand establishment date records provided by the landowner. Only sites that meet the selection criteria and can be verified as meeting the criteria for Site Classes II or III will be included in the study (as defined by "site potential tree height" in FFR 1999; Table 1).

Study site layout

Three experimental plots each measuring 325 feet by 100 feet will be established along one side of the selected stream at each study site (Figure 2). The plot dimensions, configurations, number of photo points, and photo point spacing were designed to ensure that shade measurements (hemispherical camera viewshed) for a given plot will not be influenced by areas outside of the plot for solar altitudes of 40° or greater from 1 June to 1 September (Figures 3a and 3b). Solar altitude refers to the sun angle relative to the horizon.

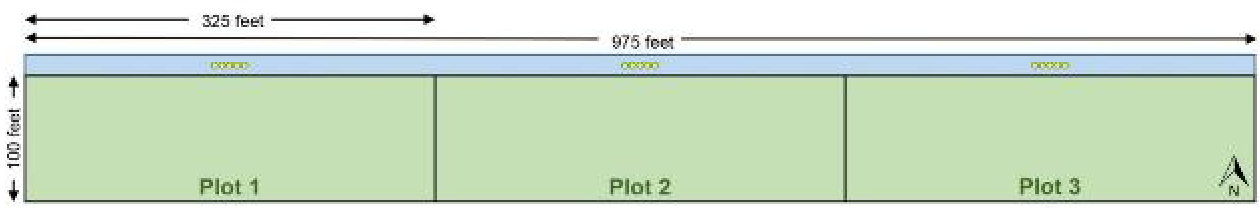


Figure 2. Experimental plot dimensions and layout for this study. Yellow circles represent hemispherical photo point locations (five per plot). This figure represents an east-west stream orientation with the treatment bank assigned to the south.

The treatment plot dimensions, configuration, and photo point locations (Figure 2) in this study are based on the maximum shadow length for riparian trees from 1 June to 1 September for solar altitudes 40° or greater. Shadow length was calculated using https://www.suncalc.org/ for the following parameters:

- Tree height: 125 feet (based on expected maximum tree height for harvested stands).
- Northernmost latitude in Washington State (~49° N, the latitude where maximum shadow lengths occur within the state).
- Photo points located 5 feet from the bankfull edge of the stream/stream-adjacent plot boundary (see Figures 3a and 3b).

Note: Photo point spacing greater than 7.5 feet would capture shade sources originating from outside the treatment plot, inhibiting our ability to isolate the treatment effects on effective shade. For this reason, we have limited the number of photos to 5 per plot with 7.5-foot spacing.

Plot boundaries will be initially drafted in a GIS platform and finalized and staked in the field. The plot boundary nearest to the stream will be located as close as possible to the bankfull width boundary (defined later) while ensuring a straight boundary line.

Five hemispherical photo points will be established for each plot. The photo points will be located at a consistent distance from the plot boundary at a manageable water depth (~<1 foot deep), to be determined after study sites are selected. If, during site selection, the photo point locations are found to be obstructed (e.g., by log jams, deep pools), then the entire 975-foot reach will be shifted by 25-foot increments in the upstream or downstream direction (determined by coin flip), until a useable configuration is determined or the site is rejected.

Photo points will be spaced 7.5 feet apart, with the middle photo point centered on the long edge of each plot (Figure 2). Photo point locations will be recorded with GPS coordinates and monumented with rebar driven into the streambed. The location of each monument, and the distance and compass bearing from the monument to the in-stream photo point will be recorded so that photo points can be duplicated later as necessary.

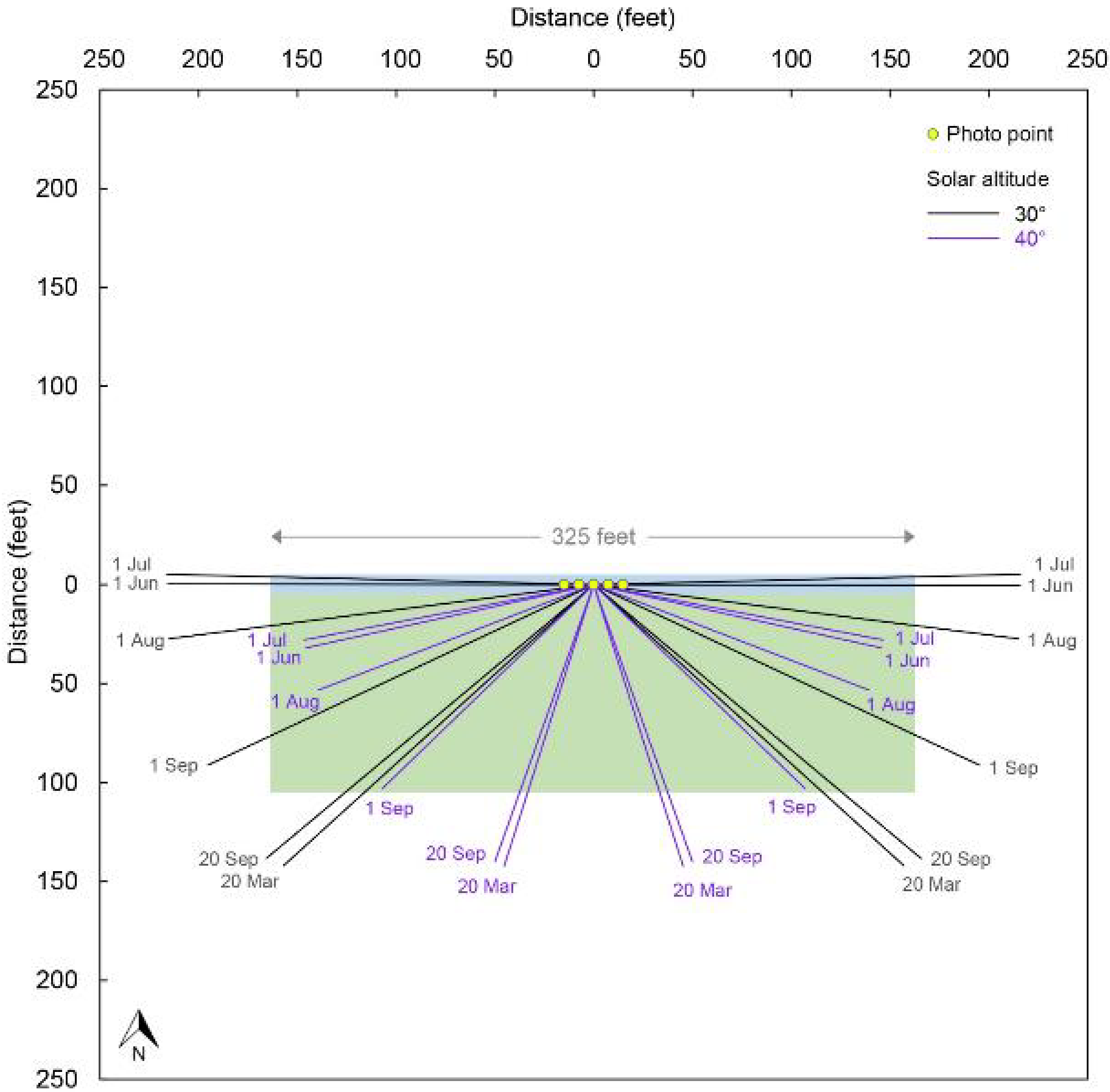


Figure 3a. Shadow length by date for 125-foot tall trees at ~49° N latitude for solar altitudes of 30° and 40° from the vantage of the central photo point (https://www.suncalc.org/). The green shaded area represents a single experimental plot measuring 325 feet by 100 feet. The blue shaded area represents an adjacent east-west oriented stream measuring 10 feet wide. Plot size and photo point spacing are based on solar altitudes of 40° or greater from 1 June to 1 September to ensure that shade measurements will not be influenced by areas upstream or downstream of the plot.

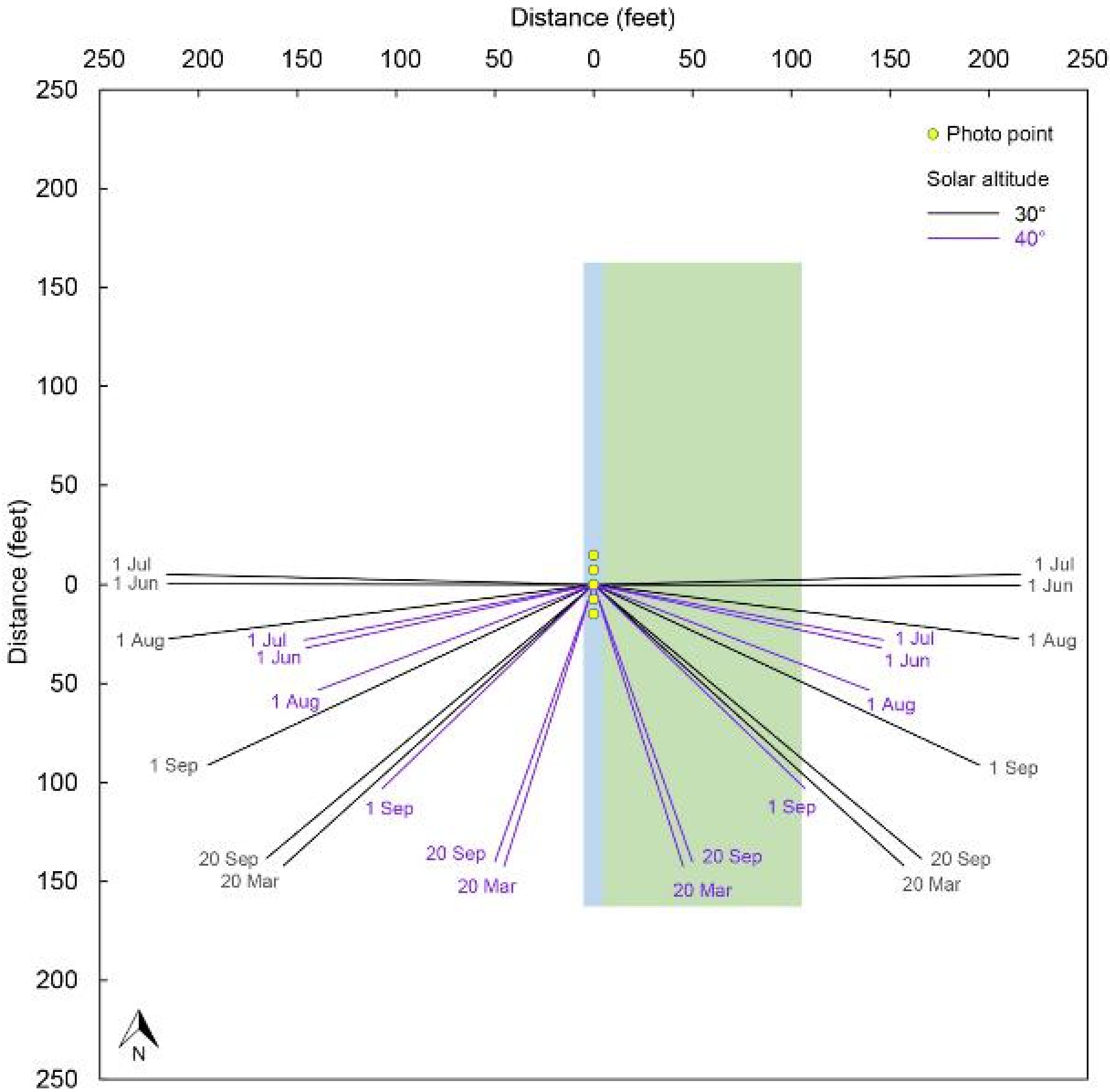


Figure 3b. Shadow length by date for 125-foot tall trees at ~49° N latitude for solar altitudes of 30° and 40° from the vantage of the central photo point (https://www.suncalc.org/). The green shaded area represents a single experimental plot measuring 325 feet by 100 feet. The blue shaded area represents an adjacent north-south oriented stream measuring 10 feet wide. Plot size and photo point spacing are based on solar altitudes of 40° or greater from 1 June to 1 September to ensure that shade measurements will not be influenced by areas upstream or downstream of the plot.

Pre-harvest data collection

Site attributes

After the plot boundaries are marked and before the harvest treatments are implemented, site attribute data including bankfull width, bankfull depth, channel confinement ratio, stream reach slope, stream reach azimuth, plot slope, plot aspect, and understory vegetation conditions will be collected (Table 2).

Table 2. Site attribute data and methods included in this study.

Attribute	Methods/equipment
Bankfull width	WFPB 2004
Bankfull depth	WFPB 2004
Channel confinement ratio	WFPB 2004, 2011; Beechie and Imaki 2014
Stream reach slope	Clinometer
Stream reach azimuth	GPS survey/GIS
Plot slope	Clinometer GIS
Plot aspect	GPS survey/GIS
Understory vegetation cover	Ranking system and oblique digital photos

Bankfull width and **bankfull depth** will be measured for each plot according to the methods described in the Washington Forest Practices Board Manual, Section 2 (2004). Specifically:

> **Bankfull width** is the lateral extent of the water surface elevation perpendicular to the channel at bankfull depth. Bankfull width will be identified as the edge of the channel that corresponds to the start of the floodplain. Indicators include: a berm or other break in slope from the channel bank to a flat valley bottom, terrace, or bench; a change in vegetation from bare surfaces or annual water-tolerant species to perennial water-tolerant or upland species; and a change in the size distribution of surface sediments (e.g., gravel to sand).
>
> **Bankfull depth** is the average distance from the channel bed to the estimated water surface elevation at bankfull flow. Bankfull depth will be measured after the edges of the bankfull channel are determined. A measuring tape will be stretched across the channel perpendicular to the direction of flow, and secured at the bankfull edges on both sides of the channel. With the measuring tape extended across the channel, the bankfull width will be divided into 10 evenly spaced sections. Depth measurements will be taken with a surveyor's rod at the center of each section. The average bankfull depth will then be calculated by dividing the sum of all depth measurements by the number of measurements (i.e., 10).

Channel confinement ratio (valley confinement ratio) will be measured at the center of each plot to provide an indicator of channel form and topographic shading (Table 2). Channel confinement ratio will be determined by measuring the width of the entire valley floor from hillslope to hillslope and comparing this value to the bankfull width of the stream (WFPB 2004, 2011, Beechie and Imaki 2014).

Stream reach slope will be measured in the field from the upstream boundary to the downstream boundary of the study reach (Table 2). **Stream reach azimuth** will be determined in GIS using GPS coordinates of the upstream and downstream study reach boundaries.

Plot slope and aspect will be measured across the plot mid-line running perpendicular to the stream-adjacent boundary (Table 2). Aspect will be determined using coordinates from a GPS survey. Additional topographic information for each site may be derived in GIS depending on the availability of LiDAR data and digital elevation models.

Understory vegetation cover will be defined as all vegetation (herbaceous and woody) occurring between 3.3 feet (1 meter) above the streambed (based on hemispherical photo elevation, described below) and below the overstory (defined as trees that would potentially be considered for harvest). Understory vegetation cover will be ranked as low, medium, or high for each plot (Table 2). This ranking will be based on observations from the central photo point associated with each plot (Figure 2). Specific ranking methods will be further described in the data collection plan.

Before the harvest treatments are implemented, a set of four oblique digital photos will be taken from the central photo point associated with each plot (Figure 2) to provide a visual record of site attributes, including understory vegetation cover (Table 2). Four photos will be taken from each point at 90° intervals (upstream, downstream, left bank, and right bank).

Stand characteristics

After the plot boundaries are marked and before the harvest treatment implementation, all standing trees $\geq$4 inches diameter at breast height (dbh; 4.5 feet above ground surface) occurring in a plot will be tallied and marked with a unique identification number (100% inventory). The identification number, **species**, **condition (live or dead)**, **dbh**, **tree height**, **height to live crown base**, and **maximum crown radius** will be recorded for all trees (Table 3).

Table 3. Stand composition and structure characteristics included in this study.

Stand characteristics	
Tree species	Basal area (feet^2 per acre)
Tree condition (live or dead)	Tree height (feet)
Tree diameter (dbh, inches)	Live crown ratio (percent)
Tree density (trees per acre)	Maximum crown radius (feet)

Harvest treatment implementation and hemispherical photo collection sequence

Stream shade (i.e., effective shade, *ES*) will be estimated for 10 riparian harvest treatment combinations using hemispherical photography methods (Rich 1990, Valverde and Silvertown 1997, Groom et al. 2011a). For the purposes of this study, effective shade (*ES*) is defined as the fraction of total possible solar radiation blocked from reaching an east-west or north-south oriented stream during the period from 1 June to 1 September for solar altitudes 40° or greater, or:

$$Effective\ shade = \frac{J_1 - J_2}{J_1}$$

where J_1 is potential solar radiation flux (un-attenuated by riparian vegetation and topography) and J_2 is solar radiation flux at the stream surface (camera elevation) during the period from 1 June to 1 September for solar altitudes 40° or greater (Cristea and Janisch 2007).

Figure 4 provides a diagram of the harvest treatment and hemispherical photo collection sequence that will be applied in the three experimental plots at each study site. The first step of the harvest sequence will be to clear-cut the upland harvest unit to the edge of a 100-foot stream-adjacent no-harvest zone (upland edge of each experimental plot). The upland edge of the 100-foot no-harvest zone will then become the upland plot boundary for all subsequent harvest treatments. Levels of adjacent-stand harvest intensity (i.e., moderate thinning, heavy thinning, clear-cut) will be randomly assigned to each plot. Different levels of stream-adjacent no-harvest zone width will be implemented sequentially in time within each plot (Figure 4, steps 'a'). Hemispherical photographs will be taken after the implementation of each level of the no-harvest zone width (Figure 4, steps 'b'). This will allow all 10 treatment combinations plus the pre-treatment condition to be applied at a single site (Table 4). If possible, the harvest treatments and associated photo collection will occur between 1 June and 1 September to coincide with the primary leaf-on period for deciduous vegetation in the study region. For a given site, treatments will be applied to the plots within a short time period (e.g., $\leq$10 days). This will provide consistency in site conditions and greatly reduce the possibility of non-treatment events (e.g., windthrow, understory growth) occurring during the harvest and hemispherical photo collection sequence.

Based on the initial 100% stand inventory, harvest trees will be identified and color marked on the bole and stump to indicate which trees to remove at every treatment interval. Thinning treatments will be applied according to Curtis's Relative Density summation formula (RD_{sum}; Curtis 2010).

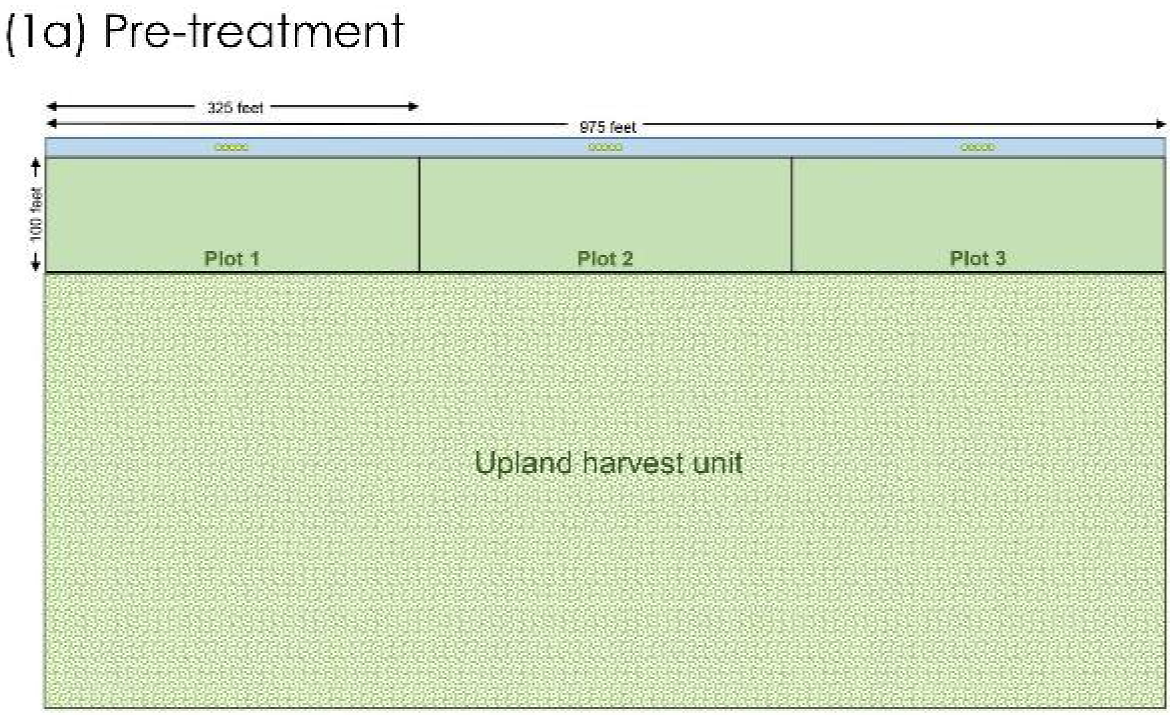
$$RD_{sum} = 0.00545415 \times \sum (d_i^{1.5})/area$$

Where d_i is the diameter of an individual tree and summation is over all trees $\geq$4 inches dbh within a given harvest zone.

The tag number of each harvested tree at each treatment interval will be recorded so that stand characteristics (e.g., basal area by species) can be computed for the harvest and no-harvest zones for each interval. Thinning will be from below and implemented so that tree crowns are spatially distributed as uniformly as possible. Following each harvest treatment interval, trees may be felled and removed from site, or left on the ground and limbed (as necessary), depending on what is most operationally feasible at a given site. Limbing of down trees will only be necessary in locations where limbs contribute to the effective shade of the stream (intersect with the hemispherical camera viewshed) for the solar period analyzed in this study.

After each thinning treatment, follow-up inspections will be conducted to ensure that all trees marked for harvest were felled and to determine if any limbing of down trees is needed to meet the study design requirements. Additionally, any unintended tree falling or damage that occurred during the harvest activities will be recorded by tree tag number.

Hemispherical photos will be taken at each photo point for all five treatment intervals for a total of 75 photos per site (5 photos per plot × 5 treatment applications × 3 plots; Figure 4). Hemispherical photos will be taken using a digital SLR camera equipped with a circular fisheye lens attached to a leveled tripod and oriented to north. Photographs will be taken when no direct sunlight is visible, at pre-dawn, post-sunset, or under an evenly overcast sky. The camera lens will be positioned at 3.3 feet (1 meter) above the streambed. This will reduce the influence of shading by low-lying vegetation and the streambank (i.e., reduce the influence of non-treatment factors on effective shade among study sites). At each photo point, multiple images will be taken using different exposure levels. The camera settings will be programed to take a series of images from -6 to 0 at 1-stop exposure value (EV) intervals to ensure that light conditions do not interfere with shade characterization during photo processing (described later).



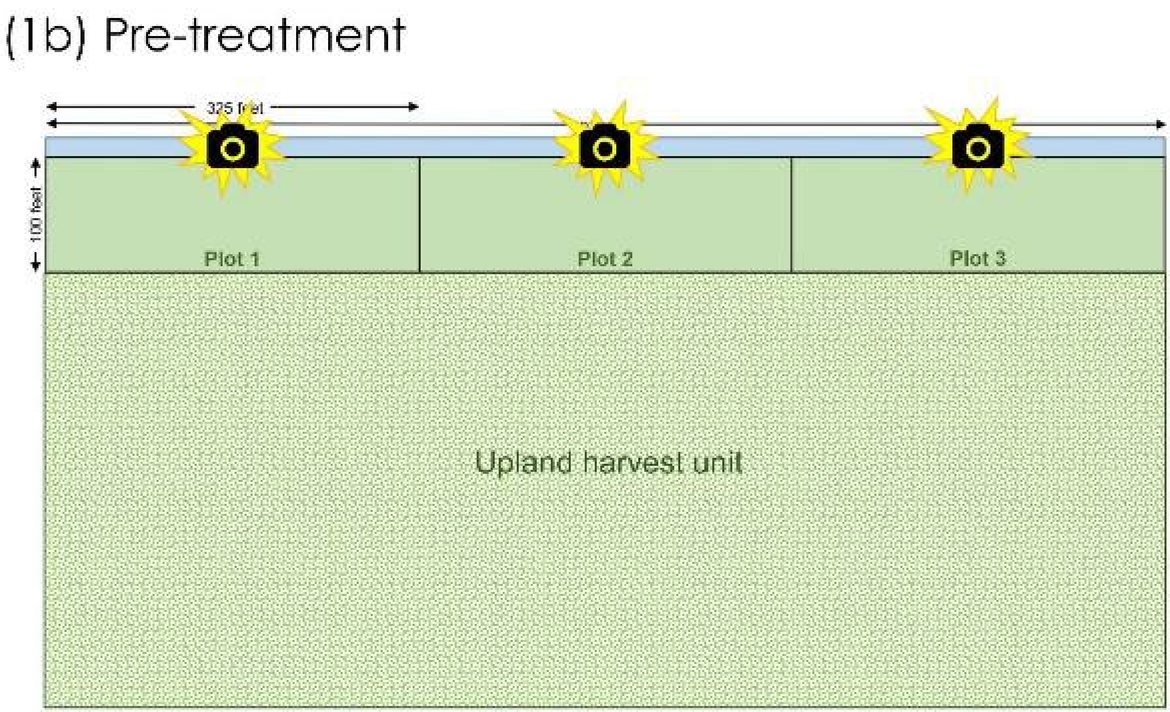
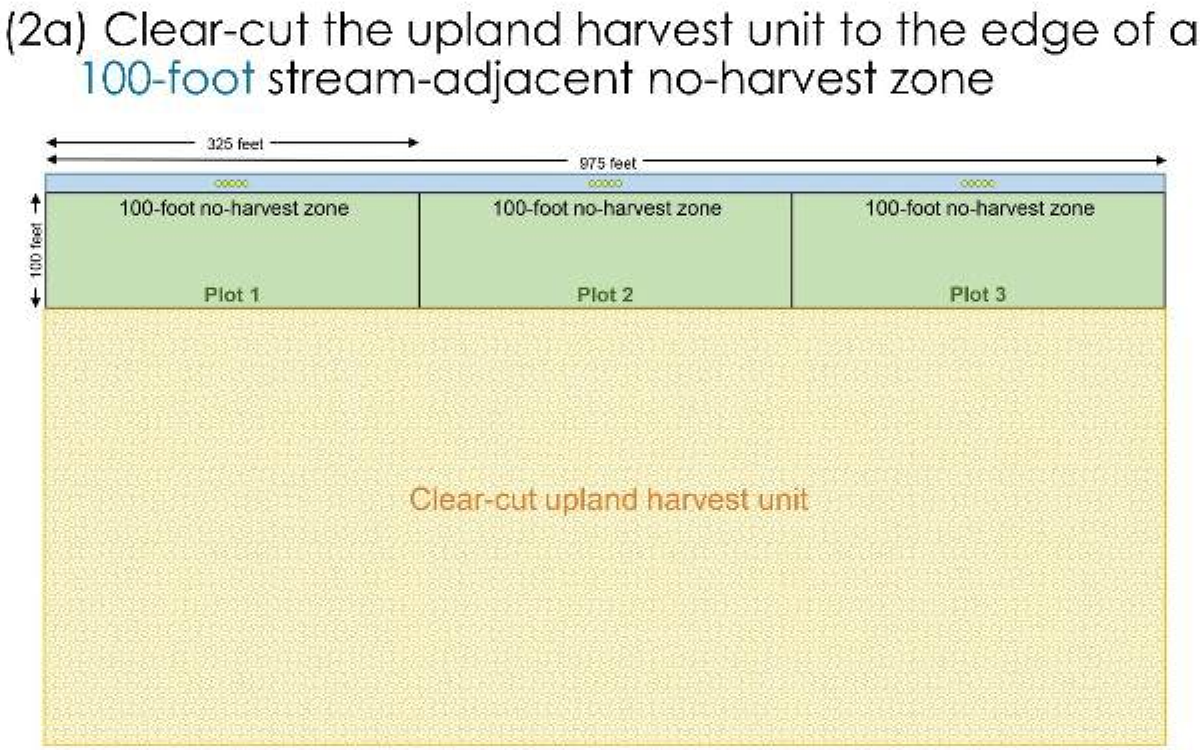
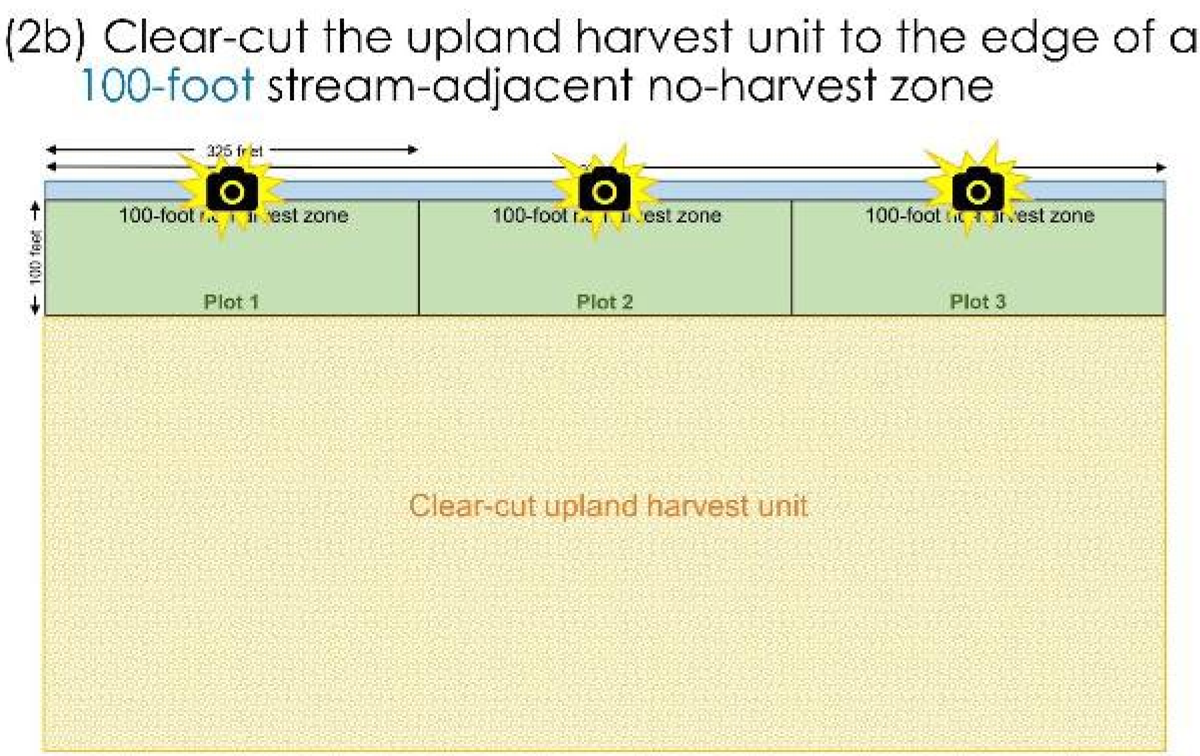
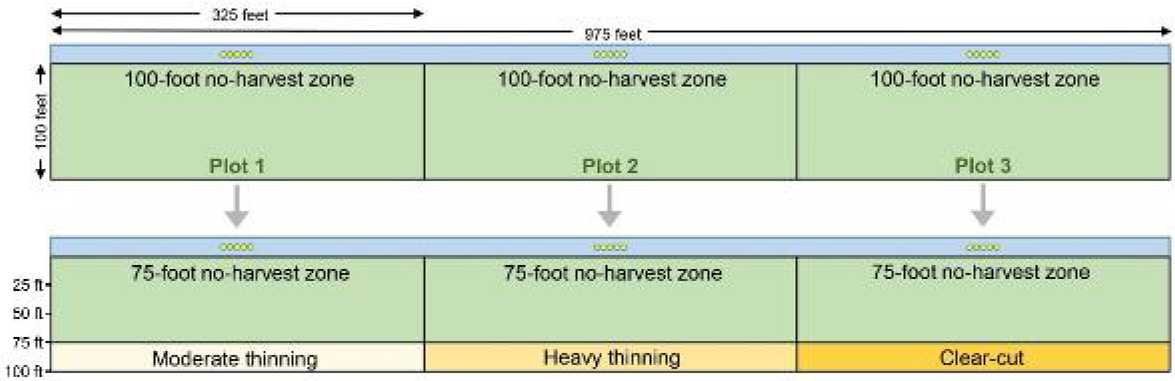


Figure 4 (continued on next five pages). The harvest treatment/hemispherical photo collection sequence used to implement the 10 harvest treatments in this study. Yellow dots represent hemispherical photo points. Camera icons represent the collection of hemispherical photos from all five photo points for each plot. Levels of adjacent-stand harvest intensity (i.e., moderate thinning, heavy thinning, clear-cut) will be randomly assigned to each plot. Moderate thinning = Curtis's Relative Density (RD) 40; Heavy thinning = Curtis's Relative Density (RD) 20.

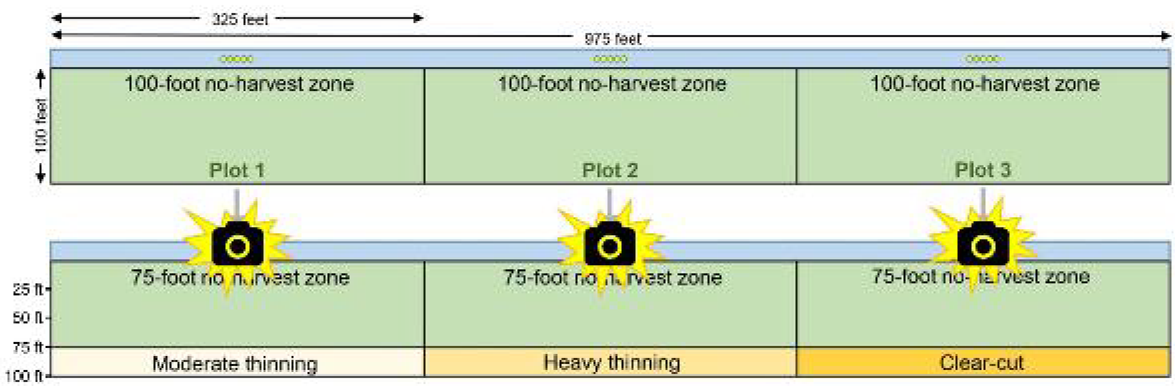

(2a) Clear-cut the upland harvest unit to the edge of a 100-foot stream-adjacent no-harvest zone
325 feet
975 feet
100 feet
100-foot no-harvest zone
100-foot no-harvest zone
100-foot no-harvest zone
Plot 1
Plot 2
Plot 3
Clear-cut upland harvest unit


(2b) Clear-cut the upland harvest unit to the edge of a 100-foot stream-adjacent no-harvest zone
100 feet
Plot 1
Plot 2
Plot 3
Clear-cut upland harvest unit

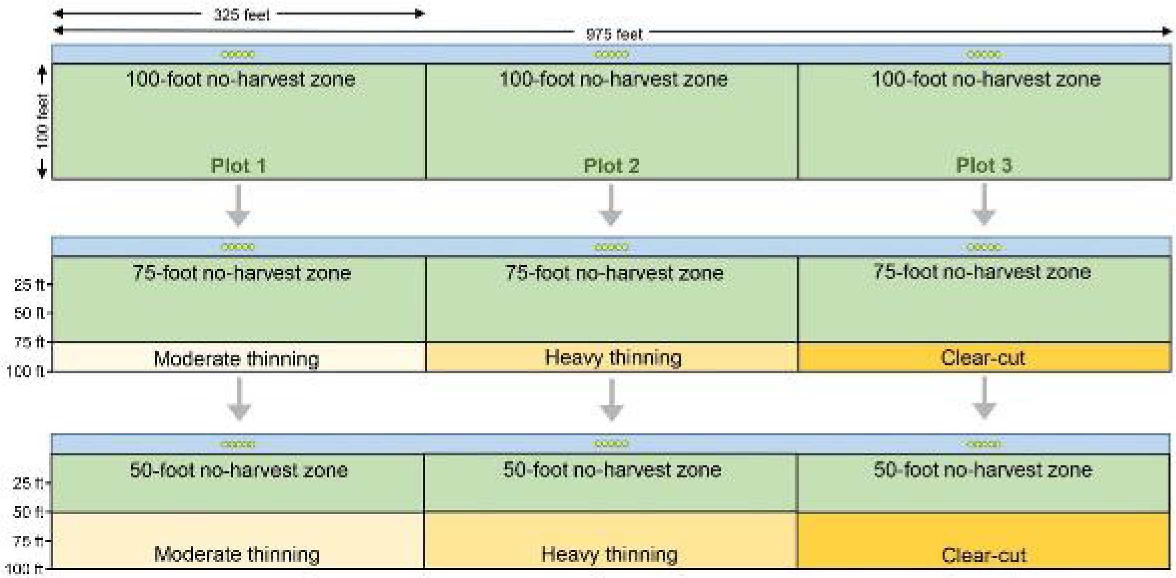
(3a) Harvest to the edge of a 75-foot wide stream-adjacent no-harvest zone



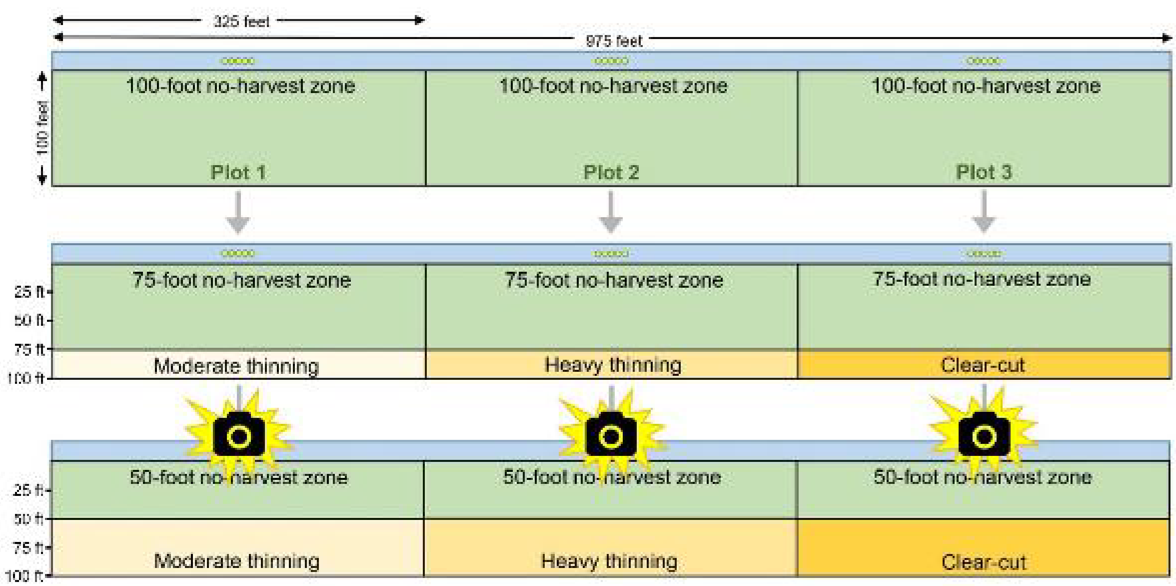
(3b) Harvest to the edge of a 75-foot wide stream-adjacent no-harvest zone



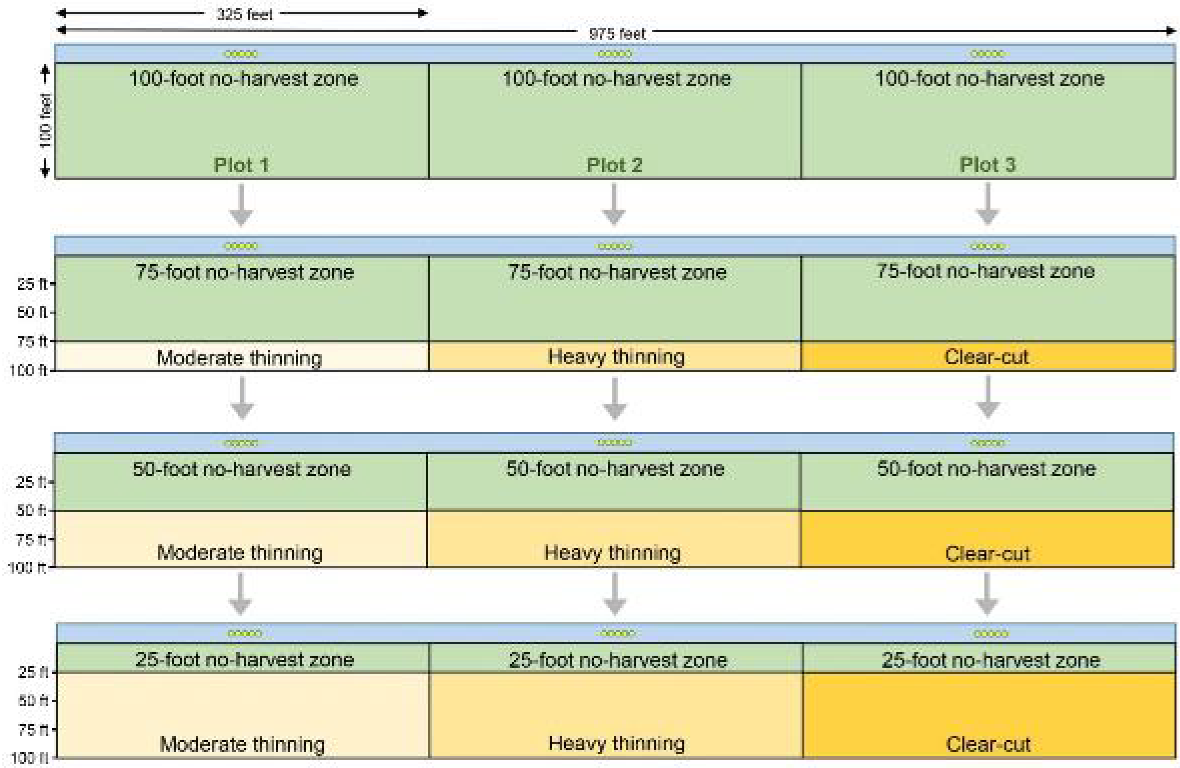
(4a) Harvest to the edge of a 50-foot wide stream-adjacent no-harvest zone



(4b) Harvest to the edge of a 50-foot wide stream-adjacent no-harvest zone



(5a) Harvest to the edge of a 25-foot wide stream-adjacent no-harvest zone



(5b) Harvest to the edge of a 25-foot wide stream-adjacent no-harvest zone

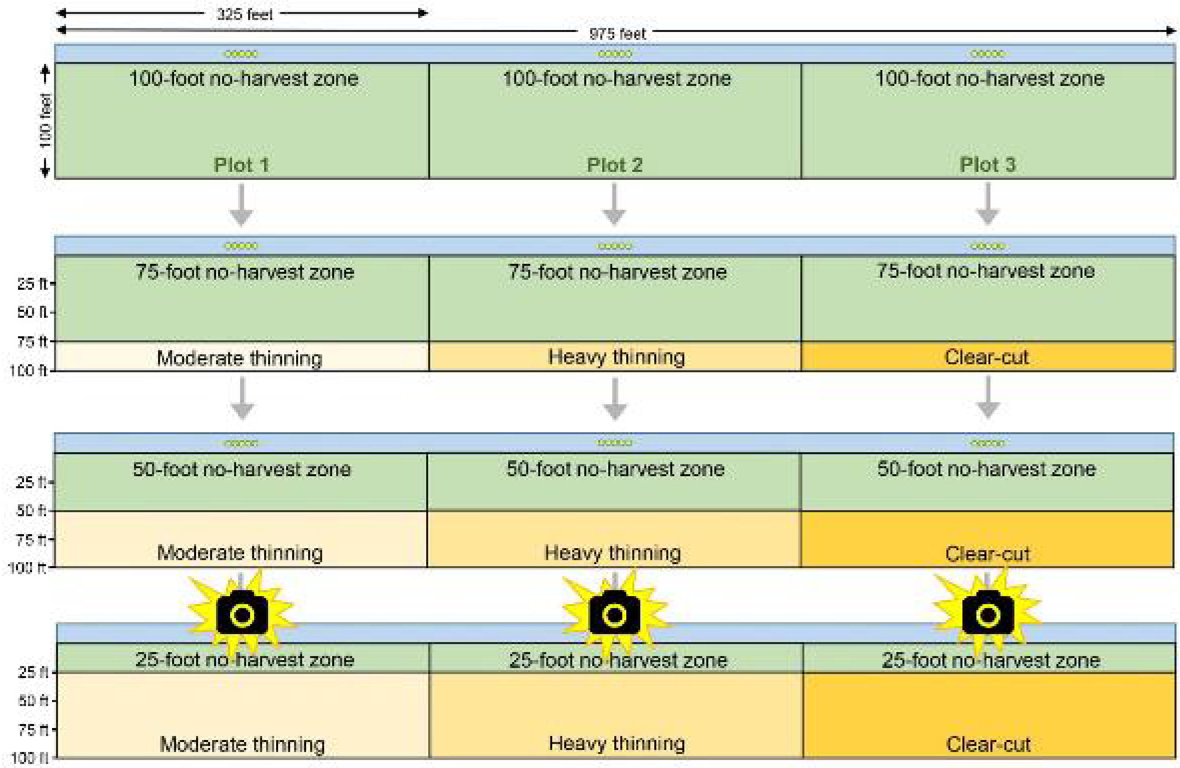


Table 4. The 10 riparian harvest treatment level combinations included in this study. Thinning treatment levels will be applied based on Curtis's Relative Density summation formula (RD; Curtis 2010).

	Adjacent-stand harvest intensity (thinning or clear-cut)		
Stream-adjacent no-harvest zone width (feet)	**Moderate thinning (Curtis's Relative Density 40)**	**Heavy thinning (Curtis's Relative Density 20)**	**Clear-cut (Curtis's Relative Density 0)**
25	X	X	X
50	X	X	X
75	X	X	X
100†			X

†The data for this treatment will be analyzed separately.

Sample Size

Five study sites containing three experimental plots will be established within each of the four ecoregions, for a total of 20 sites statewide (Table 5). This study will produce 40 treatment level/ecoregion combinations. However, for statistical estimation purposes, the Linear Mixed-effects Model (LMM) analyses described below will not include the 100-foot no-harvest buffer width with a clear-cut "thinning" level beyond. The range of treatment levels and sample size is expected to capture a treatment effect within the bounds of this study. Additionally, the total sample size of 20 sites represents what may be attainable given the known challenges and limitations with site selection based on previous CMER studies.

Table 5. Number of replicates (sample size, *n*) for each treatment type and level per ecoregion. The pre-treatment condition will be measured for every plot (*n* = 15 per ecoregion).

	Adjacent-stand harvest intensity (thinning or clear-cut)		
Stream-adjacent no-harvest zone width (feet)	**Moderate thinning (Curtis's Relative Density 40)**	**Heavy thinning (Curtis's Relative Density 20)**	**Clear-cut (Curtis's Relative Density 0)**
25	5	5	5
50	5	5	5
75	5	5	5
100†	0	0	15

†The LMM analysis will not include this treatment level.

Hemispherical photo post-processing and analysis

Hemispherical photos will be post-processed and analyzed using Hemisfer software. Photo pixel thresholding will initially be performed using the automated thresholding function in Hemisfer. If the automated thresholding function is deficient, manual thresholding procedures will be tested and implemented consistently. For example, pixel thresholding may use color band weighting using -100% green, +100% blue, and adjusting the red as needed around +20%.

Effective shade will be calculated for each photo according to the equation on page 10. For additional information, please see the [Light Regime](https://www.schleppi.ch/patrick/hemisfer/help.php?t=rad) section of the Hemisfer software user guide (https://www.schleppi.ch/patrick/hemisfer/help.php?t=rad).

The solar period selected for this study includes: (1) the time period when stream heating is generally greatest, (2) the leaf-on period for deciduous trees and shrubs in the study region, and (3) allows for experimental plot dimensions that can be practicably implemented in the field (based on maximum shadow lengths; Figures 3a and 3b). Shorter time periods of interest may be analyzed within this portion of the solar cycle (e.g., from 15 July to 15 August for solar altitudes 40° or greater). Figures 3a and 3b provide guidance for determining which time intervals (sun altitude and azimuth) are appropriate based on the plot size in this study. Note that harvest implementation may occur outside of the 1 June to 1 September window if leaf-on conditions are met.

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The 20 sites selected for this study will likely include a mix of unique stream orientations (azimuths) in the field. The amount of solar radiation reaching a stream depends not only on the amount of shade provided by vegetation and topography, but also on the stream orientation. That is, even if canopy cover and other shade sources were held constant, solar inputs/stream shade could vary depending on stream orientation.

Additionally, effective shade can vary depending on which side of the stream the treatments are implemented. For example, based on solar geometry alone, an exactly east-west oriented stream will receive more solar inputs from the south than the north. Therefore, removal of riparian trees on the south bank would be expected to result in a greater shade reduction than if the same riparian harvest treatments were implemented on the north bank, all other site conditions being equal. Note that the actual treatment bank direction will likely vary among the study sites depending on the cooperating landowners' harvest plans. Effective shade potential also varies by latitude due to solar geometry.

To eliminate the influence of the non-treatment variables of stream orientation, treatment bank direction, and latitude/longitude, these variables will be standardized during photo post-processing and analysis (Figure 5). Using the Hemisfer photo analysis software, hemispherical photos will be analyzed for the central latitude/longitude in Washington (47.3826, -120.4472) and for (1) east-west oriented streams with the treatment bank assigned to the south; and (2) north-south streams with the treatment bank assigned to the east. Note, for north-south orientations, an east-facing treatment bank was selected for purposes of consistency, but effective shade values are expected to be similar to a west-facing treatment bank.

East-west (with south-facing treatment bank) and north-south (with east-facing treatment bank) stream orientations will be used for this study because they represent the end-points for the range of stream orientations where riparian harvest treatments are likely to have the greatest effects on effective shade. It is important to target the maximum range of effective shade effects because this study is taking place within a forestry regulations context. Other stream orientations/treatment bank assignments are less relevant for the purposes of this study. For example, east-west streams with the treatment bank assigned to the north are not prioritized because this scenario is expected to have the minimum effect on effective shade due to harvest treatments, and therefore is less relevant in a rule-making context.

The untreated side (180°) of the stream will be excluded (masked) from effective shade value estimates (Figure 5). This will further reduce non-treatment influences and isolate the effects of the treatments on effective shade. That is, any variation among sites due to the untreated side of the stream will be removed from the analysis. For example, conditions on the untreated side of the stream are expected to vary among sites in terms of tree density, tree height, tree species, time since last harvest, previous planting strategy, etc. It will be important to reduce non-treatment influences as much as possible to better understand the harvest treatment effects on effective shade.

The above hemispherical photo post-processing and analysis procedures are necessary because this study aims to estimate the *change* in effective shade due riparian harvest treatments relative to the pre-harvest condition. Actual effective shade values (*ES*) are less important than the values for *change* in effective shade (ΔES) due to the treatment, all other variables being equal. These procedures will help ensure that any shade signal we detect is related to the treatment response, and not non-treatment variables.

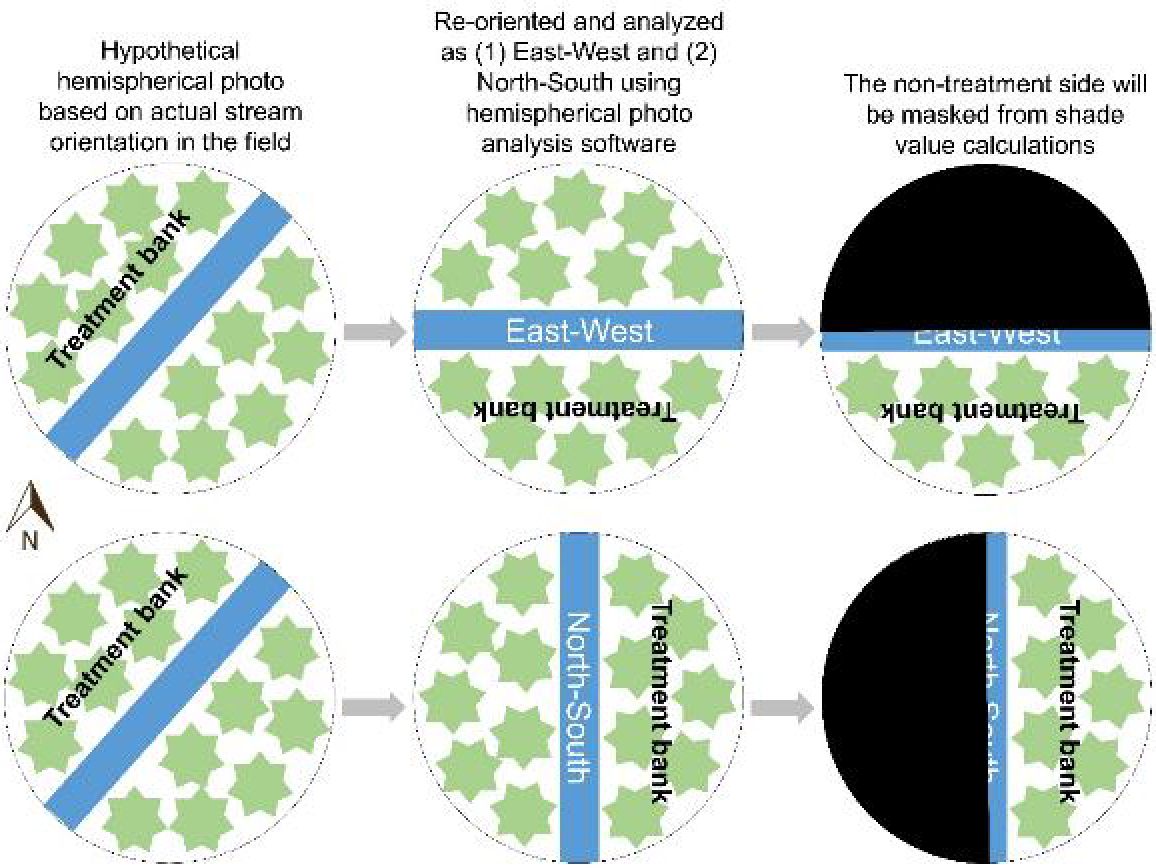

Figure 5. Example of stream orientation and treatment bank assignment that will occur during hemispherical photo analysis. This procedure will standardize estimates of effective shade by (1) east-west and (2) north-south stream orientations. The non-treatment bank will be masked from shade estimate calculations.

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As previously stated, five hemispherical photos will be taken for each treatment level (Figures 2 and 4). After post-processing each hemispherical photo by the above methods, effective shade values will be computed as the **mean** of the five photos taken at each plot for each treatment level.

Analysis

The main analysis response variable will be the difference, or change in, effective shade (*ΔES*) caused by changes in the riparian stand due to the nine different treatment level combinations (three no-harvest zone widths [the 100-foot no-harvest distance will be excluded] and all three thinning levels) and the original pre-harvest plot-level effective shade values. All effective shade values will be calculated for both east-west and north-south stream orientations and a common latitude/longitude (described above). The treatment level combination values will be subtracted from the original effective shade values to control for the initial differences in shade among sites.

Stream azimuth normalization will be addressed during hemispherical photo post-processing and analysis described above.

Difference in effective shade (*ΔES*) will be computed as:

$$\Delta ES_{hijk} = ES_{hij0} - ES_{hijk}$$

where h = ecoregion (1 through 4), i = study site (block, 1 through 5), j = plot (1 through 3), and k = treatment (0 through 4, where 0 = pre-treatment and 1 through 4 are the sub-plot treatments).

This study design may be represented as either a split-plot design with blocking or a strip-plot design with blocking. Either design is an option as we cannot randomize the order in which the buffer widths are adjusted, within or across subplots. In a split plot design, plots each receive one level of treatment and sub-plots within the plots receive all levels of a second treatment. For the split-plot design we would have plot-level thinning with the different no-harvest zone widths serving as sub-plots. The plots themselves will occur in blocks (sites), similar to the “Hard Rock” study (McIntyre et al. 2018). Every site will contain three plots, with the set of plots receiving all of the thinning treatment levels. Because of this structure, the shade values for subplots within plots and plots within sites are not independent. Measurements within a site may tend to be more similar than those among sites, and measurements within a plot may be more similar than those from other plots.

Strip plots are statistically structured differently in that each plot receives one treatment (thinning) level and then the other treatment (no-harvest buffer width) is applied perpendicularly across all plots. The assignment of the levels for each treatment type should be randomized. For this study, we would have effect estimates for three thinning levels (excluding 100 feet), each distance level, and their interactions (width-thinning combination). A random effect is assigned for each site and treatment type nested within site. The precision of estimates for no-harvest zone treatment levels from the split-plot design would be sacrificed for improving the precision of interactions of the treatments in the strip-plot design. We believe this trade-off is worthwhile as our main interest is in estimating the treatment interactions; therefore, we anticipate using the strip-plot design for the analysis.

The study design differs from a classic strip-plot design in that, within the analysis, some considered models will include an additive or interaction effect with a factor for ecoregion (with four levels). The model set will additionally include other explanatory variables as covariates in addition to the treatment and random effects variables associated with the strip-plot portion of the design.

Given that the data will be normally distributed and not fully independent due to the strip-plot design with blocking, the data will be analyzed using a Linear Mixed-effects Model (LMM). The LMM will account for nested non-independence with random effects parameters as well as produce all of the needed estimates. The model will have a random effect for site, for plot nested within site, and for thinning treatment nested within site. The fixed-effects variables will include ecoregion, the levels for both treatments, and all interactions among them. As described below, we will be addressing the study proposal by constructing and comparing the relative performance of several forms of the strip-plot model, some with additional covariates and some without. From previous CMER research, we know that *ES* may be modeled as a beta distribution and ΔES is likely to be approximately normally distributed.

The treatment combination for the 100-foot no-harvest buffer with clear-cut thinning beyond will be analyzed separately using a LMM with the same shade-change response variable, a single random effect for site, and no treatment fixed effects. The purpose of this analysis is to provide estimates of the difference in shade between a 100-foot no-harvest buffer and the initial shade values.

The study design allows for three types of analyses that could inform shade-predictive equations:

1. **Determine how treatments affect shade** (Objective 1, Critical Questions 1 and 2). The LMM, described above, will capture this analysis. Because the LMM can incorporate certain stand metrics as well, it will provide shade-predictive equations. The LMM will be used to obtain estimates (mean and 95% confidence interval) for each of the analyzed treatment level combinations. This output will be provided graphically. This level of analysis will address Objective 1 and Critical Question 1.

   Further, the analysis will test whether including ecoregions in the model improves model fit by comparing models that do and do not include the ecoregion variable (see Model Selection, below). Contrasts will be examined to statistically compare different treatment level combinations and treatment level combinations by area (Critical Question 2). The main limitation is that the study design and analysis will provide predictive capabilities only for no-harvest zones of 25, 50, and 75 feet, and for thinning out to 100 feet with no-harvest zones of 25, 50, and 75 feet. The design will not provide information about thinning treatment levels for riparian buffers other than 100 feet wide, such as buffers with a 25-foot stream-adjacent no-harvest zone and an adjacent 25-foot wide thinning zone (total buffer width of 50 feet). The design also will not provide information for thinning treatment levels in the absence of a stream-adjacent no-harvest zone.

2. **Determine how stand metrics post-harvest relate to changes in shade** (Objective 2, Critical Question 3). The experimental layout offers many conditions against which shade changes will be evaluated. This will be captured using a LMM where change in shade is the dependent variable and the independent variables are continuous site metric variables (e.g., those listed in Table 2 and Table 3). The findings may be relevant for creating predictive shade responses given specific stand conditions.

3. **Determine how treatments affect stand metrics.** Do plots with different initial stand metrics change in predictable or similar ways to the same suite of treatments? This information could be

useful for developing stand-specific or ecoregion-specific prescriptions. Multivariate analyses (e.g., MANOVA, nMDS) along with univariate analyses will be used to quantify and visualize the change in variable associations with different treatments.

During analysis, we will look for interactions among pre-harvest shade, ecoregion, and treatment.

Contrasts are comparisons of combinations of treatment means. The CMER "Hard Rock" (McIntyre et al. 2018) and "Soft Rock" (in review) studies used contrasts extensively for conveying results. As an example, the LMM output will be used to examine how the change in shade for moderate thinnings with 50-foot no-harvest zones differed between ecoregions 2, 3, and 4 relative to ecoregion 1. This sort of comparison approach will be used to address Critical Question 2 and others.

<u>Assumptions:</u>

Due to multiple treatments being applied within individual plots, the order of the within-plot treatments cannot be randomized. This requires an assumption that the results would have been the same had randomization occurred (see *Project Risk Analysis* below for more details).

The LMM assumptions will be tested following tests described in Pinheiro and Bates (2000). If the assumptions are violated we will strive to correct them.

Model Selection

Classic split-plot and strip-plot designs are typically introduced as occurring in an industrial, laboratory, or agricultural setting where there is a relatively high degree of control over environmental features. This study will be conducted in a far less controlled setting. The study site selection procedure attempts to exert some control over the more serious conditions that would affect outcomes, but certainly no two sites will be the same. We can exert further control over the analysis by statistically controlling for site features by including them as covariates in the analysis model. If they are important, they will assist with overall model fit and provide us with greater confidence in model estimates of treatment effects. However, we have uncertainty about the degree to which different possible covariates are needed in the model.

The wildlife sciences have addressed the issue of model uncertainty by performing model selection by having researchers develop, *a priori*, a suite of models to test and compare using model AIC, or Akaike's Information Criterion, scores (Burnham and Anderson 2002). Each model represents a sensible hypothesis about how the system at hand may function. See Zuur (2009) for a description of an approach for applying these techniques to LMMs. An AIC-based model selection approach protects against overfitting models with uninformative variables by penalizing models for the number of variables that they include. Similarly, by developing a set of models *a priori* and avoiding fitting all possible models, we avoid data dredging. Model comparisons convey the performance of each model relative to other models. We can assess how well certain covariates improve model fit relative to models without them and determine the information gain of our top supported model(s) relative to a model that has little information, such as an intercept model. If two or more models perform well (low AIC scores that are nearly equal) then we consider the set as each may be informative in its own way. Analyses of model AIC values also allow for the assignment of model weights, which represent the probability that a model is the best of the set of considered models. For Analyses 1 and 2 we will create a suite of models prior to analysis that contain different covariates that may assist in accounting for inter-site differences. Aside from an intercept model, we anticipate that for Analysis 1, all models will include the core model structure for the strip-plot design.

Site attributes

Site attributes including plot slope and aspect, stream channel azimuth and slope, bankfull width, and channel confinement ratio will be tabulated and summarized using descriptive statistics for each plot and each site (Table 2). This will provide additional information about the study sites, as well as the amount and type of variation within and among study sites. Site attribute data will also be available for use as covariates in shade-change analyses to control for site features not related to riparian stand metrics.

Stand characteristics

Stand composition and structure data (Table 5) will be used to help account for changes in shade in response to the treatments, variation in shade response among ecoregions, and the magnitude of model variance. Stand data will be used to control for site-specific conditions. Stand data will also be investigated independently of the LMM in relation to shade and treatment level combinations.

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All data will be post-processed and compiled in a database that can be queried to inform future questions about stream shade response to different riparian harvest treatments and for additional portions of the solar cycle. For example, analyses may be performed for shorter time intervals of interest within the primary study period, such as 15 July through 15 August for solar altitudes of 40° or greater. Figures 3a and 3b provide guidance for determining appropriate time intervals based on plot size.

QUALITY ASSURANCE AND QUALITY CONTROL

The following quality assurance and quality control procedures will be implemented to ensure accurate data collection, recording, and analysis.

Harvest treatment application and field data collection

- Field inspections will confirm that sites meet the site selection criteria.
- If possible, the same field staff will be used to inventory and mark trees for harvest to provide consistency across the thinning treatments.
- Harvest inspections will be conducted for each treatment interval to ensure that all trees marked for harvest were cut and to record any unintended tree falling or damage.
- Boundary markers will be inspected and re-established as needed following each harvest interval to correct for any disturbance by harvest crews and equipment.
- Prior to field data collection, field staff will be provided with written instructions for all data collection procedures and hands-on training with all procedures and equipment.
- Field data sheet templates will be provided that list the type, units, and sequence of data to be collected.

- Plot boundaries and photo point locations will be measured and confirmed by at least two field staff before any data collection occurs. Plot boundaries will be inspected and corrected as necessary after each harvest treatment.
- Sampling equipment including hemispherical cameras and tripods will be tested each day before data collection begins to ensure proper operation. If any sampling equipment malfunctions during data collection, field staff will note what data may have been affected and pause data collection until a replacement is issued or the equipment is repaired. Any potentially affected data will be re-measured and re-recorded.
- Trampling of understory vegetation by field staff will be avoided prior to and during all photograph collection intervals, especially along and near the stream.
- Field staff will be instructed to take detailed notes and photographs to document any anomalous situations.

Data post-processing and analysis

- Exploratory graphical analyses will be conducted to determine if any individual measurement values are clear outliers due to measurement or recording errors. If an outlier is found, the field datasheets, photos, and notes will be consulted to determine whether the data can be corrected or if it needs to be eliminated from the analysis.
- Erroneous results and how they are addressed will be documented and described in the final study report.
- As time and budget allows, a sub-sample of hemiphoto images will be analyzed by two separate observers to assess whether there are significant differences in shade estimates due to individual observer determinations for photo exposure and threshold settings.
- Statistical model assumptions will be checked. Models will be modified if they fail assumption checks.
- All data analysis procedures will be documented and explained in the final report.

PROJECT RISK ANALYSIS

There are constraints and risks inherent to most experimental research that occurs in forested environments. This section describes potential problems for data collection and analysis, as well as contingencies for addressing these problems.

Study scope

The inference of our study results will extend to all riparian stands of harvest age occurring on non-federal lands managed under the FPHCP within the Northwest Coast, West Cascades, Okanogan, and Canadian Rocky Mountains ecoregions in Washington State; located within verified Site Classes II and III; along Type Np and Type F streams with bankfull widths from 5 to 25 feet; and receiving harvest treatments according to the prescriptions described within this document.

This study is intended to provide information in a relatively short timeframe and for a relatively low cost. This sets limits on the sample size and number of treatments that can be included in the study. For example, this study will include 10 riparian harvest treatment level combinations with intervals that are expected to have a measurable difference in shade. However, these 10 treatment level combinations do not include all possible treatments of interest (e.g., additional stream-adjacent no-harvest zone widths).

The findings may be interpolated within the range of the treatments but cannot be extrapolated outside of that range with great confidence (e.g., predict the difference in shade for a 50-foot wide 100% thinning buffer at RD 60). The 10 harvest treatment level combinations included in this study will inform existing information gaps and will be sufficient to fulfill the objectives of this study.

The primary study period selected for this study (1 June – 1 September for solar altitudes 40° or greater) encompasses the time period when stream heating is generally greatest, the leaf-on period for deciduous trees and shrubs in the study region, and allows for experimental plot dimensions that can be practicably implemented in the field. The study does not focus on other periods that may be of interest, such as early morning or late afternoon/evening (i.e., solar altitudes <40°). Including solar altitudes <40° in this study would require much larger plot sizes than could be practicably implemented in the field. For example, analyzing east-west streams for solar altitudes 30° or greater would require each plot to measure 460 feet by 100 feet, for a total site length of 1,380 feet (Figure 4a). Additionally, the area of each plot would increase from about 0.75 acre to about 1 acre, increasing the costs, resources, and time needed for stand inventories and harvest activities. Thus, the study design optimizes the information gained for the primary period of interest within the logistical constraints for field implementation. However, results from this study will be compiled and made available in a public database that can be queried to inform other questions about stream shade response to riparian harvest treatments for different portions of the solar cycle. Figures 4a and 4b provide guidance for determining what time intervals can be accurately assessed based on the plot size used in this study.

Study design assumptions

A proper split-plot or strip-plot design requires a randomization of plot-level treatments (the thinning intensity inside the plot) and the within-plot treatments (the stream-adjacent no-harvest zone widths). The harvest sequence, however, does not allow randomization of the within-plot stream-adjacent no-harvest zone width order. The design must proceed with each plot starting with a 100-foot, then 75-foot, then 50-foot, then 25-foot no-harvest zone width. Based on this study design, there must be an assumption that the order of the no-harvest zone width will not appreciably affect observed responses. That is, it must be assumed that not randomizing the no-harvest zone width order will result in findings that would match a study where the harvest order could be randomized. Because this design cannot randomize the order of no-harvest zone widths within a plot, the results may be confounded by some unanticipated aspect of harvest or site response that is due to harvesting the plots in that order. This assumption can be partially supported by planned data collection methods, which will allow field crews to identify which individual trees were correctly harvested or unintentionally felled. If we verify that virtually all trees are removed as intended, this supports the assumption that the treatment level order, if randomized, would not have produced different results.

Site availability and sample size

Lack of available sites is one possible limitation to this study. It may be difficult to identify an adequate number of sites that match the selection criteria in areas where there are willing landowners or from approved Forest Practices Applications (FPAs) that will be harvested during the study period. Further, there is a small possibility that landowners may later choose not to harvest certain areas if timber markets are not favorable.

To increase the number of potential sites, sites containing discontinuous plots (plots that do not share a boundary) could be considered for inclusion in the study, as long as the site layout does not introduce any unintentional biases that could affect outcomes.

If five qualifying sites cannot be identified in one or more ecoregions, other options will be considered, such as: adding more sites in a subsequent year, continuing the study with fewer than five sites in an ecoregion, adding more sites to another ecoregion, removing an ecoregion from the study, substituting one of the four selected ecoregions with another relevant ecoregion in Washington, or adjusting the site selection criteria to include more sites. The study will include at least four sites per ecoregion and will only adjust site selection criteria if the criteria changes are carefully considered.

Variation in site conditions

Natural variation across the landscape creates variability in conditions across study sites. This variation can produce confounding factors that limit the ability to identify trends and relationships for variables of interest. Site variability will be reduced in this study by selecting sites within specified ecoregions that have similar biophysical environments. Data will be analyzed according to ecoregion. Site variability will also be reduced by using well-defined site selection criteria. Note: Reducing variability across sites will reduce the range of variation over which conclusions can be drawn. It will improve study precision but decrease the scope of inference.

During the analysis phase, stream orientation will be standardized across sites. The treatment bank will be assigned to the south to estimate shade for east-west stream orientations, and to the east to estimate shade for north-south stream orientations. Note that stream orientation will be assigned during the photo analysis phase and is independent of actual stream orientation in the field. This step will ensure that shade response to the treatments is not influenced by differences in stream orientation across sites.

Variation in understory vegetation (e.g., shrub/sapling cover and height) and topographic shading across sites may make it difficult to identify shade response due to the overstory harvest treatments. The before/after treatment design and short duration of the harvest sequence ensures that there will be minimal change in understory vegetation and topographic shading between treatments occurring in a given plot, helping to isolate the treatment effect. Hemispherical photos will be taken at 3.3 feet (1 meter) above the streambed to further reduce the influence of low-lying vegetation and channel topography on shade response to the treatments. Likewise, restricting the shade analyses to solar altitudes ≥40°, will reduce the influence of shorter vegetation and sources of topographic shade (e.g., streambank) that fall below the zone of analysis. The primary focus is the change in effective shade due to overstory harvest treatments.

Study implementation/harvest logistics

There are potential challenges with study implementation and harvest logistics due to the constraints of the study design. First, landowner schedules for the upland clear-cut may not coincide with the leaf-on conditions required for this study, so this constraint ideally will be addressed during the site selection process. Second, the study design requires that the plot harvest sequence and hemispherical photograph collection occur within a short timeframe (e.g., ≤10 days), so a large amount of coordination will be needed between field crews and cutting crews. Cutting crews may have idle periods while field crews are on site taking photographs at the designated intervals and appropriate times of day (when the sun is not in view of the camera lens). An independent cutting crew will be hired and funded through this project to apply the within-plot harvest treatments to help alleviate these logistical constraints.

Ideally, the riparian harvest treatments at a given site will occur during the same timeframe as the adjacent upland harvest. This will minimize operational constraints such as re-opening access roads, mobilizing harvest crews and equipment, or potential damage to newly planted seedlings. This will also minimize the likelihood of windthrow and other disturbances occurring during the harvest and data collection sequence. For each individual site, harvest within the experimental plots will be restricted to a short time period (e.g., $\leq$10 days) to minimize the occurrence of uncontrolled factors during the harvest sequence.

If possible, the same personnel will be used to conduct stand inventories and mark trees for harvest to provide consistency across all sites. A site selection and data collection plan (including Standard Operating Procedures [SOPs]) will be developed to ensure the consistency and quality of data and to identify and minimize logistical constraints.

Tentative budget – subject to change

Budget Task	FY 22	FY 23	FY 24	FY 25
Westside Sites				
Site Selection (Westside)	$39,415			
Layout plot and harvest zone boundaries, collect stand inventory data	$42,240			
Mark Trees for thinning treatments	$54,690			
Tree cutting within plots		$75,985		
Compliance of tree cutting		$7,500		
Data collection: Site attribute data		$21,600		
Data collection: Photo Collection		$55,840		
Eastside Sites				
Site Selection (Eastside)		$40,278		
Layout plot and harvest zone boundaries, collect stand inventory data		$22,803	$30,244	
Mark Trees for thinning treatments		$18,083	$27,124	
Tree cutting within plots			$97,515	
Compliance of tree cutting			$7,500	
Data collection: Site attribute data			$21,600	
Data collection: Photo Collection			$58,129	
Photo processing, data analysis, and report writing				
Photo processing			$25,000	
Data QA/QC, process, analyze, and summarize site attribute data			$40,000	
Final report writing and review			$40,000	
Final report revisions				$20,000
Total FY Estimated Budget	$136,345	$242,089	$347,112	$20,000

Total Estimated Project Budget: $745,546*

***It is assumed landowners will cover upland harvesting costs and removal of logs.**

References

Allen, M. and L. Dent. 2001. Shade conditions over forested streams in the Blue Mountain and Coast Range georegions of Oregon. Oregon Department of Forestry, Technical Report #13.

Beechie, T., and H. Imaki. 2014. Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA. Water Resources Research **50**:39-57.

Beschta, R. L., R. E. Bilby, G. W. Brown, L. B. Holtby, and T. D. Hofstra. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 191-232 in E. O. Salo, and T. W. Cundy, editors. Streamside Management: Forestry and Fisheries Interactions. University of Washington, Institute of Forest Resources, Seattle, WA.

Bladon, K. D., N. A. Cook, J. T. Light, and C. Segura. 2016. A catchment-scale assessment of stream temperature response to contemporary forest harvesting in the Oregon Coast Range. Forest Ecology and Management **379**:153-164.

Boggs, J., G. Sun, and S. McNulty. 2016. Effects of timber harvest on water quantity and quality in small watersheds in the Piedmont of North Carolina. Journal of Forestry **114**:27-40.

Brazier, J. R. and G. W. Brown. 1973. Buffer strips for stream temperature control. Research Paper 15, Paper 865. Forest Research Laboratory, School of Forestry, Oregon State University. Corvallis, OR.

Brown, G. W. 1969. Predicting temperatures of small streams. Water Resources Research **5**:68-75.

Bryant, G. J. , and J. Lynch. 1996. Factors for decline: A supplement to the Notice of Determination for west coast steelhead under the Endangered Species Act. National Marine Fisheries Service. Portland, OR.

Burnham, K. P., and D. R. Anderson. 2002. Model Selection and Multimodel Inference. A Practical Information-Theoretic Approach, second ed. Springer-Verlag, New York, pp. 488.

Cristea, N., and J. Janisch. 2007. Modeling the effects of riparian buffer width on effective shade and stream temperature. Washington State Department of Ecology, Olympia, WA. Publication No. 07-03-028.

Curtis, R. O. 2010. Effect of diameter limits and stand structure on relative density indices: A case study. Western Journal of Applied Forestry **25**:169-175.

Danehy, R. J., C. G. Colson, K. B. Parrett, and S. D. Duke. 2005. Patterns and sources of thermal heterogeneity in small mountain streams within a forested setting. Forest Ecology and Management **208**:287-302.

Dent, L., D. Vick, K. Abraham, S. Schoenholtz, and S. Johnson. 2008. Summer temperature patterns in headwater streams of the Oregon Coast Range. Journal of the American Water Resources Association **44**:803-813.

DeWalle, D. R. 2010. Modeling stream shade: Riparian buffer height and density as important as buffer width. Journal of the American Water Resources Association **46**:323-333.

Ehinger, W. J., G. Stewart, and S. M. Estrella. 2018. Stream temperature and cover. Chapter 7 *in* A. P. McIntyre, M. P. Hayes, W. J. Ehinger, S. M. Estrella, D. Schuett-Hames, and T. Quinn (technical coordinators) *Effectiveness of Experimental Riparian Buffers on Perennial Non-fish-bearing Streams on Competent Lithologies in Western Washington*. Cooperative Monitoring, Evaluation and Research Report CMER 18-100, Washington State Forest Practices Adaptive Management Program, Washington Department of Natural Resources, Olympia.

FFR. 1999. Forests and Fish Report. Report to the Washington Forest Practices Board and the Governor's Salmon Recovery Office. 173 p.

FPHCP. 2005. Forest Practices Habitat Conservation Plan. Washington Department of Natural Resources, Olympia, WA. https://www. dnr. wa. gov/programs-and-services/forest-practices/forest-practices-habitat-conservation-plan.

Groom, J. D., L. Dent, and L. J. Madsen. 2011a. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research **47**.

Groom, J. D., L. Dent, L. J. Madsen, and J. Fleuret. 2011b. Response of western Oregon (USA) stream temperatures to contemporary forest management. Forest Ecology and Management **262**:1618-1629.

Groom, J. D., L. J. Madsen, J. E. Jones, and J. N. Giovanini. 2018. Informing changes to riparian forestry rules with a Bayesian hierarchical model. Forest Ecology and Management **419**:17-30.

Guenther, S., T. Gomi, and R. Moore. 2014. Stream and bed temperature variability in a coastal headwater catchment: Influences of surface-subsurface interactions and partial-retention forest harvesting. Hydrological Processes **28**:1238-1249.

Hicks, M. 2018. Riparian Characteristics and Shade Response Experimental Research Study Scoping Document. Cooperative Monitoring, Evaluation and Research Report. Washington State Forest Practices Adaptive Management Program, Washington Department of Natural Resources, Olympia, WA.

Johnson, S. L., and J. A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences **57**:30-39.

McArdle, R. E., W. H. Meyer, and D. Bruce. 1961. The yield of Douglas-fir in the Pacific Northwest. Technical Bulletin 201 (rev.). USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR. 74 p.

McIntyre, A. P., M. P. Hayes, W. J. Ehinger, S. M. Estrella, D. Schuett-Hames, and T. Quinn. 2018. Effectiveness of experimental riparian buffers on perennial non-fish-bearing streams on competent lithologies in Western Washington. Cooperative Monitoring, Evaluation and Research Report CMER 18-100. Washington State Forest Practices Adaptive Management Program, Washington Department of Natural Resources, Olympia, WA.

Moore, R., D. Spittlehouse, and A. Story. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. Journal of the American Water Resources Association **41**:813-834.

Myers, J., and G. Bryant. 1998. Factors contributing to the decline of Chinook salmon: An addendum to the 1996 west coast steelhead factors for decline report. National Marine Fisheries Service, Portland, OR.

Park, C. S., B. McCammon, and J. Brazier. 2008. Changes to angular canopy density from thinning with varying no treatment widths in a riparian area as measured using digital photography and light histograms. Unpublished report.

Pinheiro, J. C., and D. M. Bates. 2000. Linear Mixed-Effects Models: Basic Concepts and Examples. In *Mixed-Effects Models in Sand S-PLUS* (pp. 3-56). New York, NY: Springer New York.

Raulerson, S., C.R. Jackson, N. D. Melear, S. E. Younger, M. Dudley, and K.J. Elliott. 2020. Do southern Appalachian Mountain summer stream temperatures respond to removal of understory rhododendron thickets? Hydrological Processes **34**:3045-3060.

Rich, P. M., 1990. Characterizing plant canopies with hemispherical photographs. Remote Sensing Reviews **5**:13-29.

Roon, D. A., J. B. Dunham, and J. D. Groom. 2021. Shade, light, and stream temperature responses to riparian thinning in second-growth redwood forests of northern California. PLoS One **16:** e0246822. https://doi.org/10.1371/journal.pone.0246822.

Teply, M., D. McGreer, and K. Ceder. 2014. Using simulation models to develop riparian buffer strip prescriptions. Journal of Forestry **112**:302-311.

Valverde, T., and J. Silvertown. 1997. Canopy closure rate and forest structure. Ecology **78**:1555-1562.

WADNR (Washington Department of Natural Resources). 2007. State of Washington Natural Heritage Plan. Washington Department of Natural Resources, Olympia, WA.

WFPB (Washington Forest Practices Board). 2004. Standard methods for identifying bankfull channel features and channel migration zones. Washington Forest Practices Board Manual Section 2. Olympia, WA. https://www. dnr. wa. gov/publications/fp_board_manual_section02. pdf?4c16hc.

WFPB (Washington Forest Practices Board). 2011. Standard methodology for conducting watershed analysis under Chapter 222-22 Washington Administrative Code (WAC), version 5.0, Appendix E, Olympia, WA, 97 p.

Wilkerson, E., J. M. Hagan, D. Siegel, and A. A. Whitman. 2006. The effectiveness of different buffer widths for protecting headwater stream temperature in Maine. Forest Science **52**:221-231.

Witt, E. L. , C. D. Barton, J. W. Stringer, R. K. Kolka, and M. A. Cherry. 2016. Influence of variable streamside management zone configurations on water quality after forest harvest. Journal of Forestry **114**:41-51.

Zuur, A. F., E. N. Ieno, N. Walker, A. A. Saveliev, and G. M. Smith. 2009. Mixed Effects Models and Extensions in Ecology with R. Springer.