Westside Type F Riparian Prescription Monitoring Project:
Best Available Science and Study Alternatives Document

Westside Type F Riparian Prescription Monitoring Project Technical Writing and Implementation Group (TWIG):

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Cooperative Monitoring Evaluation and Research Committee

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Introduction

The Cooperative Monitoring, Evaluation and Research Committee (CMER) workplan (CMER 2014) identifies the need for the Westside Type F Riparian Prescription Monitoring Project to evaluate the effectiveness of riparian prescriptions for fish-bearing streams in western Washington. CMER assembled a Technical Writing and Implementation Group (TWIG) (Table 1) and a charter to initiate the scoping and study design process. The TWIG's initial tasks were to review and revise the critical questions for this project, review relevant literature, and develop and evaluate study design options to address the critical questions. This document was prepared by the TWIG and presents:

- updated critical questions,
- a summary of literature used in the BAS comparison,
- a discussion of options for a study design approach, and
- recommendations on how to proceed.

Although this project was not among the three projects approved by the Board as LEAN Pilot projects, CMER agreed to follow the same LEAN process for this particular project. Therefore, CMER and the TFW Policy committee will use this document to inform their decision regarding how the TWIG should proceed with the next step of developing a study design for the project and which option(s) to pursue.

Table 1. Composition of the Westside Type F Riparian Monitoring Project TWIG.

Name	Affiliation
Howard Haemmerle- Project Manager	Washington Department of Natural Resources
Rebecca Flitcroft	USDA Forest Service, Pacific Northwest Research Station
Doug Martin	Martin Environmental
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Dave Schuett-Hames- CMER staff	Northwest Indian Fisheries Commission

Issue/Problem Statement

The westside Type F riparian prescriptions are an important component of the Riparian Conservation strategy of the Washington Forest Practices Habitat Conservation Plan (FPHCP) (WDNR 2005). The Riparian Conservation Strategy of the FPHCP focuses on protection of riparian habitat and processes to meet water quality standards and support recovery of aquatic and riparian dependent species (e.g. fish and stream-associated amphibians), and

> *"It includes protection measures implemented in and adjacent to surface waters and wetlands. Examples include wetland and water typing systems, channel migration zones, wetland and riparian management zones and equipment limitation zones. These measures are designed to provide adequate levels of large wood recruitment and shade, and to limit excess fine sediment delivery to surface waters and wetlands*" (WDNR 2005).

The riparian forests covered by these prescriptions are adjacent to waters that are used by fish for spawning, incubation and rearing, and the habitat is directly affected by the functions, processes and inputs provided by these forests including litter fall, shade, long-term wood recruitment, bank protection and sediment filtering.

The FPHCP contains a set of Resource Objectives that are defined as key aquatic conditions and processes affected by forest practices (http://www.dnr.wa.gov/Publications/fp_hcp_31appn.pdf).

Resource objectives consist of Functional Objectives, which are broad statements of objectives for the major watershed functions potentially affected by forest practices, and Performance Targets, which are the measurable criteria defining specific attainable target forest conditions (WDNR 2005- Appendix N).

The Westside Type F riparian prescriptions are designed to help achieve the resource objectives for heat/water temperature, LWD/organic inputs, and sediment. Although the Forest and Fish Report (promulgated into the FPHCP; WDNR 2005) led to an increase in the width of the riparian buffers and the density and basal area of leave trees, the degree to which the resource objectives and their associated functional objectives and performance targets are being achieved is unknown. Research is needed to reduce the scientific uncertainty related to the effect of the prescriptions on riparian stands, and the response of riparian functions, processes and aquatic habitat; and to provide information on prescription effectiveness for the FPHCP adaptive management program.

Purpose of the Project

The purpose of the project is to determine how riparian stand conditions respond over time to the Westside Type F riparian prescriptions, and to evaluate the effectiveness of the prescriptions in meeting FPHCP functional objectives and performance targets.

Critical Questions

The CMER work Plan (CMER 2014) contains several critical questions specific to the Westside Type F Riparian Prescription Monitoring Project. TWIG members determined it would be beneficial to reorganize and clarify the original critical questions (see Appendix A). The revised critical questions are organized around three ecological strata (riparian stand, physical stream processes, and aquatic biota). The sub-questions within each strata are similar to the work-plan questions and do not change the scope or purpose of the Type F Prescription Effectiveness program or the intent of this project. The purpose of the changes are to clarify and arrange the critical questions in a framework that better illustrates the potential cause-effect pathway from the prescriptions to the riparian stand and riparian functions, to changes in stream and channel characteristics, and to biological effects. Restructuring the questions facilitates a phased study approach that enables the addition or deletion of project elements based on the incremental accumulation of information within each strata. This approach also provides a better format for describing different study options and explaining the strengths and weaknesses of different alternative approaches to those options. Following are the revised critical questions.

1. Riparian Stand Characteristics and Riparian Functions

a) How do the RMZ and no-RMZ harvest prescriptions affect riparian stand characteristics and riparian functions?
b) How do the characteristics of riparian forest stands and associated riparian functions in areas with RMZ and without RMZ harvest change over time?
c) Do riparian forest stands in areas with RMZ and without RMZ harvest remain on trajectory to achieve DFC targets?

2. Physical Stream Characteristics and Processes

a) How do physical stream characteristics and processes respond to changes in riparian functions in areas with RMZ and without RMZ harvest?

b) Do physical stream characteristics and processes meet performance targets?

3. Aquatic Biological Response

a) What is the aquatic biological response to changes in riparian functions in areas with RMZ and without RMZ harvest?

Literature Review

Summary of Literature Reviewed To Assess Study Design Alternatives

The TWIG conducted a review of relevant literature to: 1) summarize what was known about the response of riparian forests, riparian functions, channel/water quality and biota to a variety of contemporary riparian management practices, and 2) to identify the strengths and weaknesses of various research and monitoring approaches and their potential applicability to the Westside Type F Prescription Monitoring Project. We focused on studies that evaluated the effects of forest management practices on riparian stand conditions, physical stream conditions, and aquatic biotic responses in fish-bearing (preferably) and non-fish-bearing streams. We reviewed mostly recent (i.e., after 1990) published literature and included gray literature that is highly relevant. The TWIG reviewed 67 publications including several relevant CMER reports, USFS documents and a Master's Thesis. Appendix B lists the references for the literature examined. The papers cover a wide range of topics (Table 2) including prescription effects on water temperature, shade, riparian stand composition, wood recruitment and aquatic biota.

Table 2. Frequency of topics in the reviewed literature.

Topic	Count
Water Temperature	22
Stand Response	20
Shade/cover/solar radiation	18
Macroinvertebrates/drift	17
Wood Loading	15
Tree mortality/windthrow	13
Wood Recruitment	11
Substrate	11
Aquatic Habitat	9
Fish	8
Litter fall	7
Water Quality/Nutrients/TSS	6
Organic Matter	5
Microclimate	4
Amphibians	4
Sediment Input	3
Periphyton	3
Discharge	2

The researchers utilized a variety of study designs (Table 3). Nearly half (28) of the papers reported on before-after, control-impact (BACI) studies. There were 32 post-harvest studies, of which 18 included reference sites (controls) for comparison. Several papers reported on the use of modeling efforts and meta-analyses of pre-existing data to evaluate riparian management prescriptions.

Table 3. Frequency distribution by study design.

Design	Count
After, impact (AI)	14
After, control-impact (ACI)	18
Before-after, control- impact (BACI)	28
Before-after, impact (BAI)	1
Modeling	4
Meta analysis	2

The research papers used a wide range of riparian management prescriptions, over different regions and site conditions with many focusing on headwater streams. Few studies were found that examined riparian management prescriptions for fish-bearing streams that were similar to those for western Washington as outlined in the FPHCP. Consequently, the ability to draw conclusions about the response of western Washington fish-bearing streams to the FPHCP riparian prescriptions is limited due to differences in prescription type (application and timing), climate, physiography and site conditions.

A summary of the literature that is relevant to evaluating potential study design options is presented in the following sections. The first section discusses findings organized by the resource objectives in the FPHCP (i.e. shade/temperature, wood recruitment, litter fall/organic matter, sediment, and biotic response). Appendix N of the FPHCP has additional information on the resource objectives (http://www.dnr.wa.gov/Publications/fp_hcp_31appn.pdf). The second section discusses findings concerning the efficacy of various study approaches in evaluating the effects of riparian management.

Discussion of Findings Relative to FP-HCP Resource Objectives

Shade/water temperature

The primary function of riparian vegetation in controlling water temperature is to block incoming solar radiation (direct and diffuse). Direct solar radiation on the water's surface is the dominant source of heat energy that may be absorbed by the water column and streambed. Absorption of solar energy is greatest when the solar angle is greater than 30° (i.e., 90 to 95 % of energy is absorbed as heat) and decreases as the solar angle declines due to the reflection of radiation off the water surface. 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, and buffer width (Beschta et al. 1987; Sridhar et al. 2004; DeWalle 2010). Light attenuation increases with increasing canopy height and increasing buffer density as a result of the increased solar path and extinction of energy, respectively. Buffer width has a variable influence on light attenuation depending on stream azimuth and width (e.g., effective shade cast from buffers for east-west streams may require narrower buffers than for N-S streams due to shifts in solar beam pathway from the sides to the tops of the buffers (DeWalle 2010). Riparian buffer width is important for a given stand type and age, but is not always a good predictor of stream shading among different stands because of differences in stand height and density. For example, Beschta et al. (1987) showed that shade levels similar to old-growth forests in western Oregon could be obtained within a distance of 20 to 30 m depending on stand composition. Similarly, Sridhar et al. (2004) using an energy balance model with empirical data, demonstrated that stream temperature is most sensitive to a stand's leaf area index (i.e., an indicator of light attenuation by canopy density) followed by average canopy height (an indicator of direct beam light attenuation), and lastly buffer width. They found the most effective shading for temperature control in eastern and western Washington Cascade conifer stands was predicted for mature (high leaf-area-index) canopies close to the stream (i.e., within 10 m of the stream bank) and overall buffers of about 30 m.

Shade from riparian vegetation is not the only factor influencing stream temperature. Research shows that temperature response from timber harvest of riparian vegetation is variable and can be highly dependent on the 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. For example, streams at lower elevations (i.e., warmer air temperature), or with no topographic shading, or 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 from shade loss than are streams with the following conditions: at higher elevations, or with topographic shading, or with deep-narrow channels, or with alluvial substrate.

Recent studies of buffer effectiveness in PNW streams indicates stream temperature response varied widely, and ranged from no-change to as much as 4° to 6° C within a few years after harvest (Table 4). In most cases, post-harvest temperature changes varied in relation to the level of tree retention and buffer width. However, variability in the degree of temperature response to shade loss was observed in a number of cases, particularly in headwater streams, where temperatures both decreased and increased after harvest. Such variability was attributed to post-harvest increases in stream discharge (i.e., cool groundwater input) and variable inputs of slash that provided shade (Kibler et al. 2013; Jackson et al. 2001). Also, one study found that buffer shade effectiveness was significantly reduced by post-harvest windthrow.

Studies of riparian buffer BMPs indicate that their effectiveness for maintaining shade and stream temperature are not only a function of the riparian stand characteristics (height, density, width) initially after harvest, but the temporal trend in stand conditions and prescriptive elements that address spatially variable site specific conditions. Based on this knowledge, we expect the effectiveness of the Western Washington Type F-stream riparian rules directed at providing shade will vary in relation to stand characteristics, location, and time after harvest. Further, rule effectiveness to maintain pre-harvest stream temperatures will likely vary in relation to other key physical characteristics (described above) that contribute to stream sensitivity to thermal loading.

Table 4. Research on stream temperature response to different riparian treatments on streams in the Pacific Northwest.

Reference	Location	Treatment	Response
Jackson et al 2001	Headwaters, WA coast	treatments: unharvested 2nd growth, 15-21 m wide buffers, and clearcut to bank	At the buffered streams, two became warmer (1.6 - 2.4 °C) and one cooler (-0.3° C).
Macdonald et al 2003a	Headwaters, Interior BC	tested three variable retention treatments in 20- to 30-m wide buffers	Five years post-harvest, temperatures remained 4° to 6° C warmer than in controls regardless of treatment. Initially, the high-retention treatment mitigated the effects of the harvesting, but 3 successive years of windthrow was antecedent to reduced canopy density and increased temperature impacts; delayed recovery
Fleuret 2006	Headwaters, OR coastal	clearcut and partial cut, buffers 6-60 m wide	Mean temperature gradient in treatment reaches was 0.4°C warmer than observed prior to harvesting.
Gomi et al 2006	Headwaters, BC coastal	experimental treatments: clearcut to edge, 10 m, and 30 m fixed buffers	Temperature response declined with increasing buffer width. At streams with 30 m buffer the maximum effects for maximum daily temperature was less than 2° C. Thermal recovery within two to four years depending on channel width.
Groom et al. 2011	Western OR	Private land RMAs are 15 to 21 m wide on small and med. fish-bearing, resp.. no harvest within 6 m. State RMAs are 52 m wide; no harvest within 8 m.	No change in max, temperatures for state forest streams while private sites increased pre-harvest to post-harvest on average by 0.7° C with an observed range of response from 0.9 to 2.5° C.
Janisch et al. 2012	Western WA	continuous buffer and a patch buffer 10- to 15-m	First year after logging, daily max. temperatures increased in clearcut catchments by an average of 1.5° C (range 0.2 to 3.6° C), in patch-buffered catchments by 0.6° C (range 0.1 to 1.2° C), and in continuously buffered catchments by 1.1° C (range 0.0 to 2.8° C).
Kibler et al. 2013	Western OR	Headwater basins with no buffer per OR rules	Mean maximum daily stream temperatures ranged from 1.5° C cooler to 1.0° C warmer relative to pre-harvest years
Rex et al. 2012	BC central interior	variable retention riparian treatment (min. retention of 10 stems per 100 m of channel length)	Mean weekly average and maximum stream temperatures at treatment sites increased by as much as 5° C and 6° C , respectively.
Cole & Newton 2013	Western OR	Buffers included (i) no tree, (ii) predominantly sun-sided 12 m wide partial, and (iii) two-sided BMP15–30 m wide buffers	Trends for daily maximum and mean stream temperature sig. increased after harvest in no tree buffer units. Partial buffers led to slight (<2 °C) or no increased warming. BMP units led to sig. increased warming, slight, or no increased warming.

Wood recruitment

There are three dominant processes of wood recruitment to streams in forested landscapes: undercutting of streamside trees due to bank erosion, tree fall from adjacent riparian stands, and delivery of trees from mass wasting (Martin and Benda 2001; Benda and Sias 2003). The relative importance of these processes varies depending on factors such as channel size and morphology, stand condition, and valley/hillslope stability (May and Gresswell 2003; Reeves et al. 2003). The condition of riparian stands (e.g. stand density, tree size and species composition) is an important factor controlling the availability of trees for recruitment from all three processes, although mass wasting delivers wood from both riparian and upslope stands (Van Sickle and Gregory 1990).

Timber harvest practices can affect both the magnitude and timing of wood recruitment. Table 5 summarizes research on the effect of riparian harvest on wood recruitment in the PNW. The greatest effects have occurred when riparian stands are completely harvested. In this case there is immediate input of logging slash to the channel, followed by a period of low recruitment until the riparian stand re-grows (Jackson et al. 2001; Schuett-Hames et al. 2012). Riparian buffers reduce the effects of timber harvest by leaving standing trees for future wood recruitment. The wood recruitment potential from riparian buffers depends on factors such as the initial stand conditions, the number and location of leave trees, and the site conditions (Beechie et al. 2000). Denser stands with taller, larger trees have greater recruitment potential than stands consisting of shorter, smaller trees. Differences in riparian management prescriptions, e.g. buffer width and intensity of thinning within the buffers, affect the amount of wood potentially available for recruitment.

The timing and magnitude of tree mortality processes affect wood recruitment rates. There is natural variability in mortality rates among riparian stands (Acker et al. 2003). Mortality and associated wood recruitment rates may be elevated due to competition mortality in stands in the stem exclusion stage of development, or due to episodic disturbances due to disease, insect damage, wind, flooding or mass wasting (Liquori 2000). Harvest of adjacent timber exposes the outer edges of the buffer to wind, which can increase mortality and tree fall due to wind damage. Wind mortality typically is greatest during the first few years following harvest and the greatest damage often occurs on the outer edge of the buffers on the windward side, although it can extend throughout the entire buffer (Grizzel et al. 2000; Liquori 2006). There is extensive variability in windthrow mortality among sites due to differences in site conditions and exposure (Mitchell 2012) as well as regional and local differences in the frequency, wind direction and intensity and timing of windstorms soil saturation and flooding (Ruel et al. 2001; Acker 2003). Severe post-harvest windthrow typically is limited to a sub-set of sites where topography and site conditions are conducive to wind damage. High intensity storms may significantly affect both managed and unmanaged stands in sensitive topographic locations (Ruel et al. 2001).

The effectiveness of large wood (LW) recruitment to form fish habitat is not only a function of the amount and size of wood inputs, but also of reach-scale physical characteristics (channel morphology) and stream size. For example, research shows that large wood has a stronger influence on the formation of pools in moderate gradient, unconfined channels (e.g., plan bed, pool riffle, alluvial fan) compared to either steeper gradient, confined channels or low-gradient channels (Montgomery et al. 1995; Beechie and Sibley 1997; Martin 2001). The cobble-boulder-bedrock substrate in steeper high-energy channels control bedform (e.g., step pool, cascade) and pool formation is not dependent on LW; although LW may function to trap sediment in step-pool channels (Montgomery and Buffington 1997). In low gradient meandering channels (e.g., dune ripple) the dependency on LW is limited as free-formed pools are common (Beechie and Sibley 1997). The relationship between LW and pool density is also dependent on channel width. As channel width increases, pool density is more strongly influenced by changes in LW abundance (Montgomery et al. 1995; Martin 2001).

Based on the forgoing discussion, we anticipate variation in wood recruitment rates among sites due to differences in:

- riparian stands (density, species composition, size and height, successional stage)
- dominant wood recruitment processes
- disturbance event type, frequency and magnitude (e.g. wind, fire, flood, disease, insects)
- riparian management prescription (buffer width and thinning regime)
- wind exposure and vulnerability to wind damage.

Also, we anticipate the channel and habitat response to wood loading will vary depending on:

- channel gradient and confinement (channel morphology),
- substrate composition, and
- stream size.

Table 5. Research on tree mortality/wood recruitment response to different riparian treatments on streams in the Pacific Northwest.

Reference	Location	Treatment	Response
Bahuguna et al. 2010	Western British Columbia	10m and 30m wide riparian buffers	Seven years after harvest, windthrow was higher in the 10 m buffer treatment, while competition-related standing tree mortality was higher in the controls. The major windthrow events had occurred in the first and second years after logging.
Grizzel and Wolff 1998	Northwest Washington	Headwater stream buffers-width varied	Windthrow affected 33 percent of buffer trees and ranged-from 2 to 92%. Sixty-seven percent of wind thrown trees fell to the north, northeast, or northwest. Pre-harvest large wood was significantly larger than wood recruited from buffer windthrow.
Grizzel et al. 2000	Northwest Washington	Watershed analysis buffers on fish-bearing streams, width varied	A substantial portion of debris is recruited from the outer margins of the wider buffers. Narrower buffers limit recruitment. Trees in buffers oriented perpendicular to the direction of damaging winds had a higher likelihood of being recruited relative to buffers oriented parallel. Post-harvest mortality ranged from 2.9 to 56.8% of basal area and 4.8 to 60.5% of density. Continued wind damage is likely to reduce the capacity to recruit an adequate supply of debris in the future. The quantity and quality of debris recruited will be a function of windthrow magnitude, buffer orientation, and stand characteristics.
Jackson et al. 2007	Western Washington	Forest practice HCP prescriptions on non-fish-bearing streams	Blowdown in buffers ranged from 33% to 64% of buffer trees with attendant effects on canopy cover. After blowdown, the newly fallen trees either spanned the channels or lay beside the channels, so blown down trees were not adding woody debris to the channels or altering channel structure at this time.
Liquori 2006	South-central Washington	Forest practice HCP buffers of varying widths on fish-bearing streams	Wind-related post-harvest tree fall rates in buffers up to 3 years post-harvest were 26 times greater than competition-induced mortality rate estimates. Tree fall rates were strongly tied to tree species and relatively unaffected by stream direction. Observed tree fall direction is strongly biased toward the channel, suggesting that models that utilize a random fall assumption significantly under-predict recruitment. Post-harvest wind effects may reduce the stand density enough to reduce or eliminate competition mortality, resulting in different wood recruitment dynamics in buffers as compared to unmanaged forests.
Martin and Grotefendt 2007	Southeast Alaska	20m wide buffers on fish-bearing streams	Cumulative stand mortality (CSM) was greater in buffers compared to reference units. Mortality varied with distance from the stream. In the inner zone (0–10 m from stream), the difference between buffer and reference units was relatively small (22% of unlogged CSM), but CSM in the outer zone (10–20 m from stream) was more than double (120%) the CSM of reference units. There was a significant increase in mortality by windthrow at a small proportion (11%) of the logged units. Logging caused an increase in the proportion of tree recruitment from the outer zone of buffers and changed the shape of the LWD source distance recruitment curve reducing the future potential supply of LWD by 10% compared with an unlogged reference stand.
Reid and Hilton 1998	Northern California	30 to 60 m wide buffers	The probability of failure for buffer trees increased by an order of magnitude during the first 6 years after logging, and a more modest increase in fall rate persists beyond 6 years. Woody debris was recruited from as far as 70 m from the channel in the buffers and 40 m in un-reentered forests. About 90 percent of the instances of debris input occurred within 35 m of the channel in un-reentered forests and within 50 m of the channel in buffers. The pattern for un-reentered forests approximately follows the distributions for mature and old-growth forests, however these distributions under-represent the importance of trees falling from greater distances in the buffers.
Schuett-Hames et al. 2012	Western Washington	Forest practice HCP buffers on non-fish-bearing streams	During the first three years, mortality was 3.5 times higher in the 50-ft buffers than in the references, a statistically significant difference. Wind was the dominant mortality agent in the 50-ft buffers, while suppression mortality exceeded wind mortality in the reference reaches. The cumulative percent mortality over the entire five year post-harvest period was 27.3% in the buffers compared to 13.6% in the references, but the difference was not statistically significant. Live tree density decreased in both 50-ft buffers and reference stands during the first 5 years after harvest. The pattern of response to the treatments for large woody debris (LWD) recruitment was similar to tree mortality.

Sediment

Sediment input to streams is an important management issue in the Pacific Northwest due to potential effects on water quality, fish and other aquatic life. Sediment input to streams in forested watersheds in the Pacific Northwest occurs from a suite of processes including soil creep, tree throw, landslides, surface erosion, and stream bank erosion (Roberts and Church 1986). The rates and processes of sediment production in forested watersheds varies greatly due to differences in tectonic history, geology, soils, and climate (Swanson et al. 1987). Mass wasting and surface erosion associated with forest roads and timber harvest practices can increase sediment input (Reid and Dunne 1984). Disturbance associated with timber harvest in or adjacent to riparian management zones can affect sediment supply due to increases in tree throw and root-pit formation, exposure of soils due to harvest or yarding activities, and bank erosion or mass wasting due to loss of root strength after timber harvest (Swanson et al. 1987). Table 6 summarizes research on the effects of riparian management practices on sediment delivery in the Pacific Northwest.

The most likely source of increased sediment delivery associated with the westside Type F riparian prescriptions appears to be the potential for increased tree throw due to wind exposure in buffers after harvest of adjacent timber (Grizzel et al. 2000; Liquori 2006). Yarding corridors, narrow swathes cut through the buffer in order to transport logs suspended by cables to the other side of the stream, are another possible source of sediment delivery. However, since riparian vegetation and woody debris on the forest floor are effective in limiting the movement of soils exposed by windthrow, only root-pits in close proximity to the stream are likely to deliver sediment, and the research suggests that sediment input from tree throw is limited (Grizzel and Wolff 1998; Schuett-Hames et al. 2012). An increase in sediment delivery due to soil disturbance or mass wasting associated with timber harvest and yarding activities within the RMZ seems unlikely due to the width of the no harvest zone (50ft). Additionally, the efficiency of the vegetation and wood on the forest floor helps limit the movement and delivery of sediment (Rashin et al. 2006; Lakel et al. 2010). The wide no-harvest zone also makes it unlikely that riparian management practices themselves would result in an increase in bank erosion due to loss of root strength, however bank erosion rates could increase due to changes in stream flow or mass wasting events from upstream areas.

Table 6. Research on sediment response to riparian harvest treatments in the Pacific Northwest.

Reference	Location	Treatment	Response
Grizzel and Wolff 1998	Northwest Washington	Headwater stream buffers-width varied	Seventeen percent of uprooted trees delivered sediment to stream channels. The average volume input was 0.16 cubic meters per uprooted tree and 0.48 cubic meters per 100 meters of stream channel at 39 sites where rnass wasting did not occur. At most sites the volume of sediment input to the stream was small relative to the amount stored behind obstructions.
Jackson et al. 2007	Western Washington	Forest practice HCP prescriptions on non-fish-bearing streams	Because trees were felled downslope and branches and tops were left where they fell, the dominant effect of clearcutting to the banks of headwater streams was the addition of large amounts of organic debris to the channels. This debris impeded flow, preventing the flushing of fine sediments, and thus particle size distributions became much finer. This effect was still pronounced 2 years after timber harvest.
MacDonald et al. 2003b	Central British Columbia	20 m buffer strips with variable thinning	Other significant point sources of sediment were not found along the entire channel of either stream, despite substantial riparian windthrow following harvesting, particularly in B3, nor was there any obvious evidence of channel instability (e.g., channel and (or) bank erosion or woody debris redistribution).
Rashin et al. 2006	Washington	Variable width (pre 2000) buffers	Stream buffers were effective at preventing chronic sediment delivery to streams and physical disturbance of stream channels.
Reid and Hilton 1998	Northern California	30 to 60 m wide buffers	Sediment input from root-throw depends strongly on the proximity of the tree throw mound to the channel. In general, only those uprooted trees originally located within a few meters of the channel contributed sediment from root wads. Observations after the 1995 storm suggest that 90 percent of the sediment introduced directly by tree fall in the un-reentered forested reaches originated from within 15 m of the channel, while in buffer strips, sediment was introduced by trees falling from considerably farther away (fig. 5). Rates of direct sediment input by tree fall during the storm were on the order of 0.1 to 1 m3 of sediment per kilometer of main-stem channel bank.
Schuett-Hames et al. 2012	Western Washington	Forest practice HCP buffers on non-fish-bearing streams	Soil disturbance from timber harvest within the 30 ft wide equipment limitation zone (ELZ) was minimal in the 50-ft because few harvested trees fell into the buffers. On average, soil disturbances occupied 0.29% of the ELZ area in the 50-ft buffers compared with 6.2% for the clear-cut patches. The rate of soil disturbance from uprooted trees during the first five years after harvest was about twice the reference rate in the 50-ft buffers. The percentage of root-pits with evidence of sediment delivery was greater in the reference patches (26%) than the 50-ft buffers (19.8%). Mean horizontal distance to the stream for root-pits that delivered sediment was 8.2 ft compared to 28.0 ft for those that did not deliver.

Litter fall, organic matter, food chain, biotic response

Mechanistic studies of riparian zones have identified specific ways that these areas create and maintain habitat. Trees and understory plants provide habitat complexity to terrestrial species. Plants stabilize stream banks, reduce erosion, and their leaves contribute to the development of rich soils for subterranean species. The leaves themselves are a critical food source for terrestrial and aquatic invertebrates (Richardson 2001). Shade provides cover keeping stream reaches cool. Light that reaches the stream through openings in the canopy serves to enhances primary productivity (Stovall et al. 2009; Kiffney et al. 2004).

Research that explores the effect of timber harvest on riparian ecosystem processes has centered on the quantification of organic matter availability – including litter fall, species inventories including food chain responses such as the composition of functional feeding groups, stream temperature and sediment. There is a paucity of literature that explores riparian ecosystem responses to forestry buffers beyond headwater areas. Research of headwater streams indicate that buffers are important for maintaining riparian function including low stream temperatures, availability of organic matter, and trophic guild diversity and abundance (Bisson et al. 2013). DeGroot et al. (2007) found that careful logging in headwater streams that maintained intact buffer zones did not detrimentally effect growth or abundance of coastal cutthroat trout. Additionally, riparian buffers of headwater streams in Western Oregon have been shown to preserve macroinvertebrate diversity, amphibian diversity, and microhabitat conditions (in order: Carlson et al. 1990; Olson and Rugger 2007; Anderson and Poage 2014). However, work in headwater streams in SW British Columbia by Kiffney and Richardson (2010) found a long-term reduction of organic matter in streams with different riparian buffer widths.

Due to the difficulty in controlling for multiple factors that influence the distribution, composition and abundance of biota in fish-bearing streams (at both the reach and watershed scale), few studies have attempted measuring the effects of contemporary timber harvest on fish (Wilzbach et al. 2005). Given the difficulty in dealing with confounding factors associated with experimental studies of biota in fish streams, other studies have used meta-analyses to create habitat models to apply to highly variable landscapes (Andrew and Wulder 2011; Jones et al. 2006; Ode et al. 2005; Rehn et al. 2007). Acknowledging such limitations, the Washington FP-HCP uses in-channel and riparian conditions contributing to habitat-forming processes as surrogates for fish recovery and long-term viability by maintaining resource objectives and performance targets (FP-HCP, Appendix N 2005). Table 7 summarizes some of the recent literature.

Table 7. Research on biotic response and modeling techniques of riparian condition / treatments.

Reference	Location	Case Study / Treatment	Response
Andrew and Wulder 2011	Vancouver Island, British Columbia Canada	analyzed the relationships between the population trends of Pacific salmon (1953–2006) and land cover, fragmentation, and forest age derived from remotely-sensed, landscape level datasets	The spatial variation in these population trends was related to landscape variables at watershed and riparian scales with regression trees. Results were found to be species specific, but characteristics indicating a legacy of historic and current forest management (such as fragmented forests and non-forested or early-successional forest cover) generally had negative effects, driven by a small subset of highly fragmented watersheds. Chum and coho had strong negative relationships with fragmentation, pink had a strong positive relationship with wetland abundance, and Chinook and sockeye were most closely related to geomorphology. There was no 'single best' scale of analysis. Salmon trends were generally more closely related to variables estimated over the entire watershed, however, the relative importance of watershed and riparian level predictors varied by both variable and species.
Richardson et al. 2004	Vancouver, British Columbia Canada	Treatment included 5 experimental stream reaches. Three species of leaf litter monitored for decomposition rates and macroinvertebrate colonization during summer and fall.	Leaf litter: Alder lost mass 40–100% more quickly than the two conifer species. During summer, hemlock lost mass significantly more quickly than cedar, but this trend was reversed in autumn. Measures of relative lignin concentration and carbon content did not differ significantly between litter species. Nitrogen content was nearly twice as high in alder as the two coniferous species. Decomposition rates were positively related to initial nitrogen content of the litter and negatively related to C : N ratio. Invertebrate species associated with particular types of leaf litter were clearly distinct during the autumn, but less so during summer. In the autumn, invertebrate assemblages on alder and cedar were distinguished from those on hemlock by the high numbers of detritivores on the former litter types. Cedar had more mayflies and fewer orthoclad midges than alder. There were no significant differences between litter types in densities of any invertebrate taxon per gram of leaf tissue, although alder always had higher numbers.
Wilzbach et al. 2005	Northern California	Supplemented 3 out of 6 streams with salmon carcasses January 2002, 2003.	Differences in total density and biomass of cutthroat trout (Oncorhynchus clarki) and rainbow trout (Oncorhynchus mykiss) from pretreatment levels responded positively to canopy removal but were not detectably affected by carcass addition. Differences in specific growth rates of the fish between open and closed canopy reaches were greater in sites without carcasses than in sites with carcasses. In addressing the study limitations the authors state: "Our future project plans include an amended design in which carcasses will be added to the lower ends of all six streams to further resolve the extent of any carcass effect." And that "Another potential limitation of this study concerns the spatial scale of investigation. The low overwinter retention of tagged fish within reach boundaries raises the possibility that extensive seasonal movement may have affected the results. This raises questions about the appropriate scale for addressing questions about the effects of carcass and riparian manipulations."
Wipfli and Gregovich. 2002	Southeast Alaska	Quantified the export of aquatic and terrestrial invertebrates and detritus to fish-bearing streams.	Invertebrates and detritus were exported from headwaters throughout the year, averaging 163 mg invertebrate dry mass stream/1 day and 10.4 g detritus stream/1 day, respectively. The amount of export was highly variable among streams and seasons (5–6000 individuals stream/1 day and <1–22 individuals m3 water; <1–286 g detritus stream/ day and <0.1–1.7 g detritus m3 water. Delivery of invertebrates from headwaters to habitats with fish was estimated at 0.44 g dry mass m2/ year. Based on such export levels, the study estimated that every kilometer of salmonid-bearing stream could receive enough energy (prey and detritus) from fishless headwaters to support 100–2000 young-of-the-year (YOY) salmonids. These results illustrate that headwaters are source areas of aquatic and terrestrial invertebrates and detritus, linking upland ecosystems with habitats lower in the catchment.
Jones et al. 2006	Georgia, USA	Compare and contrasted riparian buffer widths to predict the likelihood of meeting water quality standards and fish abundance	Compared with streams with 30-m wide buffers, streams with 15-m wide buffers have: 1) higher peak temperatures (average increase during the warmest week of the year ~2.0 ± 0.3°C); and 2) more fine sediments in riffle habitats (approximately 25% increase). Models predicted an 87% reduction in young trout biomass. 63% of Georgia's 2nd- to 5th-order trout stream segments could maintain stream temperatures likely (>50% probability) to support young trout in streams bordered by 30-m wide forested riparian buffers. Less than 9% of those streams (only those at the highest elevations) would maintain such temperatures with 15-m wide riparian buffers. The results portend substantial reductions or elimination of trout populations in northern Georgia streams where vegetated riparian buffer widths are reduced to 15 m.

Nakano and Murakami 2001	Japan	Sampled one fish stream and adjacent riparian / upland forest documenting interactions between consumers (birds and fish) and prey.	Mutual trophic interactions between contiguous habitats were measured for 12 consecutive months of a small fish-bearing stream and an adjacent forest upland. In a deciduous forest and stream ecotone, aquatic insect emergence peaked around spring, when terrestrial invertebrate biomass was low. In contrast, terrestrial invertebrate input to the stream occurred primarily during summer, when aquatic invertebrate biomass was nearly at its lowest. Such reciprocal, across-habitat prey flux alternately subsidized both forest birds and stream fishes, accounting for 25.6% and 44.0% of the annual total energy budget of the bird and fish assemblages, respectively. Seasonal contrasts between allochthonous prey supply and *in situ* prey biomass determined the importance of reciprocal subsidies.
Ode et al. 2005	Southern California	Developed a benthic macroinvertebrate index of biological integrity for the semiarid southern California coastal region	This study screened 61 candidate metrics for inclusion in the B-IBI based on three criteria: sufficient range for scoring, responsiveness to watershed and reach-scale disturbance gradients, and minimal correlation with other responsive metrics. Final metrics included: percent collector-gatherer + collector- filterer individuals, percent non-insect taxa, percent tolerant taxa, Coleoptera richness, predator richness, percent intolerant individuals, and EPT richness .B-IBI scores were not correlated with elevation, season, or watershed area. Application of the B-IBI to an independent validation dataset (69 sites) produced results congruent with the development dataset and a separate repeatability study at four sites in the region confirmed that the B-IBI scoring is precise. The SoCal B-IBI is an effective tool with strong performance characteristics and provides a practical means of evaluating biotic condition of streams in southern coastal California.
Rehn et al. 2007	California	This study used data from 193 sites in California for the Environmental Monitoring and Assessment Program (EMAP)	This was a "follow-up" study from the above (Ode et al. 2005) that builds on the southern California data. This study more specifically compared Targeted-riffle (TR) and reach-wide (RW) benthic samples collected across the entire state of CA. Metrics calculated from TR and RW samples showed similar dose–response relationships to stressor gradients and similar raw scoring ranges. Biological indices (B-IBI, O/E0, and O/E50) derived from RW samples were more precise than those derived from TR samples, but precision differences were not substantial. This analyses indicated that raw data sets and biological indicators derived from TR and RW samples may be generally interchangeable when used in ambient biomonitoring programs.
Richardson 2001	Vancouver British Columbia Canada	Documented seasonal differences in life cycle, emergence and growth patterns of detritivors	The timing of life cycles, including growth rates, was determined for eight common species of detritivorous insects in a second-order stream in southwestern British Columbia, Canada. Six of the species (Zapada cinctipes, Z. haysi, Malenka californica, M. cornuta, Capnia sp., and Lepidostoma roafi) had simple, univoltine life cycles. The leuctrid stonefly Despaxia augusta has a 2-year life cycle, with an apparent egg diapause of about 6 months. The chironomid Brillia retifinis produced at least three generations per year. Adults of several species exhibited seasonal declines in size at emergence, but one species had larger adults as the emergence period proceeded. Closely related taxa had more similar life cycle timing than more distantly related species suggesting a degree of phylogenetic constraint in phenology of their life cycles. The influence of the timing of leaf drop on timing of life cycles for these animals does not fit with proposed scenarios based on fast and slow leaf processing.
Wipfli and Musslewhite 2004	Southeast Alaska	Compared fluvial exports of invertebrates and detritus from fishless streams feeding fish-bearing streams	Sites with more riparian red alder exported significantly more invertebrates than did sites with little alder (mean range across 1–82% alder gradient was about 1–4 invertebrates m^{-3} water, and 0.1–1 mg invertebrates m^{-3} water, respectively). Three-quarters of the invertebrates were of aquatic origin; the remainder was of terrestrial origin. Aquatic taxa were positively related to the alder density gradient, while terrestrially-derived taxa were not. Streams with more riparian alder also exported significantly more detritus than streams with less alder (mean range across 1–82% alder gradient was 0.01–0.06 g detritus m^{-3} water).

Study Design Alternatives

Our review of the literature indicates that the after/control-impact (ACI) approach and the before-after/control-impact (BACI) approach are the study designs implemented most often and have been successfully used to evaluate the effects of forest practices on riparian and aquatic resources similar to those described in the FP-HCP. An after/impact (AI) approach involving post-harvest sampling of treatment sites may also have limited applicability to our critical questions. A before-after/impact (BAI) sampling approach may also provide flexibility in answering select critical questions. We also considered a meta-analysis approach, but did not pursue that option since we could not identify adequate research on similar prescriptions in similar environmental settings to conduct a robust meta-analysis.

The following section introduces the ACI, AI, BACI, and BAI approaches. The next section goes through each of the critical questions and discusses the advantages and limitations of study design alternatives in terms of their ability to answer the critical question and handle design issues particular to the western Washington and the westside Type F prescriptions. Examples of issues specific to this project that are considered in this evaluation include:

1) a complex prescription package (10+ prescription options which are derived from different combinations of site class, stream width and inner zone harvest potential and option),
2) variability in stream, site, riparian stand and climatic conditions,
3) vulnerability to stochastic disturbance processes (e.g. wind, flooding and fire),
4) lengthy time frames over which riparian stands and processes respond to management,
5) interaction of physical and biological factors affecting channel habitat and aquatic biota, and the multiple scales across which the response can occur.

The unit of analysis for all study design alternatives is the stream reach (a length of Type F stream where the treatment is applied). We considered a watershed-scale approach, and believe it is well-suited to answering questions concerning the cumulative effects of forest practices. A watershed-scale study provides the opportunity to evaluate the response of aquatic resources to a suite of forest practices including both Type F and Type N riparian prescriptions, upland timber harvest, and forest roads. However these are not the critical questions we were directed to address in this study.

Introduction to the ACI, AI, BACI, and BAI Study Designs

ACI (After/Control-Impact) Approach

The ACI approach is a time-tested study design that has been commonly used to evaluate riparian management practice effectiveness. The basic design for ACI is the comparison of post-harvest conditions to infer if differences exist between the treatment and reference populations (Table 8). The underlying assumption for this approach is that the variables examined at treatment and reference sites were, on average, identical prior to treatment. Either a paired-sample or two-sample statistical approach can be used to test for differences depending on similarities between the sampled populations. If the environmental factors controlling the response variables can be matched between paired treatment and reference sites, the paired-sample test is preferred because of the improved sensitivity for detecting treatment effects. If pairing is not possible (i.e., two samples are independent), we could test for population differences using the two-sample approach as was successfully done by Schuett-Hames et al. (2012) for the BCIF study. Examples of BMP effectiveness studies that used the ACI or AI approach are summarized in Appendix C and information on how the ACI approach would be applied is located in Appendix D.

BACI (Before-After/Control-Impact) Approach

A BACI (Before-After/Control-Impact) study design offers a controlled and experimental setting in which to test specific research questions. In a BACI study, a comparison is made between sites that experience a treatment, and control sites that do not. Pre-treatment monitoring of site conditions for at least a year is also characteristic of the BACI study design. In the field of forestry, BACI designs have been effectively implemented to answer ecological or management (e.g., prescription effectiveness) questions outside a laboratory setting. In forestry or landscape-scale studies, they often include a paired (reference and treatment) watershed design that is intended to control for a broad suite of environmental and geophysical conditions that may confound the detection of treatment effects (e.g. Alsea watershed study - http://www.ncasi.org/Programs/Forestry/Forest-Watersheds/Alsea-Watershed-Study/Index.aspx ; CMER "Hardrock Study"). Also, the BACI approach is well suited for reach-scale examinations of BMP effectiveness (e.g., Eastside temperature-shade study, Cupp and Lofgren 2014; Oregon RipStream Temperature Study, Groom et al. 2011).

BACI studies require pre- and post-treatment data to evaluate the effects of a treatment action. Initial post treatment data collection typically includes a minimum of two years, and more time may be needed to measure long-term effects. BACI studies tend to be intensive and focused on specific research questions. Depending on the sample design, the BACI approach may offer the most definitive answers to specific research questions and allow for the exploration of multiple hypotheses at once (e.g., testing how certain physical settings influence treatment effects). Statistically, the power of a BACI design rests on the control of variability between control and treatment sites, and the inclusion of pre-treatment data collection (i.e., detection of treatment effects is statistically robust) .

In practice, BACI studies associated with long-term experimental forests or paired watersheds provide the backbone of ecological knowledge regarding the results of forest practices and treatments. They have been instrumental in the development of ideas spanning the range of ecological (Haggerty et al. 2004; DeGroot et al. 2007; Kreutzweiser et al. 2010; Bisson et al. 2013) and geophysical results of timber harvest (Brosofske et al 1977; Surfleet and Skaugset 2013; Cupp and Lofgren 2014). They provide to managers some of the most substantive and reliable results of the effects of forest practices. More detailed information on how the BACI approach would be applied in the context of Westside Type F Prescription Monitoring is located in Appendix D.

AI (After-Impact) Approach

The AI approach involves post-harvest sampling at treatment sites without reference sites for comparison. This approach can be used to characterize the distribution of post-harvest conditions. Data can be compared with pre-existing performance standards or targets to determine the proportion of treated sites meeting or exceeding these targets. However, it is not possible to determine the extent to which the post-harvest conditions are due to the treatments, result from differences in conditions prior to harvest, or are influenced by climatic or other factors during the post-harvest period.

BAI (Before-After-Impact) Approach

The BAI approach involves pre- and post-harvest sampling at treatment sites without reference sites for comparison. The treatment effect can be estimated by comparing pre- and post-harvest values for response variables to estimate the direction and magnitude of change. Lack of reference data limits the ability to distinguish change associated with treatments from inter-annual variability or natural disturbance events. The need for pre-harvest data extends the timeframe and increases the cost of a BAI study. Since reference sites are not needed, a larger sample of treatment sites can be sampled.

Table 8. Characteristics of study design approaches for selected topics.

Topic	**ACI**	**BACI**	**AI**	**BAI**
Range of Treatments	Large sample size allows inclusion of a broad range of treatments.	Small sample size requires decision on select range of treatments.	Large sample size allows inclusion of a broad range of treatments.	Large sample size allows inclusion of a broad range of treatments.
Geographic Extent/	Large sample size allows broad geographic coverage, providing context for evaluating treatment applications.	Small sample size limits geographic coverage, reducing the spatial context for evaluating treatment response.	Large sample size allows broad geographic coverage, providing context for evaluating treatment applications.	Large sample size allows broad geographic coverage, providing context for evaluating treatment applications.
Variability	Does not assess inter-annual variability. May quantify variability among site conditions.	BACI design controls for inter-annual variability and variability among selected site characteristics.	Does not assess inter-annual variability. May quantify variability among site conditions.	Does not assess inter-annual variability. May quantify variability among site conditions.
Inference	Inference to a broader population of sites may be possible if the sampling design is based on randomization.	BACI designs at a reach-scale, if sites are selected randomly, may have direct inference to a broader population of sites.	Inference to a broader population of sites may be possible if the sampling design is based on randomization.	Inference to a broader population of sites may be possible if the sampling design is based on randomization.
Detection of Treatment Effect	Treatment effects are based on a weight-of-evidence assessment that benefits from a large sample size. Absence of pre-treatment data requires the assumption that control and reference conditions were, on average, identical prior to treatment. Use of paired-sample design would improve sensitivity.	Treatment effects are quantified directly with a small sample size that captures inter-annual variability. More intentional control of between-site environmental variability reduces noise in the data, allowing for statistically robust detection of treatment effects.	Does not detect a treatment effect. Can only be used to compare post-harvest conditions with a pre-existing performance target.	Treatment effects are quantified directly with pre- and post harvest data at treatment sites, however lack of reference sites reduces ability to distinguish treatment effect from inter-annual variability in environmental conditions.
Explanation of Treatment Effect	Detecting a treatment effect may be confounded by natural variability, especially where effects are small. Provides ability to assess interaction of physical setting and treatment effect by stratification of large sample.	Strong ability to detect changes caused by treatment because of ability to assess relative strength of treatment and non-treatment effects. Ability to assess interaction of physical setting and treatment depends on strata included in sample.	Potential ability to correlate success or failure in meeting a performance target with site conditions or prescription variant.	Moderate ability to detect changes caused by treatment using pre and post-harvest data, but lacks reference sites. Ability to assess interaction of physical setting and treatment depends on strata included in sample.
Temporal perspective	Long temporal perspective is possible. Can assess short- and long-term response/recovery depending on site selection.	Short temporal perspective. Typically assesses initial response (2 years post-harvest), but could track longer-term recovery depending on duration of study.	Long temporal perspective is possible from single sample event (space for time substitution). Can assess short- and long-term response/recovery depending on site selection.	Short temporal perspective. Typically assesses initial response (2 years post-harvest), but could track longer-term recovery depending on duration of study.
Time-frame for Study	Can be accomplished within 3-4 years.	Can be accomplished within 7-8 years to investigate initial post-harvest response.	Can be accomplished within 2-3 years.	Can be accomplished within 7-8 years to investigate initial post-harvest response.

Study Design Alternatives by Critical Question

This study has a large suite of critical questions. There are important differences in the ability of the different approaches to answer these questions. In the following section, we review each critical question and discuss the advantages and disadvantages of different approaches.

Critical Question 1a

Critical question 1a: **How do the RMZ and no-RMZ harvest prescriptions affect riparian stand characteristics and riparian functions?**

The wording of this question indicates that we intend to detect potential changes in riparian stand conditions and riparian functions such as shade, wood recruitment, litter fall, streambank integrity (bank erosion) and sediment filtration in response to harvest prescriptions relative to unharvested reference sites. The BACI is the best approach, since the pre-post design allows us to determine the magnitude of change in response to harvest, and the control-impact design distinguishes the treatment effect from change due to other factors (e.g. climatic variability). However, the intensive before and after sampling regime required by the BACI approach would reduce the total number of sites that could be sampled (Table 9). Consequently, it would not be feasible to include all ten prescription variants under the present budget. The ACI approach is a potentially a less costly alternative to the BACI that would allow a larger sample size, increasing the number of prescription variants that could be examined.

However, there is less certainty interpreting the results of an ACI study. Because the ACI approach compares post-harvest conditions between reference and treatment sites, the lack of pre-harvest data in the ACI requires the assumption that differences between the treatments and control populations are due to changes that occurred following treatment rather than pre-existing differences, or due to other factors during the post-harvest period (e.g. climatic variability). The BAI or AI approaches are not suitable to answer this question because the lack of untreated reference sites makes it problematic to distinguish the treatment effect from other sources of variability.

Table 9. Advantages and limitations of potential study designs in answering critical question 1a.

ACI Study	BACI Study
Advantages: • Because there is only one sample event per site, more sites can be sampled for a given budget compared to approaches that require pre-harvest sampling • Lower cost per site may allow for sampling more prescription variants and/or site conditions, providing context for assessing relative risk (high, low) of different prescriptions and site conditions on riparian functions and performance targets • Short turn-around time for results (<4 yrs) Limitations: • Lack of pre-harvest or reference data reduces ability to isolate treatment effect from confounding factors such as differences in initial stand conditions and interannual variability. • Requires permission from many landowners. Lack of cooperation could complicate random sampling.	Advantages: • High level of certainty in distinguishing the treatment effect (magnitude and direction of change) • Ability to detect differences between inner and non-inner zone harvest. • Controls allow the magnitude and direction of change in stand conditions to be assessed and attributed to forest practices vs. environmental factors. • Greater certainty for estimates of mortality and wood recruitment. Limitations: • Multiple sample events increase cost per site, so fewer sites can be sampled for a given budget compared to approaches with a single post-harvest sample. • Higher cost per site may reduce the number of sites that can be sampled, limiting the number of prescription variants or range of site conditions sampled and the ability to extrapolate results. • Requires considerable cooperation and coordination with landowners, especially for reference sites. • Longer time frame for results (6-7 yrs minimum).

Critical Question 1b

Critical Question 1b: How do the characteristics of riparian forest stands and associated riparian functions change over time in areas with and without RMZ harvest?

The wording "change over time" indicates we intend to determine the magnitude and direction of change that occurs from the pre-harvest condition. Answering this question requires pre- and post-harvest data, but does not necessarily require control data (although control data would improve the ability to interpret results). Sampling could be done at just one post-harvest interval, but a more thorough answer would be supplied by looking at changes over a range of time following harvest. Pre- and post-harvest data are necessary to document the magnitude of change over time associated with the treatment, so this question can be answered with certainty by either a before-after impact (BAI) study or a BACI study. The BAI study would only answer this specific question, while the BACI could answer both 1a and 1b and include control data to improve interpretation of results. Both approaches would begin sampling prior to harvest, so a long timeframe would be necessary to track changes over an extended period following harvest. The ACI approach could provide a less certain answer to this question by comparing post-harvest conditions at the control and treatment sites, however the lack of pre-harvest data requires the assumption that differences between the treatment and control populations are due to, and represent, changes that occurred following treatment rather than pre-existing differences or change over time due to other factors. However, the ACI approach would provide an answer much more quickly than either a BACI or BAI approach (Table 10).

Table 10. Advantages and limitations of potential study designs in answering critical question 1b.

ACI Study	BACI Study	BAI Study
Advantages: • Can either examine multiple post-harvest ages up to 10 yrs post-harvest in a single sample event. • 1 sample event per site, so more sites can be sampled for a given budget compared to approaches that require pre-harvest sampling. • Lower cost per site may allow for sampling more prescription variants and/or site conditions, providing context for assessing response. • Short turn-around time for results (<4 yrs) Limitations: • Lack of pre-harvest or reference data reduces ability to isolate treatment effect from confounding factors such as differences in initial stand conditions and interannual variability. • Requires the assumption that differences between the treatment and reference populations equals change due to the treatment. • Requires permission from many landowners. Lack of cooperation could complicate random sampling.	Advantages: • Pre-harvest sampling provides high level of certainty in distinguishing the treatment effect (magnitude and direction of change). • Controls provide ability to distinguish change from treatments from change due to. environmental factors. • Multiple post-harvest samples document short term patterns of disturbance and recovery. • Greater certainty for estimates of mortality and wood recruitment. Limitations: • Multiple sample events increase cost per site, so fewer sites can be sampled for a given budget compared to approaches with a single post-harvest sample. • Higher cost per site may reduce the number of sites, limiting the number of prescription variants or range of site conditions sampled and ability to extrapolate results. • Requires considerable cooperation and coordination with landowners, especially for reference sites. • Longer time frame for results due to pre-harvest sampling (6-7 yrs).	Advantages: • Pre-harvest sampling provides high level of certainty in magnitude and direction of change from preharvest condition. • Multiple post-harvest samples document short term patterns of disturbance and recovery. • Greater certainty for estimates of mortality and wood recruitment. Limitations: • Lack of reference data reduces the ability to isolate treatment effects from confounding factors such as post-harvest interannual variability from environmental factors. • Multiple sample events increase cost per site, so fewer sites can be sampled for a given budget • Higher cost per site may reduce the number of sites, limiting the number of prescription variants or range of site conditions sampled and ability to extrapolate results. • Requires considerable cooperation and coordination with landowners, especially for reference sites. • Long time-frame for results due to pre-harvest sampling (6-7 yrs).

Critical Question 1c

Critical Question 1c: Do riparian forest stands in areas with RMZ and without RMZ harvest remain on trajectory to achieve DFC targets?

To answer this question, post-harvest data from treatment sites would be used to run the DFC model and determine the proportion of RMZs that are "on" or "off" trajectory to achieve the DFC basal area performance targets. Since neither pre-treatment or reference site data are required for this procedure, an AI (after-impact only) design is the most efficient approach to accomplish this objective. This approach would provide the largest sample size per given budget, which is desirable since there are 10 prescriptions plus additional no inner zone harvest variants and a large range of site conditions that could affect success in remaining on trajectory to DFC. The ACI and BACI approaches would also provide answers to this question, but would have smaller sample sizes for a given budget because they include reference sites that are not needed for this objective. The BAI and BACI approaches also include pre-harvest sampling that are not necessary to answer this question, although pre-harvest data would be useful in establishing the starting point for no-RMZ-harvest treatments where pre-harvest DFC worksheets are not available. Both the AI and ACI approach involve collecting data from the treatment sites during a single post-harvest sample of multiple sites with different time periods since treatment. This would provide data to evaluate riparian stand conditions at up to 10 years from a single post-harvest sampling event, which would be useful for evaluating if stands remain on trajectory to DFC over time. Because there is only one post-harvest sampling event, these approaches provides a relatively quick turnaround time for information, compared to the BAI or BACI approaches that would begin with pre-harvest sampling and take many years to evaluate trajectory to DFC at five or ten years intervals after harvest (Table 11).

Table 11. Advantages and limitations of potential study designs in answering critical question 1c.

AI	ACI	BACI	BAI
Advantages: • Can evaluate post-harvest trajectory to DFC from a single visit. • Largest sample per budget allows evaluation of stand trajectory for a broad range of prescriptions and site conditions. • Largest geographic coverage. • Short turn-around time for results (3-4 yrs). Limitations: • Snapshot in time limits DFC model output to 15 years post-harvest conditions. • Large sample size requires multiple landowner cooperation and coordination. • Lack of cooperation could complicate random sampling.	Advantages: • Can evaluate post-harvest trajectory to DFC from a single visit. • Large sample per budget allows evaluation of stand trajectory for a broad range of prescriptions and site conditions. • Large geographic coverage. • Short turn-around time for results (3-4 yrs). Limitations: • Snapshot in time limits DFC model output to 15 years post-harvest conditions. • Large sample size requires multiple landowner cooperation and coordination. • Lack of cooperation could complicate random sampling.	Advantages: • Controls allow assessment of DFC trajectory relative to both prescription variants and environmental factors relative to untreated reference sites. • Pre-harvest data can establish starting trajectory for no-RMZ harvest sites. Limitations: • Reference sites and pre-harvest sampling reduce sample size for a given budget, limiting the number of prescription variants or range of site conditions that can be sampled and potential ability to extrapolate results. • Monitoring trajectory to DFC over a post-harvest timeframe will require many years to produce results, since BACI begins with pre-harvest sampling.	Advantages: • Pre-harvest data can establish starting trajectory for no-RMZ harvest sites. Limitations: • Pre-harvest sampling reduces sample size for a given budget, limiting the number of prescription variants or range of site conditions that can be sampled and the ability to extrapolate results. • Monitoring trajectory to DFC over a post-harvest timeframe will require many years to produce results, since BAI begins with pre-harvest sampling.

Critical Question 2a and 2b

Critical question 2a: How do physical stream characteristics and processes respond to changes in riparian functions in areas with RMZ and without RMZ harvest?

Critical question 2b) Do physical stream characteristics and processes meet performance targets?

These questions focus on potential changes in physical stream/channel characteristics and aquatic habitat conditions (e.g. water quality, substrate, pool:riffle habitat, wood loading) in response to harvest prescriptions and whether sites meet performance targets such as stream temperature or suspended sediment standards (Table 12). The BACI design is the strongest approach for answering these questions because the pre-harvest and reference data can be used to quantify a treatment effect and to separate the treatment effect from change caused by inter-annual variability in factors such as discharge, climatic conditions, and disturbance processes. This is of critical importance, because many stream and channel metrics are affected by interannual differences in climatic factors such as temperature, precipitation or disturbance events. The ACI approach involves collecting data from the treatment sites during a single post-harvest sample and comparing results with unharvested treatment sites. The ACI approach is limited in ability to answer these questions because it relies on the assumption that conditions at the treatment site are similar to those at the reference sites before treatment and that responses measured at the site are related to the prescription applied at that location. Further, the ACI approach assumes that conditions at the site are related to the treatment adjacent to the site rather than to upstream environmental conditions. Therefore any differences in pre-harvest conditions, such as inter-annual variability in environmental conditions between treatment and reference sites, may confound the ability to detect responses due to the treatment. Since both approaches involve reach-scale (harvest unit) treatments, the results could be confounded due to channel disturbance or imports into the study reach originating from areas upstream of the study sites.

Table 12. Advantages and limitations of potential study designs in answering critical questions 2a or 2b.

ACI Study	BACI Study
Advantages: • Because there is only 1 sample event per site, more sites can be sampled for a given budget compared to approaches that require pre-harvest sampling • Lower cost per site may allow for sampling more prescription variants and/or site conditions, providing context for assessing the interaction of different physical settings and different treatments (prescriptions) on stream characteristics (e.g. temperature, LWD, substrate, habitat, water quality). • Short turn-around time for results (3-4 yrs). • Evaluates change up to 10 years post-harvest. • Ability to assess performance targets across a broad range of site conditions and prescriptions. Limitations: • Lack of pre-harvest data reduces ability to isolate treatment effect from confounding differences in initial conditions or environmental/climatic factors. • Uncertainty about the effect of the prescription on achieving the performance targets. • Actual harvests may vary substantially from the maximum allowed by regulation thus confounding ability to assess and differentiate the effects of different prescriptions. • Large sample and need for upstream references requires landowner cooperation and coordination. • Lack of control over upstream conditions may confound ability to relate response to prescriptions.	Advantages: • High level of certainty in distinguishing treatment effect. • Controls allow the magnitude and direction of change in physical stream characteristics (e.g. temperature, LWD, substrate, habitat, water quality) to be assessed and attributed to forest practices vs. environmental factors. • High confidence in assessment of in-stream performance targets because treatment effect can be distinguished from change due to differences in initial conditions or environmental/climatic factors.. • Multiple post-harvest samples document short term patterns of disturbance and recovery. Limitations: • Multiple sample events increase cost per site, so fewer sites can be sampled for a given budget compared to approaches with a single post-harvest sample. • Higher cost per site may reduce the number of sites that can be sampled, limiting the number of prescription variants or range of site conditions that can be sampled and the ability to extrapolate results.. • Requires cooperation and coordination with landowners. • Longer time frame for results (6-7 yrs minimum). • Lack of control over upstream conditions may confound ability to relate in-stream response to prescriptions.

The BAI or AI approaches are not suitable to answer questions 2a and 2b because there is no frame of reference with untreated reference sites to distinguish the treatment effect from pre-harvest condition (AI) or from inter-annual variability or changes due to other factors (AI and BAI). Post-harvest data from either a AI or BAI study could be compared with performance targets for physical stream characteristics where they exist (e.g. temperature standards) to attempt to answer critical question 2b. However, the potential confounding effects of inter-annual variability and other environmental factors and the inability to distinguish these from treatment effects would add too much uncertainty to provide a robust answer to the question, so these approaches are not viable options and are not included in Table 12.

Critical Question 3a

Critical question 3a: What is the aquatic biological response to changes in riparian functions in areas with RMZ and without RMZ harvest?

Critical question 3a addresses potential changes in aquatic organisms that may be the result of riparian prescriptions (Table 13). As with critical question 2a, the BACI design is the strongest approach because the pre-harvest and reference data can be used to quantify a treatment effect and distinguish the treatment effect from change caused by inter-annual variability in factors such as discharge, climatic conditions, disturbance processes, and population fluctuations. This is of critical importance, because biotic populations are sensitive to interannual differences in climatic factors such as temperature, precipitation or disturbance events. The ACI approach is limited in ability to answer this question because it relies on the assumption that conditions at the treatment site are similar to those at the reference sites before treatment and that functions and responses measured at the site are related to the prescription applied at that location. Therefore any differences in pre-harvest conditions, inter-annual variability in environmental conditions, or fluctuations in populations between treatment and reference sites may confound the ability to detect responses due to the treatment. Since both approaches involve reach-scale (harvest unit) treatments, the results could be confounded due to channel disturbance or imports into the study reach originating from areas upstream of the study sites.

Table 13. Advantages and limitations of potential study designs in answering critical question 3a.

ACI Study	BACI Study
Advantages: • Because there is only 1 sample event per site, more sites can be sampled for a given budget compared to approaches that require pre-harvest sampling • Lower cost per site may allow for sampling more prescription variants and/or site conditions, providing context for assessing aquatic biological conditions following application of different prescriptions over a variety of physical settings. • Short turn-around time for results (3-4 yrs). • Evaluates change up to 10 years post-harvest. Limitations: • Lack of pre-harvest data reduces the ability to isolate relationships between aquatic biological conditions and prescriptions due to environmental/climatic factors. • Large sample size and need for upstream reference requires multiple landowner cooperation and coordination. • Lack of control over or standardization of upstream harvests may inhibit ability to relate in-stream response to treatments.	Advantages: • High level of certainty in distinguishing treatment effect. • Controls allow the magnitude and direction of change in biological response (e.g. fish, macro-invertebrates, amphibians) to be assessed and attributed to forest practices vs. environmental factors. • High confidence in assessment of biological response because treatment effect can be distinguished from change due to other factors. Limitations: • Measurements typically limited to a short-time period (2-5 yrs post-harvest). • Limited inference, applicability to a limited set of treatments and stream conditions. • Requires cooperation and coordination with landowners. • If landowners are unwilling to restrict management activity upstream of study sites, disturbance may inhibit ability to relate in-stream response to treatments. • Longer time frame for results (5-6 yrs minimum).

Recommendations for Selection of Study Design Alternatives

The TWIG determined that more than one approach is possible, and the selection of the study approach depends on the priority given to the critical question(s) to be answered. Since no single approach is optimal for answering all of the critical questions, the appropriate approach depends upon the interests and priorities of the Adaptive Management Program participants (TFW Policy and the Board). There are two possible pathways forward:

1) Focus on answering one or two high priority critical question(s) and design a focused study using the optimal study approach for the selected question(s), or
2) Pursue answers for all critical questions by developing an integrated research program with linked studies.

Alternative 1. Focused Study on High Priority Question(s)

The assumption behind this alternative is that not all critical questions are of equal priority, and that the best use of funding and human resources is to prioritize the questions and design a focused study to answer the question(s) using an optimal study design approach. Prioritization and selection of the highest priority questions would require input from CMER and the TFW Policy Committee. The recommended study approach for each individual question is shown in Table 14.

Table 14. Critical questions with recommended study approaches.

Critical Question	Optimal Approach	Alternative Approach
1a	BACI	ACI
1b	BACI, BAI	ACI
1c	AI, BAI	ACI
2a	BACI	None
2b	BACI	None
3	BACI	None

Recommended Approach for Question 1a or 1b

If the priority for the Adaptive Management Program is to understand the effects of the prescriptions on riparian stand conditions and riparian functions, either a BACI or ACI study would provide estimates of the effect of a limited suite of prescription variants on measures of riparian stand conditions and riparian functions (shade, large wood recruitment, streambank integrity/bank erosion, sediment attenuation, and litter fall). A BACI study approach would provide the most robust evaluation of causal relationships, and the most reliable estimate of the magnitude and direction of change in the treatment effect. However, the number of prescription variants (e.g., 5 site classes x 2 stream widths = 10 variants) that could be examined in a BACI study would likely be limited by the current budget in the CMER Master Schedule. An ACI approach is potentially a less costly alternative for providing information on the effect of the prescriptions on riparian stand conditions and riparian functions. However, the ACI approach is not as robust as the BACI because it lacks pre-harvest data and would be limited to estimates of the treatment effect by comparing post-harvest conditions at treatment sites with those of the reference population. The lower cost per site would allow more prescription variants to be evaluated than the BACI, and an ACI study could be completed more quickly than a BACI study.

Recommended Approach for Question 1c

If the priority for the Adaptive Management Program is to understand to what extent RMZs harvested under the Westside Type F riparian prescriptions remain on trajectory to meet the DFC performance standards over time, then we recommend an AI or BAI study approach. These approaches are optimal for this particular question because reference sites are not needed for this analysis so the budget can be devoted to increasing the number of treatment sites, enabling us to sample a wider range of prescription variants, site conditions, or time since harvest. The AI approach would provide a relatively shorter turn-around time to answer this question, since it would involve a single visit to treatment sites. The BAI approach would have a higher cost per site and a much longer turn-around time to yield results, since it would begin with pre-harvest sampling and then revisit sites following harvest. However the BAI approach would produce a more robust analysis of sites where no RMZ harvest occurred and there was no pre-harvest data, because it would begin by establishing the pre-harvest condition and then track changes in trajectory following harvest. Both the ACI and BACI approaches could also provide answers to this question, but they are not optimal approaches because they would devote substantial resources to reference sites not required for this type of analysis.

A BACI or ACI study focused on critical questions 1a and 1b should provide an estimate of the proportion of sites that remain on trajectory meet the DFC performance target, but the sample size would be smaller than for a AI or BAI approach for a given budget.

Recommended Approach for Questions 2a, 2b or 3

If the priority for the Adaptive Management Program is to understand the effects of the prescriptions on in-channel habitat and water quality (question 2a or 2b) or aquatic organisms (question 3), then we recommend a BACI study focused on the question(s) of interest because the BACI approach is the most robust alternative for determining causal relationships. This approach should provide substantive information regarding the relationship between forest harvest prescriptions, riparian stand conditions, physical stream/channel characteristics and aquatic life. To effectively associate changes in physical stream/channel characteristics and aquatic life with the prescriptions, the treatment effect must be detected and quantified while controlling for potentially confounding effects introduced by differences in pre-treatment conditions and inter-annual variability in environmental conditions. Understanding and detecting causal links can only be done rigorously using a BACI sample design.

A BACI approach includes data collection prior to treatment in order to understand the range of variability inherent within the variables of interest. A BACI approach operates on a longer timeframe and therefore, is more expensive due to the need to collect several years of pre-treatment data, and multiple years of post-treatment data as demonstrated by other CMER effectiveness studies. The long-term nature of a BACI approach is balanced by careful selection of a small, but adequate set of sample sites. Because of the need to balance long-term data collection with the number of sites, we anticipate that the selection of treatments and site conditions will be instrumental to the utility of the final experimental results. Therefore, we recommend that a review of harvest prescription types, their distribution on the landscape, and the frequency of prescriptions be completed prior to site selection.

A BACI study focused on critical question 2a and 2b should provide estimates of the effect of a limited suite of prescription variants on measures of instream habitat and water quality responses (e.g., wood loading, instream habitat composition and complexity, stream temperature) and the proportion of sites meeting in-channel performance targets from Schedule L-1. A BACI study focused on critical question 3 should produce an estimate of the effect of a limited suite of prescription variants on measures of aquatic biotic responses (e.g., macroinvertebrates, fish).

Alternative 2: Approaches to Answer All Critical Questions

The assumption behind this strategy is that getting the answers to all the critical questions are equally important, and therefore the study (or a series of studies) should be designed to provide answers for all questions in the most efficient manner possible. We identified two options to pursue this strategy, an BACI study with an expanded sample size and timeframe, or a hybrid, phased approach. Both options are described below.

A BACI Approach to Answer All Critical Questions

A BACI approach can be used to address all the critical questions simultaneously. However, a BACI study that effectively addresses all questions will require a larger sample and a longer timeframe than the BACI approach for only questions 2 and 3 (presented above). The broad range of riparian harvest conditions identified under critical question 1a, 1b, and 1c will require the selection of an adequate sample size through a range of riparian harvest prescriptions and landscapes.

A BACI approach includes pre-treatment data collection in order to document the range of variability of the variables of interest. A BACI approach operates on a longer timeframe and therefore, is more expensive due to the need to include several years of pre-treatment data, and multiple years of post-treatment data. Generally, the long-term nature of a BACI approach is balanced by careful selection of a small, but adequate set of sample sites. However, due to the extensive nature of prescription variants of interest in Critical Question 1a, b, and c, sample size will need to be adequate within a stratification of harvest types and environmental settings. This will necessitate the development of an extensive sample frame. In addition, the timeframe should be extended up to 10 years post-harvest to determine if stands remain on trajectory to DFC (or this question could be addressed by a separate study).

A BACI approach is the most scientifically rigorous approach currently available in applied ecological settings. A well designed BACI study focused on all of the critical questions should produce the following information for the adaptive management program:

1. the level of riparian functions associated with the prescriptions (i.e., post harvest large wood recruitment, shade, sediment attenuation),
2. riparian stand conditions associated with prescriptions and the proportion of sites on trajectory to meet DFC over time,
3. the frequency and magnitude of windthrow effects on buffer tree mortality rates,
4. the relative influence of different site conditions and geographic location on 1-3 above.
5. an estimate of the effect of the specific prescription variants on riparian stand conditions, mortality and trajectory to meeting DFC targets ,
6. a measure (direction and magnitude of change) of treatment effects on key riparian functions (shade, large wood recruitment, streambank integrity/ bank erosion, sediment attenuation, and litter fall),
7. measures of instream habitat, water quality and aquatic biotic responses (e.g., wood loading, habitat composition and complexity, stream temperature, macroinvertebrates, fish) to treatments.

The study design process for the BACI study approach would need to include an initial assessment of the prescription variants (five site class x two stream widths = 10 variants) and the potential effects of landscape conditions on treatment effects to define the population of interest for the study.

A Hybrid, Phased Approach to Answer All Three Critical Questions

Since no single approach is optimal for answering all the critical questions, if the priority is to answer all questions a hybrid, phased approach could optimize research results. Consequently, we suggest a strategy that utilizes both the ACI and BACI designs in sequence to answer the full suite of critical questions. We propose an approach that would be implemented in three steps.

Step 1 would occur during the study design phase and would involve an office review and analysis of forest practice applications and GIS data to determine how frequently different riparian prescription variants are being implemented, regional distribution patterns, and information on the characteristics of the sites and adjacent streams where the prescriptions are being applied.

Step 2 would begin with a pilot study using an ACI (or combined ACI/AI approach) that focuses on assessing riparian stand conditions and selected riparian functions across a wide range of prescription variants and site conditions. This will provide a large-scale, coarse-level assessment of current riparian conditions that focuses on addressing scientific uncertainty about mortality, stand trajectory (DFC), and riparian functions associated with different prescription variants following harvest (critical question 1). This assessment would be done in the context of differences in site conditions across the landscape. The study could be completed in approximately 3 years. At the conclusion, the adaptive management program would have information for most westside Type F prescription variants including:

- post-harvest riparian stand conditions relative to unharvested sites,
- the level of post-harvest riparian functions (e.g. shade, large wood recruitment, streambank integrity/bank erosion, sediment attenuation, litter fall) relative to unharvested reference sites,
- an estimate of the proportion of treatment sites on trajectory to meet DFC,
- the frequency and magnitude of windthrow effects on buffer tree mortality rates,
- additional information on the potential influence of site conditions and geographic location on 1-3 above that may be useful in identifying “sensitive” situations affecting riparian stand conditions and riparian functions.

The results of the pilot study could help better define the population of interest for the BACI study (step 3) by providing information on the condition of riparian stands and level of functions associated with different prescription variants as well as information on the potential effect of site conditions. See Appendix C for examples of studies that used this approach.

Step 3 would utilize results from the pilot study to estimate the direction and magnitude of change associated with the prescription variants and the potential influence of site conditions on riparian stand conditions and functions following treatments. This information would be used to tailor and focus the study design to provide fine-scale assessments of treatment effects for a select set of prescription variants and site conditions. This study would improve our understanding and decrease scientific uncertainty about the linkage between riparian prescriptions, changes in riparian stands and riparian functions, and the aquatic resource response (habitat, wood recruitment, temperature, and aquatic organisms). This study could be completed in approximately eight years. Depending on the specific research question, this study could provide the following information for the adaptive management program:

- an estimate of the effects of specific prescription variants on riparian stand conditions, mortality and trajectory to meeting DFC targets,

- a measure (direction and magnitude of change) of treatment effects on key riparian functions (e.g. shade, large wood recruitment, streambank integrity/bank erosion, sediment attenuation, litter fall),
- measures of instream habitat, water quality and aquatic biotic responses (e.g., wood loading, habitat composition and complexity, stream temperature, macroinvertebrates, fish) to treatments,
- an assessment of riparian prescription effectiveness over the short-term (i.e., initially 2-years post-harvest with the potential to extend sampling for metrics of interest).

Summary of Recommendations

The TWIG's recommendations for a study approach depend upon the feedback and guidance we receive from the TFW policy committee concerning the relative importance of the critical questions. If the guidance is to focus on a specific high priority critical question or to tackle the questions sequentially in individual studies, then we recommend the study design approaches identified in Table 14 and the associated text for the priority question. If the guidance is to pursue answers to all the critical questions in the most efficient manner, then the TWIG recommends the hybrid, phased strategy as outlined above.

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Appendix A. Original Critical Questions

The Westside Type F Riparian Prescription Monitoring Project is expected to address the following Westside Type F Riparian Effectiveness Program critical questions and objectives from the CMER work plan (CMER 2014):

1. How do stand conditions change over time (i.e. forest growth, mortality regeneration) following application of the Westside Type F RMZ inner zone harvest prescriptions, and do stands remain on trajectory to achieve DFC targets?
2. What level of riparian functions are provided by stands following application of the Westside Type F riparian prescriptions allowing inner zone management? Do riparian functions meet FP HCP resource objectives and performance targets for shade, stream temperature, LWD recruitment, and litter fall?
3. What level of riparian functions are provided by stands where no RMZ inner zone management is allowed (does not meet DFC basal area/acre targets) under Westside Type F riparian prescriptions? Do riparian functions meet FP HCP resource objectives and performance targets for shade, stream temperature, LWD recruitment, and litter fall?

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Appendix C. Summary of ACI and AI Study Examples

Table C-1 lists studies that used either the ACI or AI approach to examine the effectiveness of various riparian buffer strategies or forest practice BMPs to maintain riparian and instream habitat and ecological functions. The list is intended as an example of the various treatments, variables, and statistical analyses that have been used along with the ACI/AI study design. We believe the ACI/AI approach is best suited for assessing riparian or upslope conditions (e.g., hillslope erosion) compared to assessing instream habitat or aquatic populations because the latter can be influence by both on-site and upstream transport processes. However, we found a number of study examples (see table C-1) that have used ACI to evaluate the effects of logging on instream habitat, algae, macroinvertebrates and fish populations. Although the resolution for measuring response is less than can be obtained with a BACI approach the ability to include a broad range of strata with the ACI approach has enabled research to identify key factors (e.g., loss of large wood) influencing habitat and aquatic populations. For example, Richardson and Béraud (2014) conclude that the direction and magnitude of ecological response to logging effects is often dependent on site-specific conditions. Therefore, studies that examine a range of BMPs among a range of physiographic conditions facilitate the evaluation and relevance of such context-specific factors on ecological response.

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Table C-1. Examples of forest practice effectiveness studies that use a post-harvest (AI) or after-control-impact (ACI) approach.

Reference	Location	Treatments examined	Variables	Experimental Design	Statistical analysis	Findings
Schuett-Hames et al. 2012	Western Washington	clearcut, 50-ft buffer, reference	stand density & mortality, LW recruitment, channel slash, shade, bank erosion	ACI, random selection of treatment sites (N = 8, 13), each with reference site in vicinity.	Mann-Whitney two-sample comparison of treatment and reference means. Also, pre- to post-harvest stands compared by reconstruction of pre-harvest conditions using decay class aging	Results provided insights into the harvest unit-scale effects of the westside Type Np riparian prescriptions on riparian stand condition, and riparian processes and functions including tree fall, wood recruitment, channel debris, shade, and soil disturbance. The nature and magnitude of responses varied, depending on whether the reaches were clear-cut or buffered, and in the case of the buffered reaches, on the magnitude of post-harvest disturbance from wind-throw.
Martin & Grotefendt 2007	Southeast Alaska	20-m wide buffer, reference old growth	stand mortality, LW recruitment	ACI, stratified random sample of treatments; each paired with a reference unit having similar orientation, confinement, and stand density	paired analyses using either a t-test or nonparametric Wilcoxon depending on normality	Cumulative stand mortality (CSM) was significantly greater in buffer units compared with reference units and mortality varied with distance from the stream. The greater CSM in the buffer units is primarily the result of a significant increase in mortality by windthrow at a small proportion (11%) of the logged units. We found that logging caused an increase in the proportion of tree recruitment to the stream from the outer zone of buffers and changed the shape of the LWD source distance recruitment curve.
Rashin et al. 2006	Washington	Variable width buffers	volume of sediment delivered to streams	AI, 26 study sites located in six physiographic regions with different BMPs	A weight-of-evidence approach was used to determine BMP effectiveness based on assessment of erosion with sediment delivery to streams, physical disturbance of stream channels, and aquatic habitat conditions during the first two years following harvest.	Stream buffers were effective at preventing chronic sediment delivery to streams and physical disturbance of stream channels. Practices for ground-based harvest and cable yarding in the vicinity of small streams without buffers were ineffective or only partially effective at preventing water quality impacts. The primary operational factors influencing BMP effectiveness were: the proximity of ground disturbing activities to streams; presence or absence of designated stream buffers; the use of special timber falling and yarding practices intended to minimize physical disturbance of stream channels; and timing of harvest to occur during snow cover or frozen ground conditions.
Litschert & MacDonald 2009	Northern CA	45-m and 90-m wide SMZs	sediment delivery through SMZ	AI, direct measure of rill length and connectivity in 200 harvest units with SMZs	Summary statistics for frequency of connectivity. Linear regression used to model relationship between rill connectivity and independent variables	Only nineteen erosion features were found below harvest units ranging in age from 2 to 18 years. Feature lengths ranged from 10 m to 220 m, and the length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient (R2 = 64%, p = 0.004). Six of the nineteen features were connected to streams and five of the six connected features originated from skid trails. The results indicate that timber harvest alone rarely initiated large amounts of runoff and surface erosion, particularly when newer harvest practices were utilized

Reference	Location	Treatments examined	Variables	Experimental Design	Statistical analysis	Findings
Ralph et al. 1994	Western Washington	old-growth, variable harvest with and without buffers	pool frequency, depth, LW	ACI, three harvest categories (intensive, moderate and unharvested)	ANOV to examine difference among harvest categories and regression to examine influence of channel width, basin area, and/or stream gradient for each harvest category.	The number sf pieces of large woody debris (LWD) within stream channels was unaffected by timber harvest, but here was a clear reduction in LWD size in harvested basins. Timber harvest also resulted in a shift in location of LWD towards the channel margins, outside the low-flow wetted width of the channel. Intensive harvest simplified channel habitat by increasing riffle area and reducing pool area and depth. Given the natural variation from stream to stream, we conclude that simple counts of instream LWD and channel units (habitat types) are not useful as management objectives. instead, these attributes should be used collectively as indicators of the complexity and stability of in-stream habitat with respect to the specific channel and valley geomorphology.
Hoover et al. 2007	north-central British Columbia	clearcut, 10-m buffer, reference	invertebrate drift	ACI, 14 sites with reference and treatments paired at 7 sites.	multivariate analysis of variance used to examine differences among treatments	The density (concentration) of aquatic invertebrates in the drift was significantly lower in streams with 10 m riparian reserves compared to control streams (P<0.002), and this effect was stronger when the data were expressed in terms of flux (i.e., individuals m–2 s–1; P <0.001). Terrestrial invertebrate drift density tended to be higher in treatment streams compared to control streams and the magnitude and variation of this pattern correlated with the openness of forestry canopy (e.g., clear cut streams > 10 m defoliated > 10 m foliated). There was significantly more aquatic drift in downstream vs. upstream locations of control streams, but this pattern was reversed for harvested streams (P = 0.51) leading to a significant interaction term in the analysis (P = 0.046; which indicates that the upstream-downstream comparison differed significantly between control and treatment streams in this double-control design). These types of changes in the drift of aquatic and terrestrial invertebrates are known to affect stream ecosystems through trophic interactions among periphyton, benthic grazers, and fish. Consequently, both the quantity and quality of riparian reserve strips must be considered for the effective mitigation of forestry practices
Nislow & Lowe 2006	northern New England	Variable harvest with and without buffers	riparian forest conditions, macroinvertebrate community, trout abundance	ACI, examined chronosequence of logging history (<2 to >80 years since logging) at 22 streams	Principal component analysis was used to collapse forest data into two independent variables representing variation in logging history, riparian forest structure and canopy cover.	Catchments with high PC1 scores (recently logged, high-density stands with low mean tree diameter) and low PC2 scores (low canopy cover) had significantly higher total macroinvertebrate abundance, particularly with respect to chironomid larvae (low PC2 scores) and invertebrates in the grazer functional feeding group (high PC1 scores). In contrast, proportional representation of macroinvertebrates in the shredder functional feeding group increased with time since logging and canopy cover (high PC2 scores). Brook trout density and biomass was significantly greater in young, recently logged stands (high PC1 scores) and was positively related to overall macroinvertebrate abundance. In addition, three variables – trout density, invertebrate abundance and shredder abundance – successfully discriminated between streams that were less-impacted versus more impacted by forestry.

Reference	Location	Treatments examined	Variables	Experimental Design	Statistical analysis	Findings
Mellina & Hinch 2009	PNW & AK	clearcut to bank, stream cleaned of LW	pool size, pool number, LW, juv. salmonid densities	mostly ACI, some AI and BACI	Meta-analysis of 37 case studies using regression to examine relationship of response variables to stream size, gradient and time since harvest	The majority of studies reported negative post-logging responses for LW and pool habitat but positive responses for salmonid density and biomass, with the greatest reductions in all variables generally associated with a thorough removal of in-stream LW. The magnitude of post-logging responses was largely independent of stream size, gradient, and time since logging last occurred. In terms of density and biomass, juveniles were more negatively affected by logging than fry. Of the surveyed species, steelhead trout appeared to be most resilient to riparian logging. Within the time frame covered by the analyses, streams whose riparian zones have been logged may be able to sustain salmonid populations (and even exceed preharvest levels) as long as rigorous removal of LW is not undertaken.
Richardson & Béraud 2014	world wide	harvest ranged from 20% to a total clear-cut, no buffers	water chemistry, algae, fine particulate and coarse particulate organic matter, and benthic invertebrates	ACI, meta analysis of 34 studies with replicated reference and treatment sites located on different streams with response data within 2 or 3 years after harvesting	Computed effect sizes for each study to measure the magnitude and direction of the response to logging and a fixed-effects model to compare reference to harvested. Used regression to evaluate the relation of response variables to gradient, stream width and potential evapotranspiration (PET.	There was a very large amount of variation in the effect sizes between studies, and for many measures, the effect sizes from different studies were positive or negative, indicating site-specific responses. The relations to stream size, stream gradient and regional PET were weak, but suggestive that some of the context-specific, individual outcomes might be due to underlying environmental differences between sites. Despite relatively low numbers of replicated studies, we found significant overall effects of riparian forest harvesting although the magnitude and direction of responses within individual studies were site specific. This lack of consistency in the direction of effect sizes suggests we need a more context-dependent approach to the protection of freshwaters from forest management.

Appendix D. Comparison of Approaches for Westside Type F Prescription Monitoring

ACI

The ACI approach balances both study efficiency and sensitivity to detect treatment effects as shown in the list of advantages and limitations (Table 8). Both time and funding is economized because the ACI does not require pre-treatment data. Therefore, the study duration may be shortened and the cost savings can be allocated to increasing sample size, expanding geographic coverage, and adding stratification of treatments. For example, stratification of treatments by differences in site conditions and wind exposure may increase the ability to associate changes in response metrics with site-specific factors (e.g., high stand mortality may be associated with thinning prescriptions in wind exposed areas). The identification of such context-specific factors are less likely with a more intensive-small-sample approach. Such context provides rapid feedback for adaptive management by identifying relationships that could lead to potential adjustments in the prescriptions or specific conditions where additional research is warranted.

The upstream-downstream ACI model would work best for assessing terrestrial riparian conditions and ecological functions as opposed to the evaluation of in-stream ecological and geophysical response metrics (e.g., temperature, fish populations). The latter metrics are influence by both upstream watershed processes and riparian processes. Therefore, lack of control over upstream management practices and disturbances (i.e., upstream of the reference reach) may confound the evaluation of treatment effects. This concern would apply to any reach-based study design and points to the importance of selecting sites where upstream activities are minimized.

The strategy behind an ACI approach for the Westside Type F Riparian Prescription Monitoring project is to collect data on post harvest conditions at a relatively large number of sites in order to determine the extent to which prescriptions are effective over a wide range of prescription variants, regions and site conditions. This would be accomplished by comparing post-harvest stand conditions and riparian functions to relevant performance targets and by comparing the distribution of conditions in the treatment sites with conditions in unharvested reference sites. There is also the potential for conducting a retrospective assessment of pre-harvest conditions for certain stand characteristics (e.g. pre-harvest stand density reconstructed from stumps) that would facilitate assessing treatment effects on stand mortality. The ACI approach is best suited for sampling on a reach (harvest unit) scale. Because no pre-harvest sampling is needed, study sites could be randomly selected from completed FPAs. Since the prescriptions have been in effect since 2000, it would be possible to sample harvest units at different times since harvest (up to 15 yrs), providing information on the magnitude and duration of stand differences over an extended post-harvest period.

We anticipate an ACI study would involve a one-time post-harvest sample of riparian stand conditions (e.g. density, basal area, species composition). The data could also provide a snapshot in time of some riparian functions (e.g., shade and litterfall). An estimate could also be made of large wood recruitment based on decay class, although the accuracy of the estimate decrease as the length of time since harvest increased due the confounding effect of decay and transport into and out of the study reach. The sample population would likely be stratified by Type F prescription variants (i.e., Site Class/stream size categories) and time after harvest. The latter would facilitate an assessment of short- and longer-term responses to the prescription treatments. The analysis would also use current stand data and the DFC model to determine the proportion of sites that are on trajectory to meet DFC targets. The ACI study would not include sampling of instream physical or biotic variables (e.g., water temperature or fish) because the absence of pre-harvest data reduces the power to detect treatment response for these variables which are influenced by a combination of on- and off-site factors as well as inter-annual variability.

The expected outcome from the ACI approach would be an analysis that would:

1) Estimate the proportion of post-harvest riparian stands that meet performance targets.
2) Determine the extent to which the post-harvest distributions of riparian stand and riparian function metrics differ among unharvested reference sites and the RMZ and no-RMZ harvest treatment sites.
3) Identify potential associations between geophysical site characteristics (e.g., climatic, valley morphology, elevation) and treatment response metrics (riparian stand conditions and riparian function indicators e.g. shade, LWD recruitment, sediment delivery).

The riparian stand and function data would allow us to validate the assumption that riparian stands and functions are performing as expected (e.g., on trajectory to DFC, adequate shade and potential LWD recruitment in comparison to targets and relative to untreated reference sites) and identify specific situations and physical settings (i.e., context-specific factors) where that is not the case and where a follow-up study may be needed. The results facilitate a weight-of-evidence assessment for evaluating riparian effectiveness and would be broadly applicable to a range of BMPs and landscapes.

Limitations to this approach include:

1) Small differences in response variables between reference and treatment sites may be undetectable.
2) Proposed focus on riparian stand and function response variables does not directly address water quality, instream habitat related performance targets or biota.
3) The absence of pre-treatment data confounds the evaluation of treatment effects (i.e., does not measure treatment effects but only associations) and reduces the confidence with which we can ascribe post-harvest conditions with particular prescriptions.
4) More landowner cooperation needed to acquire large sample.

BACI

The strategy behind a BACI approach for the Westside Type F Riparian Prescription Monitoring Project is to examine a selected subset of prescriptions that would be applied to riparian stands with similar site/watershed conditions. Sampling would likely involve two years of pre-harvest sampling, a treatment year, and a minimum of two years post-harvest sampling to measure initial treatment responses and to distinguish the treatment effects from inter-annual variability. In addition to riparian metrics (i.e., stand conditions, functions, DFC), a suite of water quality and habitat response variables (e.g. water temperature, pool/riffle habitat, wood loading) and biotic variables (e.g., macroinvertebrates, fish) could be investigated. This approach would focus on detecting potentially small treatment effects by minimizing differences in site conditions that contribute to variability (e.g. the Eastside temperature-shade study, Cupp and Lofgren. 2014).

Because the BACI approach involves greater sampling effort per site due to the need for pre-harvest sampling and the larger suite of variables, it will be necessary to limit the number of sites, making it cost prohibitive to sample the full range of westside Type F prescription variants (5 Site Classes x 2 channel widths = 10 variants). Consequently, a critical decision will involve deciding which subset of prescriptions to include. There are different approaches to addressing this issue, for example: 1) selecting the most widely used prescriptions in the most commonly occurring situations, 2) selecting the prescriptions/sites considered to be most sensitive (narrow buffers, low stand density), or 3) selecting prescriptions at discrete points along a gradient (narrow vs. wide buffers) to allow extrapolation to intermediate prescriptions. Also, because the study is focused on riparian prescriptions, implementation at the reach-scale would facilitate a greater range of prescription study options than would a watershed approach. The latter is constrained by a host of factors including the difficulty of finding suitable paired watersheds and significantly greater cooperation needed to manage forest practices activities on a larger scale.

The expected outcome from the BACI approach would be an analysis that would:

1) Quantify the treatment effect of the prescriptions on riparian stand condition, riparian functions, DFC trajectory, water quality, habitat and possibly biota associated with the prescriptions.
2) Provides high confidence for measuring the effectiveness of selected Type F prescriptions to maintain riparian functions (shade, wood, litter) and instream resources (temperature, aquatic habitat, biota).
3) Determine differences in relative effectiveness between the RMZ and no-RMZ harvest prescriptions in terms of in the magnitude of change in riparian functions and instream resources

Limitations of the BACI approach include:

1) The limited set of prescriptions/site conditions sampled in the BACI approach may miss a critical sub-set of situations that merit further examination (i.e. a prescription with infrequent application, but potentially high impacts),
2) The longer timeframe (compared to ACI) necessary to complete an assessment of the initial post-harvest response. Proposed 5-yr design is similar to other CMER BACI studies (Type N Hard Rock Experimental; Type F Solar / Shade),
3) Potential difficulty in obtaining long-term study sites (especially reference sites),
4) Potential difficulty in getting the necessary treatments applied in a timely manner, and in keeping the harvest on schedule.