# Riparian Study Plan
# for the
# T3 Watershed Experiment[§]

Riparian Study Module Principal Investigators:
Kyle D. Martens[1], Bernard T. Bormann[2], Teodora V. Minkova[1], Deanna H. Olson[3], Stephen M. Bollens[4], David Butman[2], Peter M. Kiffney[5], Kevin Alexander[1], and Martin Liermann[5]

T3 Watershed Experiment Principal Investigators:
Bernard T. Bormann[2], Teodora Minkova[1], Bill Wells[1], Marc L. Miller[2]

[1] Washington Department of Natural Resources, Olympic Experimental State Forest
[2] University of Washington, College of Environment
[3] USDA Forest Service, Pacific Northwest Research Station
[4] Washington State University, School of the Environment and School of Biological Sciences
[5] National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center

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[§] "T3" refers to the stream type 3 (uppermost reaches with fish present). "Watershed experiment" is a study title based on active adaptive management concepts (e.g., Walters 1997, Bormann et al. 2017). The original proposal (Bormann and Minkova 2016) uses the title "Large-Scale Integrated Management Experiment on the Olympic Experimental State Forest."

## Executive Summary

This study represents a major new collaboration between two State of Washington institutions, the WA Department of Natural Resources (WADNR) and the University of Washington (UW)'s Olympic Natural Resource Center (ONRC), and other key academic and federal research agencies. This multi-agency experiment, called the Type-3 Watershed Experiment, was developed to assess the impacts of current and alternative forest management strategies on a holistic vision of ecosystem wellbeing (with co-equal weighting of both environment and community wellbeing). The core question of the experiment is "Will a higher, sustainable level of rural ecosystem wellbeing emerge from an array of land management strategies implemented and compared across the Olympic Experimental State Forest (OESF) landscape?" The experiment is designed to go beyond the scope of most previous studies on forest harvesting effects in its evaluation of the integrated responses of social science, upland silviculture, forest operations, and riparian zones and streams. This riparian study plan focuses on the riparian and stream component. The scientific concepts, design, and components of the entire experiment are described in a separate document titled T3 Watershed Experiment Overview Plan. A separate study plan will address the upland silviculture component of the study

The T3 Watershed Experiment's riparian study takes a novel approach by:

1. Considering people (and communities) as part of the ecosystem in the study design;
2. Comparing combinations of experimental treatments at multiple scales implemented over a decade or longer rather than examining immediate responses to individual treatments at one scale;
3. Applying watershed management at the complex landscape scale (strategies) and at operational scales affecting only a portion of a watershed (prescriptions);
4. Developing management strategies that link to different constituencies and stakeholders variably focused on the priority of environment or community wellbeing;
5. Examining how strategies extrapolated to the entire 110,000-hectare (270,000 acres) of the OESF landscape would affect community wellbeing (social and economic); and
6. Applying experimental strategies and prescriptions through regular agency planning and operations using a collaborative, science-based adaptive-management model.

The riparian portion of the T3 Watershed Experiment evaluates 5 experimental riparian management prescriptions (experimental treatments) within 4 management strategies across 16 watersheds (215-1077 ha each) on the western Olympic Peninsula, Washington. The four management strategies are alternative 1 integration (Alternative 1), alternative 2 integration (Alternative 2), current OESF management (Standard), and a no-action control (Control). Each experimental watershed has one riparian prescription except the four watersheds representing Alternative 2 which have two riparian prescriptions. The active habitat restoration prescription within the Alterative 1 strategy was designed to increase ecosystem wellbeing by better integrating community and environment wellbeing by applying the latest environmental science. This strategy emphasizes active management of factors thought to limit salmonid (family Salmonidae) habitat on the Olympic Peninsula (low amounts of instream wood and heavy canopy shading) as well as producing some revenue. The prescriptions in Alternative 2 strategy were designed to increase ecosystem wellbeing by better integrating community and environment wellbeing, seeking inspiration and innovation through social-science-based engagement with stakeholders and elevated concerns for rural livelihoods. The watersheds within this strategy will include two riparian prescriptions: (a) thin second-growth, riparian conifers very widely and under-plant and grow repeated red alder (*Alnus rubra* Bong.) rotations; and (b) a site-specific variable-width buffer that would increase the amount of area available for timber harvest while protecting ecologically sensitive areas. The Standard strategy includes a no-entry OESF Riparian Buffer prescription most often applied under the OESF Forest Land Plan. Finally, the Control strategy will not apply any active prescriptions - - the entire watershed will remain unharvested for 10 years.

Four replications, blocking, and a Before-After and Control-Impact (BACI) approach including pre- and post-treatment monitoring will help distinguish experimental effects from background changes. Pretreatment monitoring began in 2020 and will include at least two years of pre-treatment monitoring (2020-summer 2021). Riparian treatments will be applied between the fall of 2021 through 2023. Post-treatment monitoring will include at least four years of monitoring. Monitoring will take place in reaches and sub-catchments with riparian treatments and at stream control and watershed pour points, and will assess effect of treatments on salmonids, macroinvertebrates, stream temperature, instream wood, canopy coverage, and stream sediment.

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## Problem Statement

Increasing regulations on management of riparian forests, developed to avoid impacts on water quality and protect riparian- and stream-dependent species, have reduced forest harvesting primarily by setting aside fixed-width no-cut riparian forest buffers. Many have speculated on whether these regulations are working as designed, too restrictive, or even could be altered to accelerate the recovery of protected species. In this study, we plan to evaluate current and alternative riparian management strategies designed to better integrate social-economic and ecological function, including riparian species' habitat development and timber harvest.

## Introduction

The Olympic Experimental State Forest (OESF) consists of 110,000 ha (270,000 ac) primarily forested lands managed by Washington State Department of Natural Resources (WADNR) on the western side of Washington's Olympic Peninsula. The OESF has been designated as both a working forest and a place for experimentation with a vision of "A productive, healthy, biologically diverse working forest that provides a perpetual supply of revenue to trust beneficiaries as well as ecological values." The mission of the OESF is to learn how to better integrate revenue production and ecological values across the landscape and deliver the knowledge to WADNR managers for continuous improvement of sustainable land-management practices. University of Washington (UW) runs the Olympic Natural Resources Center (ONRC), lying in the center of the OESF. Its mission, established by the Washington State Legislature, is to develop new place-based approaches to better integrate ecological and economic concerns in forestry and aquatic resource management.

Given their overlapping missions and locations, the two institutions (UW/ONRC and WADNR) have developed a collaborative study (called the Type-3 or T3 Watershed Experiment) to assess the effects of current and alternative forest-management strategies with an overarching goal of ecosystem sustainability (Figure 1). Ecosystem sustainability is defined as achieving high levels of ecosystem wellbeing, with coequal focus on community and environment wellbeing, and maintaining this wellbeing through learning mechanisms to guide innovation and adaptation. These aims are reflected in the core question of the overall study: "Will a higher, sustainable level of rural ecosystem wellbeing emerge from an array of different land-management strategies implemented and compared across the Olympic Experimental State Forest?" The riparian study described in this report is a core effort, nested within a series of other studies, needed to address broad ecosystem

**Figure 1. The ecosystem sustainability framework.**

sustainability goals at watershed and larger scales. Ecosystem sustainability and affiliated studies are described in an Overview Plan (https://drive.google.com/file/d/1UCqI9N5ERyF14LJEyjLSlwtjuK-elfTl/view?usp=sharing).

## Social, Economic, Environment, and Policy Changes

In the aftermath of World War II, extensive intensive timber production resulted in unforeseen ecological impacts. As these became apparent, forest regulations were often created or adapted using the best available science at the time. Into the late 1950s streams were often cleared of obstructions (often instream wood) and small dams (splash dams) were constructed to transport logs downstream once the dam was removed. This practice ceased once it was understood that log drives typically removed anything including fish habitat in their path (Bilby and Ward 1991). As the industry developed, advances in technology led to increased harvests and allowed loggers to enter areas that were previously cost prohibitive. During this advancement, logging roads were often built close to streams, restricting natural stream movement, and often included stream crossings that either partially or fully blocked fish passage. Starting after World War II and lasting into the early 1980s, instream wood was actively removed, sometimes associated with forest harvest operations, to assist anadromous salmon passage. Ultimately, this practice did more harm than good by reducing rearing and spawning habitat (Bisson et al. 1987). Into the late 1980s WADNR policy required that the oldest forests be targeted first since they would generate the most timber revenue, and between 1970 and 1990 over half of the state trust lands on the OESF were harvested (WADNR 2016). WADNR's OESF harvest projections in 1988 found that if WADNR continued to harvest at then current levels, the remaining old-growth forests would be gone within 15 years (WADNR 2016). The use of riparian buffers, designed to protect streams from the negative impacts of timber harvest, began in the late 1960s but were often not mandatory throughout the 1970s and 1980s (Bilby and Ward 1991; Richardson et al. 2012). In the OESF, riparian buffers were regulated by 1976 and ranged from 10 to 100 m wide in forests older than 200 years (Cederholm and Reid 1987). Riparian buffer regulations were updated in 1987 and ranged between 8 to 30 m for Type-1 through Type-3[2] streams (see stream type descriptions below).

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[2] Type 1 water - "all waters, within their ordinary high-water mark, inventoried as "shorelines of the state" under Chapter 90.58 RCW and the rules promulgated pursuant to Chapter 90.58 RCW, but not including those waters' associated wetlands as defined in Chapter 90.58 RCW."
Type 2 water - "segments of natural waters that are not classified as Type 1 Water and have a high fish, wildlife, or human use."
Type 3 water - "segments of natural waters that are not classified as Type 1 or 2 Water and have a moderate to slight fish, wildlife, and human use."
Type 4 water - "segments of natural waters which are not classified as Type 1, 2 or 3, and for the purpose of protecting water quality downstream are classified as Type 4 Water upstream until the channel width becomes less than 2 feet in width between the ordinary high-water marks".

Many rural communities in the Pacific Northwest grew rapidly from 1960 into the 1990s when timber production was at its peak and when ecological impacts and mitigation against them were not fully understood. However, even with increasing trends, the timber industry has always been volatile with markets closely following housing starts (Haynes et al. 2017). During the 1980s, timber jobs began declining on the Olympic Peninsula despite an increase in timber production, signaling increasing efficiencies of harvesting and milling equipment (Kirschner 2010). Volatile markets and changes in efficiencies had already started to negatively impact rural communities but one of the largest impacts to the timber industry came with enhanced regulations that led to widespread reductions in available timber in the 1990s. Timber harvests dropped from 8.5 billion board feet (BBF) to less than 0.5 BBF in the first decade of this downward trend in the US National Forests covered by the Northwest Forest Plan (in the range of the Northern Spotted Owl [*Strix occidentalis caurina*]; initiated in 1994); during this period the Olympic National Forest federal workforce dropped from 500 to 216 employees (Bormann et al. 2006). In Jefferson and Clallam counties, two counties that are partially within the boundaries of the OESF, the estimated job loss was 1.2% (163 jobs) and 1.6% (543 jobs), respectively (Eichman et al. 2010).

Unanticipated outcomes of historic forest harvest practices, a better understanding of the mechanisms of interaction between forests and streams, and the realization that forests were being harvested at unsustainable rates led to wide-spread regulation changes in state land management in the late 1990s (Tuchmann et al. 1996; WADNR 1997). On state-managed lands managed by WADNR in western Washington, the biggest changes came in 1997 with the adoption of a state lands Habitat Conservation Plan (HCP; WADNR 1997). The HCP was developed amid fears that all state lands would be shut down due to the declines of multiple species (Northern Spotted Owl, Marbled Murrelet [*Brachyramphus marmoratus*], and salmonids) and their subsequent listings under the Endangered Species Act (Cederholm and Reid 1987; Marshall 1988; Doak 1989; USFWS 1990, 1992; Nehlsen et al. 1991; FEMAT 1993; Reeves et al. 2018). The HCP provided WADNR with incidental take permit for listed species in exchange of habitat conservation commitments for state lands. This provided WADNR with certainty to continue forest harvest operations into the foreseeable future (up to 80 years). Under the HCP, clear-cut harvesting was replaced by variable-retention harvests (VRH). VRH is "a type of regeneration, or stand replacing harvest in which elements of the existing stand, such as down wood, snags, and leave trees, are left for incorporation into the new stand" (WADNR 2016).

The riparian conservation strategy for the OESF, as described in the 1997 HCP (WADNR 1997), is unique and was ahead of its time. It didn't call for mitigating the effects of forest practices by creating stream buffers of fixed width and specific forest conditions. Instead, it aimed to support viable salmonid populations and other riparian dependent species by maintaining "habitat complexity as afforded by natural disturbances". The conservation strategy recognized the temporal and spatial dynamics of the landscapes and its objectives were to maintain and aid the restoration of the natural hydrological regimes, sedimentation regimes, and stream temperature regimes. This was to be achieved through landscape-level planning, use of innovative silviculture, and adaptive management. The latter was envisioned as learning through experimentation and applying the best available science to either provide greater confidence in existing management strategies or improve practices (Minkova and Arnold 2019). The end result, however, was effectively the same as on federal and private lands (fixed-width riparian buffers) likely because there was more certainty in the outcome than more aggressive ideas. Nevertheless, because of the forward ecological thinking, the OESF kept the flexibility to use variable-width buffers and to tailor them according to the watershed conditions and the OESF Forest Land Plan (WADNR 2016) with its implementation procedures represent the current management approach. However, due to its complexity the only current variability in buffer width is due to additions for unstable widths and when there is a high threat of wind-throw.

## Management Impacts on Streams and Salmonids

The relative effect of historic forest practices on aquatic-dependent organisms such as fish populations compared to over-fishing, changes in ocean conditions, artificial barriers, urbanization, and hatcheries has been widely debated (Nehlsen et al. 1991; Hare et al. 1999; Tschaplinski et al. 2000; Kaeriyama et al. 2009). Historic timber harvest practices have been identified as one of the causes of regional salmonid (family Salmonidae) declines (Cederholm and Reid 1987; Hicks et al. 1991; Nehlsen et al. 1991; Burnett et al. 2007). Forest harvest practices found to harm salmonids include direct and indirect effects on instream fish habitats such as: land-use conversions; the amount and distribution of forest harvest; harvesting trees adjacent to or through streams; the placement of roads next to streams; stream road-crossings; splash damming, and wood removal from streams (Hicks et al. 1991; Sheer and Steel 2006; Bilby and Mollot 2008; Warren et al. 2016; Steel et al. 2017). These practices often led to increased stream temperatures and fine sediments, decreased stream shading and instream wood, increased landslide activity, changed macroinvertebrate communities, and blocked fish passage (Bisson et al. 1987; Cederholm and Reid 1987; Hicks et al. 1991; Sheer and Steel 2006; Warren et al. 2016). Negative impacts on streams from historical forest management practices are thought to have reduced salmonid fitness by altering species composition, reducing abundance, altering the food base, diminishing spawning success, or reducing fish access to upstream habitat (Newbold et al. 1980; Bisson et al. 1987; Cederholm and Reid 1987; Sheer and Steel 2006). Negative impacts can last anywhere from a few years to centuries (Murphy and Koski 1989; Beechie et al. 2000; Johnson and Jones 2000; Meleason et al. 2003; Pess et al. 2014).

Although many previous studies have assessed the effects of forest harvest practices on stream reaches embedded in the managed forest matrix, forested stream ecosystems also are naturally heterogeneous such that they can represent a portfolio of states across a region (Penaluna et al. 2018, 2019). Due to this heterogeneity, there are still many uncertainties around the forest-and-stream dynamic and we lack a full understanding of many of the cause-and-effect relationships of multiple stream states or conditions. Further complicating things, past management actions have led to large-scale changes across the landscape where there once was a shifting mosaic forest stages often dominated by older forests to forests now dominated by mid-successional forests with reduced levels of older forests (Donato et al. 2020). Interactions of past management and natural heterogeneity might help explain differences among regional stream and fish responses. This framework is an important context for the T3 Watershed Experiment, as the study is planned for managed forest lands which likely have legacy effects of the "ghost of land-use past" on their stream ecosystems (e.g., Olson et al. 2020.

## Management Uncertainties

The best management practices for forested streams have been evolving since their conception, to integrate goals of both the US Clean Water Act, Endangered Species Act as well as state regulations, and to extend to contemporary ecosystem management goals for both fish and fiber sustainability (Olson et al. 2020). In managed forests, riparian buffers (strips of uncut or partially harvested forests) are left alongside streams for a variety of reasons; however, the details of buffer widths and management actions within buffers vary across regions or jurisdictions depending upon local priorities and regulations. Although all of these regulations were designed to protect riparian forests and streams, they vary by the agency missions and desired balance of resource use and environmental protection. With conflicting ecological and socioeconomic goals, policy makers typically try to balance the latest scientific evidence and lack of undue economic hardship to develop forest practice regulations. Scientific gaps and differing results from studies with limited inference make decisions difficult to support a single stream-riparian mitigation. Federal agencies have typically taken the most ecologically risk-averse approach, while private landowners (regulated through states) have incentives to take on the most ecological risk. Consequently, regulations adopted by the various federal, state, and private landowners have often been inconsistent with each other (Wilhere and Quinn 2018), and there is limited information on their effectiveness. Furthermore, the majority of forest-management-related riparian and stream studies have focused on comparing past forest harvest-riparian practices to current regulations, which contribute little to novel stream-riparian designs.

In this study, we develop and evaluate new riparian prescriptions that have the potential to increase both community and environment wellbeing over current practices. The study is designed to compare four broad management strategies at the watershed scale, with four replications each (16 watersheds). Watershed-scale strategies include upland and riparian prescriptions that can then be compared among themselves at reach and sub-catchment scales:

- Alternative type-1 integration strategy (**Alternative 1**) is designed to enhance ecosystem wellbeing through increased integration and innovation using new environmental science to suggest ways to increase benefits. This strategy includes one riparian prescription (Active Habitat Restoration) with light riparian thinning, gaps, and wood additions to actively restore ecosystem functions.
- Alternative type-2 integration strategy (**Alternative 2**) is designed to enhance ecosystem wellbeing through increased integration seeking inspiration and innovation through social-science-based engagement with stakeholders and elevated concerns for rural livelihoods. Two riparian prescriptions will be tried under this strategy: (1) growing repeated alder rotations under widely thinned conifers; and (2) varying buffer widths based on specific conditions.
- The third strategy looks at the prevailing management in the OESF (**Standard**). The only prescription within this strategy uses a 30-m no-entry riparian buffer[3] (expanded to protect against unstable slopes, windthrow, or wetlands) that is one of the more commonly applied management approaches on the OESF;
- A passive management strategy (**Control**) with a no action prescription that precludes additional harvest activities during the first decade of the study.

# Scientific Background

## Effectiveness of Riparian Buffers

Riparian buffers have been designed to: 1) protect against the impacts of active timber harvest operations; and 2) reverse some of the negative impacts from past management activities. Determining the appropriate riparian buffer size is often viewed as a trade-off between economic and ecological benefits (Lundstrom et al. 2018) and the decision differs among regulators because of local regulatory differences, which are often determined through societal values expressed through numerous legal frameworks (Wilhere and Quin 2018). Sweeney and

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[3] The OESF implementation procedure (Appendix 1) allows limited riparian entry in the form of thinning to relative density of 35 or several acres regeneration harvest in some basins and those entries are expected outside the study watersheds. However, for the purpose of this experiment we narrowed the practice to no riparian entry because riparian entries have been and will be implemented in limited number of OESF watersheds, the harvest type and acreage vary across watersheds, and it is not possible to capture this variability through the 4 replicates of the Standard OESF management strategy. This is discussed in detail later in the study plan.

Newbold (2014) found that riparian buffers greater than 30 m were needed to protect streams from nitrogen inputs, sediment, changes in channel configurations, temperature increases, changes in wood recruitment, and changes to macroinvertebrate and fish communities. Davies and Nelson (1994) found that the impacts of forest harvest on stream habitat, invertebrate species composition, and fish abundance were only significant when riparian buffer widths were less than 30 m. In addition, Kiffney et al. (2003) found that riparian buffer widths of 30 m or more were needed to limit biotic and abiotic changes. Other studies, however, found that 15-m riparian buffers largely maintained the stream microclimate within an upland thinning context (Anderson et al. 2007) and identified headwater-dependent aquatic species that may warrant consideration during forest management, for their habitat maintenance and landscape connectivity considerations (Olson et al. 2007; Olson and Burnett 2009, 2013; Olson 2012; Olson et al. 2014; Olson and Burton 2014; Olson et al. 2020).

Although fixed-width riparian buffers are widely employed and accepted, it is unclear whether buffer configurations more focused on-site conditions could be enacted to achieve similar or enhanced environmental conditions and allow for more timber harvesting. Cassie (2006) found that the most effective riparian buffer width depends on the type of forest and stream size. Others have suggested that riparian buffer zones could be more effective by using site-specific designs (Tiwari et al. 2016; Lundstrom et al. 2018). As such, it is likely that, with an advanced understanding of timber harvest impacts and riparian functions, site-specific or variable-width riparian buffers could be employed to provide similar if not more effective protections against the potential negative impacts from timber harvests (Olson et al. 2020).

Another question is whether stream habitat with unmanaged riparian buffers, is returning to a pre-harvest range of conditions. To achieve this will require assessment of riparian forests that are similar to those present prior to management disturbances, since streams are heavily influenced by their surrounding forests (Bisson et al. 2009; Benda et al. 2016; Warren et al. 2016). This may take time as coastal northwestern forests are disturbance driven, with historical evidence suggesting that large disturbances occur every 200 to 500 years (Donato et al. 2020). However, it is possible that these forests may not be able to return to former ranges given the extent of past management and that climate change has potential to alter both species suitability and disturbance regimes. Slow rates of natural forest development and infrequent large-scale disturbances are likely causes for the duration of some forest harvest related impacts. Tschaplinski and Pike (2017) found that some of the effects of forest harvest (the continuing movement of bedload and lack of instream wood) continued or were delayed for several decades. Martens et al. (2019) identified reduced instream wood, increased canopy shading, and similar stream temperatures in second-growth forests 18 years after regulatory changes in the OESF. Meleason et al. (2003) found that the maximum level of instream wood using a 30-m riparian buffer would occur when forests were 500 years old. Others have also determined that the effects of past harvest could last 100 years or more (Murphy and Koski 1989; Connolly and Hall 1999; Kaylor et al. 2017). Given this time for recovery, riparian or stream manipulations, such as wood additions or thinning to speed up forest development (towards riparian forests with a similar amount of forest developmental stages that existed prior to wide-spread forest harvesting), may provide an opportunity for mitigating past forest management influences on salmonids over a shorter timeline (Martens et al. 2020).

## Instream Wood

Instream wood is important for creating and maintaining salmonid stream habitat. Instream wood directs flow, influences stream velocity, supports a food web, and scours stream beds, helping to create a diversity of stream conditions important for salmonids (Montgomery et al. 2003; Coe et al. 2009). Instream wood also allows for sediment storage and movement that can maintain spawning areas (Bilby and Ward 1989) and acts as cover to protect stream inhabitants against predation (Allouche 2002). In the forests of the Pacific Northwest, instream wood has been diminished as a result of management activities such as splash damming, instream wood removal, and removal or changes in streamside vegetation (Bisson et al. 1987; Bilby and Ward 1991). As a result, the complexity of salmonid habitat has been greatly reduced. One of the functions of riparian buffers is to allow for continuous instream wood recruitment (Sweeney and Newbold 2014). In riparian forests, most instream wood is recruited from trees relatively close to streams. Benda and Biglow (2014) found that 90% of the wood volume is recruited from within 10 to 35 m from a streams bankfull width (10 m without landslides), while Burton et al. (2016) found that 82 to 85% of instream wood volume came from within 15 m of the stream. Wood accumulation is also affected by riparian forest developmental stage, stream morphology, and the amount of existing wood in a stream. Wood accumulations follow a U-shaped pattern over the course of forest succession with the highest amounts of wood recruitment following a stand-replacing disturbance and in the old growth stage, and declining amounts of wood through the early to middle stages of development (Spies et al. 1988; Martens et al. 2020). The type of wood (hardwood or conifer), position within the channel, presence of a root wad, and geometry of the wood can affect retention in streams (Murphy and Koski 1989; Bilby et al. 1999). Wood retention is likely to be highest when it consists of larger diameter pieces of coniferous wood (Naiman et al. 2002; Benda et al 2003) that are most commonly supplied from forests in the later stages of forest development. In addition, streams create a positive feedback loop where increased wood in streams allows for increased wood retention. Martin and Benda (2001) found that pieces of wood in small, jam-rich streams travel on average 200 m, while pieces in larger channels with few jams moved around 2,500 m. As a result, streams with reduced instream wood take longer to recover from wood-depleting management activities without some form of active restoration.

Active restoration has been used both to accelerate riparian forest development (through thinning) and to add wood directly into streams. Active wood placement has been controversial with some studies casting doubt on the effectiveness of wood addition projects (Stewart et al. 2009; Doyle and Shields 2012). However, Roni et al. (2015) concluded that streams with active wood placement have generally produced positive results for salmonids, but also stated the need for more studies that assessed the long-term watershed response to wood additions. Both Benda et al. (2016) and Reeves et al. (2018) supported the idea of adding wood (tree tipping) in riparian areas. Thinning riparian forests can increase growth of residual trees and hence eventually increase the size of wood delivered to streams (Beechie et al. 2000). However, it is possible that total delivery of wood may decline for a period of time after thinning (Benda et al. 2016). Most thinnings in riparian zones focus on removing smaller trees so larger ones can grow faster and can reduce density-driven tree mortality. Thinning in second-growth stands remove small and often decayed trees that might have fallen into the stream but eventually will shorten the time for large-tree contributions. Alternatively, Pollock and Beechie (2014) warned that riparian thinning may favor one species over another and suggested the use of passive restoration. This study highlights some of the potential risks of active restoration and highlights the need for more studies with riparian thinnings. Thinning prescriptions could be written to use cable yarding equipment to bring in larger logs harvested elsewhere to be placed in the stream as an interim measure.

## Stream Sediment

Stream sediment can be altered through forest harvest practices both directly and indirectly (Cederholm and Reid 1987; Lakel et al. 2010). Indirect sources of sediments can come from landslides or bank erosion created as the result of forest harvest operations and road use, maintenance, and construction. Increases in fine sediments can infiltrate salmonid spawning redds (nests) and reduce spawning success (Cederholm and Reid 1987; Kemp et al. 2011). In Carnation Creek on Canada’s Vancouver Island, the impacts of landslides associated with historical forest harvests have been blamed for reduced juvenile salmonid habitat after a 20-year lag, creating a wider, less physically complex stream (Tschaplinski and Pike 2017). Reductions in instream wood (often resulting from forest harvest practices) can reduce the storage of spawning gravels and fine sediments (Bisson et al. 1987). Changes in sediment have been found to alter macroinvertebrate communities and to ultimately impact salmonids (Bisson et al 1987; Kemp et al. 2011). Suttle et al. (2004) found that changes in macroinvertebrate communities, resulting from increased fine sediments, decreased growth and survival of juvenile salmonids. Salmonids also use large substrate for cover and increases in smaller sediments can fill spaces around larger substrates, thereby reducing fish cover and capacity (Bisson et al. 1987; Cederholm and Reid 1987). Although modern regulations around road building and forest harvest have likely reduced sediment delivery to streams, sediment changes can impact salmon and remain a focus for assessing both potential current management impacts and explaining current conditions.

The use of riparian buffers maintains existing root structures which can help stabilize banks and filter or trap increases in sediment associated with roads or forest harvest operations. Lakell et al. (2010) found that 15.2-m wide riparian buffers could be used to mitigate the impact of fine sediments on streams. However, landslides associated with forest management (road and harvest) can be a source of sediment from greater distances from steams (Gomi et al. 2005). This suggests that smaller riparian buffers (<30 m) may provide streams adequate protection from fine sediment inputs as long as measures are also taken to protect against landslides.

## Riparian Vegetation and Stream Temperature

Riparian forest canopies regulate the amount and timing of solar radiation to the ground or stream. Light can have both beneficial and negative effects. Increased amounts of light can increase both stream algae and insect production (Kiffney et al. 2004) and water temperatures (Johnson and Jones 2000; Moore et al. 2005). Salmonids have a preferred temperature range and can be harmed if temperatures fall below (Tschaplinski 2000) or above (Wedemeyer 1973; Lawson et al. 2004; Pisano 2012) this range. For example, depending on food availability, optimum rearing temperature of juvenile Coho salmon (*Oncorhynchus kisutch*) is between 8 and 15.6°C (Stenhouse et al. 2012), while cutthroat trout (*O. clarkii*) is between 10 and 14°C (Sauter et al. 2001). Some studies that assessed the impacts of clear-cut forest harvests found that both salmonid abundance and size increase after harvest for up to 30 years (Johnson et al. 1986; Bilby and Bisson 1987; Tschaplinski and Pike 2017). Initial positive effects of forest harvest were likely due to increased stream invertebrate productivity or stream temperatures becoming more bioenergetically favorable for salmonids, or both. If existing temperatures are within a species suitability range, it is likely that increased invertebrate productivity will lead to positive impacts on fish populations. However, if current stream temperatures are higher than a species' suitable temperature range, further temperature increases could be harmful depending on food availability (Lusardi et al. 2020). In the Alsea watershed study, Oregon, clearcutting of 80% of Needlebranch creek watershed without buffers increased maximum water maximum temperature by 14°C (Hall et al. 2004). This study was repeated from 2006-2012 using contemporary logging practices including a 15-m riparian forest buffer, with researchers finding no evidence a of stream temperature change after forest harvest (Bladon et al. 2016). In another study, Feller (1981) found that a 66% watershed harvest without buffers resulted in a 5°C increase in stream temperature. Such increases could raise stream temperatures above the suitable ranges for salmonids. Overall, the temperature response will likely vary based on the type of riparian treatment, physical landscape, and existing thermal regime and riparian conditions. Furthermore, temperature increases at individual logged sites may not persist downstream. A model by Davis et al. (2015) suggests that stream temperatures

300-m downstream of a harvested site would be 56% of the temperature increase observed within the reach. More generally, the effects of forest harvest on water temperature will be dependent on the physical landscape, current riparian conditions and riparian management.

Forest canopies and stream temperatures can recover relatively quickly (~15 years or less) after canopy removal (either from natural disturbances or historical forest practices) but recovery often results in dense, uniform vegetation that can block most of the light from smaller streams for period of time (Hicks et al. 1991; Johnson and Jones 2000; Kiffney et al. 2003;). Forest canopy is influenced through forest development with denser canopies typical in the early to middle stages of forest development and increased amounts of light (from gaps created through small disturbances or tree mortality) in the old-growth stage (Franklin et al. 2002; Kiffney et al. 2004; Warren et al. 2016; Martens et al. 2020). The old-growth stage is typically reached after 200 years or more of development (Franklin et al. 2002). However, Reeves et al. (1995) found that fish populations varied between the development stages of riparian forests with the oldest forests not necessarily the most productive streams. It is possible that certain forest developmental stages may favor different life stages of salmonids (Reeves et al 2018). This study highlights the need to reach a diversity of forest developmental stages similar to what existed prior to the large-scale riparian forest harvests that existed prior to modern forestry regulations that created an overabundance of riparian forests in the middle stages of development. Pacific Northwest forests currently have limited amounts of older forests (30%) compared to historic conditions (median 70%; Donato et al. 2020). After more older riparian forests have developed, natural disturbances could once again control the amount of riparian forests that are within each stage of forest development.

During the period of maximum forest shading in the mid-successional stage of stand development (the most abundant stage), Kaylor and Warren (2018) found reductions in salmonid biomass. Wilzbach et al. (2005) found that an increase in light in the summer, by reducing hardwood along California coastal forest streams, was more beneficial to the biota than increased nutrients through salmonid carcass additions. Kaylor et al. (2017) found lower summer shade in a second-growth riparian canopy consisting of mostly alder than in old-growth along a stream in the central Cascades of Oregon. Hanley et al. (2014) found soil-surface under upland forest dominated by alder in SE Alaska had 19% of open sunlight while conifer stands had only 1.7%. Some of the biggest differences between hardwood and conifer canopy shading occur in the fall to winter when hardwood trees lose their foliage. Unfortunately, little information exists on the seasonal impacts of hardwood and conifer dominated riparian canopies on stream biota. Although there is substantial documentation that canopy cover is high in the mid to young stages of forest development (Kiffney et al. 2003; Kiffney et al. 2004; Warren et al. 2016; Kaylor et al. 2017), there is limited information on whether vegetation type is more or less favorable to stream biota. It is also unclear if small changes in canopy cover related to vegetation type during the early to mid-stages of forest development would be biologically significant. Regardless of the vegetation type, salmonid production is likely to increase as a result of reduced canopy shading during the early to middle stages of forest development as long as water temperatures remain within a bioenergetically favorable range and sediment levels remain low.

Riparian thinning or gap creation could be used to increase available light in streams, with gaps typically creating more light than thinning (Anderson and Meleason 2009; Swartz et al. 2020; Roon et al. 2021). The use of gaps would also be more reflective of old growth conditions. However, it is relatively unknown at which point biological gains from canopy openness would be negated through increases in stream temperatures and sediment.

## The Role of Hardwood Trees and Shrubs

Deciduous shrubs and trees can dominate or co-dominate natural succession for 10 to 50 years after natural disturbances and harvest especially following some degree of soil disturbance—so are considered an important early-seral constituent of coastal Pacific Northwest forests (Swanson et al. 2014; Bormann et al. 2015). The time and space they dominate often has been considerably truncated by dense conifer planting and active vegetation control, particularly on industry lands (Swanson et al. 2014). Red alder is a well distributed, $N_2$-fixing hardwood tree, often found in previously managed or naturally disturbed riparian areas (Van Pelt et al. 2006). In disturbed coastal forests without alder control, Sitka spruce (*Picea Sitchensis* Bong. Carriere), western red cedar (*Thuja Plicata* Don ex D. Don), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) often develop in the understory and eventually overtop alder. A common condition in the late 1800s in coastal Oregon (Bormann et al. 2015), and today in a few places in the lower Clearwater River watershed, is a “scattering” of large conifers standing above a sea of alder and other hardwoods, suggestive of a dominant path of old-growth development or survivors from recent disturbances. This is supported by evidence that many of the largest, oldest conifers have much wider growth rings in the first century than modern conifers trees (Poage and Tappeiner 2002).

Hardwood removal was proposed to accelerate development of older conifer forests with the goal of shortening the natural timeline for creating canopy diversity and recruitment of instream wood (MacCracken 2002). However, ecological benefits may be derived through encouraging hardwoods in riparian areas by increasing nutrients, leaf litter, mixed conifer growth, and terrestrial macroinvertebrates inputs (e.g., Volk et al. 2010), as well as increasing winter light transmission relative to evergreen conifer stands. Alder plays a number of ecological roles, in addition to increasing nitrogen, soil organic matter, and weathering release of other nutrients (Yamanaka et al. 2003). Alder leaf litter is rich in nitrogen (often > 2%) and other nutrients compared to Douglas-fir litter (about 0.6%; Thomas and Prescott 2000). Having one of the highest recorded rates of symbiotic $N_2$ fixation, alder can increase the growth of associated conifers trees (e.g., Binkley 1983; Bormann et al. 1994; Miller et al. 2017). Many hardwood shrubs and trees have much deeper rooting than conifers and play roles of enhancing soil stability on unstable slopes and calcium uptake and redistribution (maples are known for this; Dijkstra and Smits 2002).

A number of studies have linked increased invertebrates to harvesting and disturbance, especially when hardwood shrubs and trees are increased (e.g., Kiffney et al. 2000; Clarke et al. 2008; Wipfli and Baxter 2010). In one study on the Oregon Coast, watersheds with mixed hardwood/conifer riparian vegetation received nearly 30% greater influx of terrestrial invertebrate biomass than streams with conifer-dominated riparian areas (Romero et al. 2005). Piccolo and Wipfli (2002) noted that maintaining an alder component in previously harvested stands may offset other potentially negative effects of timber harvest (e.g., sedimentation and loss of instream wood) by increasing invertebrate inputs. In addition, insects that feed on and pollinate flowering plants such as salmonberry (*Rubus spectabilis* Pursh) can contribute to the forest food web (Pers. Comm. Steve Wondzell). Alternatively, maintaining alder may keep conditions in the canopy closure stage of forest development (Martens et al. 2020) indefinitely by using continuous alder rotations, sustaining periods of decreased productivity relative to open areas and reducing (at least temporarily) instream wood recruitment (Benda et al. 2016; Warren et al. 2016).

## Large-Scale Studies and Long-Term Monitoring

In the Pacific Northwest, the most prominent long-term study on historic forest harvesting on streams and fish is on Carnation Creek on the southern portion of Canada’s Vancouver Island, which has biogeoclimatic conditions similar to the OESF. Pretreatment monitoring began in 1970. Between 1976 through 1981, 41% of the watershed was intensively harvested using forest industry practices of that period. The harvest included complete riparian forest removal but excluded roads near or through streams. As monitoring continued for many years, different conclusions emerged and some changed. The initial sedimentation of the spawning gravels led to the rapid and sustained decline in chum salmon (Hartman and Scrivener 1990). Coho salmon by various measures both increased and decreased through time and were plausibly linked to some management effects (both ways) as well as other factors, particularly shifts in ocean conditions. Particularly interesting was the continual reductions in freshwater habitat. Details of the stream and Coho responses (e.g., stream sediment movement, instream wood, temperature, emergence, winter survival, and residency) have been complex (Holtby and Scrivener 1989; Hartman and Scrivener 1990; Tschaplinski et al. 2004; Tschaplinski and Pike 2017). Although management at Carnation Creek was considerably more aggressive than what is proposed in the current T3 Watershed Experiment, this long-term record helped our development of more quantitative expectations and testable hypotheses.

Another important long-term study of forest management occurred in coastal Oregon's Alsea watershed. This study began in 1959 and has consisted of two phases: the first phase 1966 to 1981 compared the effects of harvesting, with, and without riparian buffers, and not harvesting of previously unharvested stands. The second phase in 2006 to 2017 assessed Oregon's current forest harvest practices rules in previously harvested stands (<40 years prior). The original study examined three watersheds with complete harvest on 0, 25, and 80% of the watershed that were 200, 70, and 300 ha in size (respectively). Results indicated negative impacts of fine sediments on salmonid spawning habitat and changes in salmonid-rearing habitat. In the clear-cut section maximum stream temperatures increased by 14°C during the first post-harvest year. Juvenile cutthroat trout abundance was initially reduced by 40% (1966 to 1973). Over a decade later, age-0 cutthroat trout appeared to recover, but the abundance of age-1 or older age classes were reduced to 20% of pre-logging levels. Juvenile Coho experienced a 50% reduction in survival; however, smolt production was not significantly reduced through 1987 (Hall et al. 2004). In the second phase of the study, using a 15-m fixed-width buffer, the study found no change in stream temperatures or streambed sediments, but persistent reductions in summer low flows (Bladon et al. 2016; Hatten et al. 2018; Segura et al. 2020). No significant effects were observed on coastal cutthroat trout or Coho using Oregon's current forest harvesting best management practices and increases in late-summer density and total biomass of age-1+ coastal cutthroat trout were observed (Bateman et al. 2018).

Similar to the OESF, the University of British Columbia has operated the Malcolm Knapp Research Forest as a 5,200-ha working forest since 1949. This forest has hosted many long-term studies on forest management. One of these studies included a 24-year study (beginning in 1973) assessing the impacts of clear-cutting through streams with and without the removal of instream wood and logging debris. Throughout the study stream temperature, instream habitat, and cutthroat trout density in the stream without wood removal was similar to a reference stream while the stream with wood removal showed increased stream temperatures and decreases in fish densities (Young et al. 1999). Another study within the forest assessed the effectiveness of no, 10-m, and 30-m riparian buffers. This study found that small streams are sensitive to riparian canopy removal and riparian buffers (10 and 30 m) can reduce the magnitude of the response, however there was a wide variation in results between streams. Due to this high amount of variability between sites, they noted the importance of collecting pre-treatment data (Richardson et al. 2010).

## Management Uncertainties and Research Needs

Effects of forest harvesting practices on stream resources vary by site conditions (Richardson and Béraud 2014). This is likely due to differences in stream size, stream direction, stream gradient, channel type, elevation, and other geophysical characteristics as well as localized species adaptations (Reeves et al. 2018). Salmonids evolve to favor their local environments (Fraser et al. 2011). It is likely that these adaptions may alter the way a fish responds to either anthropogenic or natural disturbances. Some disturbances to stream and fish are more likely to occur than others based on the surrounding environment. For example, in the OESF, where most streams flow from the Olympic Mountains, landslides have been associated with past forest harvest operations (Cederholm and Reid 1987). Obviously, the threat of forest harvest related landslides would not be nearly as high in wide-valley streams with fewer unstable slopes than narrow-valley streams with more unstable banks. However, within streams, sediment is more likely to be problematic in lower gradient sections of streams where sediment is more likely to accumulate. In warmer locations such as eastern Washington and Northern California, stream temperature changes resulting from forest harvest practices are more likely to be harmful for salmonids than in coastal areas with milder climates.

Another large difference within Pacific Northwest streams is peak-flow timing. Streams driven by snow accumulation and subsequent melt experience peak flows during spring while streams driven by rain experience their peak flows during storms in the late fall and winter. Both physical conditions and local adaptations have potential to change the degree of impact on stream habitat and salmonids resulting from forest harvest practices. In areas such as the Pacific Northwest, an area with large variations in stream size and geophysical characteristics, there is a risk that localized potential impacts from forest harvest practices may be assumed to occur everywhere. Further complicating matters is the unknown impacts of climate change and separating the impacts of climate change from forest harvest practices. These complications highlight the need for long-term replicated studies with controls.

Second-growth riparian forests (often in the mid-successional stages of development), that currently dominate many riparian areas across the Pacific Northwest, need more time to start delivering riparian functions such as recruitment of large pieces of instream wood (Bilby and Ward 1991; Benda et al. 2016). Two strategies (passive and active) exist for restoring or improving ecological processes of aquatic ecosystems. Passive restoration accommodates natural succession and disturbance to alleviate impacts of past production forestry (Martens et al. 2019). Active restoration includes riparian silviculture to promote the development of complex forest structure, placement of large wood in streams, dam removal, invasive species control and tree or vegetation plantings to increase productivity and habitat complexity in riparian forests and streams (Kauffman et. al 1997). Within the Pacific Northwest, passive restoration has been the most common form of restoration (Reeves et al. 2018). Passive restoration, although cost-efficient and low risk of creating conditions outside of the natural range, may take too long to allow for species recovery. Overall, active restoration is not likely to be used everywhere, due to the costs and the amount of degraded area (an over-abundance of previously harvested mid-successional riparian forests), however when and where possible it may benefit salmon recovery. Temporal dynamics of ecosystems are understood only by long-term observation and very few long-term studies exist. When the aquatic conservation strategy for federal lands was first developed as part of the Northwest Forest Land Plan (USDA and USDI 1994), (1) quite a bit was known about general habitat requirements, but not about the spatial and temporal distribution of habitat elements through even a single species' life cycle; and (2) the lack of long-term studies using multiple watersheds limited the ability to assess the cause and effect relationships needed to change forest management practices (Sedell et al. 1994). In the 10-year interpretive report of the Northwest Forest Plan, Bormann et al. (2006) concluded: "A network of more controlled management experiments, with aggressive treatments and taking perhaps 20 years, is likely needed to substantially improve our understanding to better manage these resources." In addition, the 20-year interpretive report for the Northwest Forest Plan (Reeves et al. 2018) expressed a need for: "a better understanding of the highly dynamic nature of aquatic-riparian systems; improvement of the metrics used to evaluate systems; managing multiple aspects together rather than individually; and production of aquatic biota responding to upland vegetation and restoration treatments."

To this end, we have identified five areas where the riparian component of the T3 Watershed Experiment could provide information to reduce the knowledge gaps described above:

- Site specificity – How the effects of forest practices are expressed in coastal spruce-hemlock forests.
- Temporal dynamics – Identify differences between short (e.g. 2-4 years) and long-term e.g., 5 or more years) responses to harvest and post-harvest activities.
- Spatial dynamics – Assessing effects at the sub-catchment and reach scales and comparing them to downstream reaches and watershed pour points to examine cumulative contributions.
- Ecological processes – Examining how biotic (e.g., live plants, invertebrates, and fish) and abiotic factors (e.g., sediment, dead wood, and temperature) interact to affect watershed functions. For example, live plants and trees help to stabilize stream banks by holding/trapping sediment and directing steam flows.
- Forest management alternatives – comparing the effects of passive to a variety of active management activities on stream habitat and selected biota (e.g., vegetation, invertebrates and salmonids).

The knowledge expected to be gained from other components of the T3 Watershed Experiment, such as upland silviculture and social science, are described in the Overview Plan (provided in the review package) and the respective study plans (in development).

## T3 Watershed Experiment

The T3 Watershed Experiment is designed to assess the environmental and economic impacts of OESF current- and two alternative-management strategies against an unharvested control at a landscape scale (Table 1). Management, primarily timber harvest, will apply to portions of both upland and riparian of the watersheds. Two strategies (Alternative 1 and Alternative 2) will assess alternative management strategies for future decision makers to consider. They include innovative upland and riparian entry in limited places to explore whether environment and community benefits can be raised together. The two remaining strategies (Standard and Control) rely on passive restoration in protected riparian areas (the Standard strategy uses a 30-m buffer, expanded for unstable slopes, wetlands, and potential windthrow).

**Table 1. Management strategies being compared in the T3 Watershed Experiment**

| Title | Core concept |
|---|---|
| **Alternative 1** | **Alternative type-1 integration.** Seeks greater integration of trust income and environmental and other benefits at the stand and reach scale by applying the latest environmental-science developments. It seeks higher environment and community benefit including increased early- and late-seral biodiversity, some riparian harvest, and higher fish production. |
| **Alternative 2** | **Alternative type-2 integration**. Seeks greater integration by applying perspectives from diverse collaborators, along with social and environmental science developments. This is intended to better connect people to management of trustlands. It seeks higher environment and community benefit including an increase in managed landbase, and higher alder, cedar, elk, and fish production. |
| **Standard** | **Standard OESF management.** Represents current best practice in the OESF at the stand scale outside of the other study watersheds by applying the OESF Forest Land Plan (DNR 2016a); follow management pathways for each Landscape Planning Unit. |
| **Control** | **No-action control.** Establishes background changes, but can be construed to represent people interested in maximizing carbon sequestration (assuming DNR could participate in C markets—which it currently cannot). |

The study will apply various stand and reach-level harvest prescriptions (Table 2) with a goal of implementing prescriptions in 13% of the upland portion of each watershed's area (actual range between 7% to 16%). The targeted (13%) proportion of the watershed harvested was determined by approximating the decadal sustainable harvest level for the OESF (WADNR 2019). Without an outlier watershed (7% harvest), the range would be between 11% to 16%. In the outlier watershed, a decision was made to reduce the amount of harvest acres because it had recently been thinned and harvesting this area would be unprofitable and inconsistent with management practices on state lands. The percent of experimentally treated riparian areas within a prescription will vary from 0% (in Control and Standard) up to 100% (in the Alternative 2 strategy alder rotations). The allocation of upland treated areas is primarily determined by economic viability of timber sales controlled by current stand ages, landscape features such as unstable slopes, road costs, and other factors. The amount and allocation of treated riparian areas is largely constrained by having upland management that provides economical access.

**Table 2. Experimental stand-scale upland and riparian prescription-treatments nested within the four management-strategy, watershed-scale treatments on the T3 Management Experiment**

| Management Strategy | Stand/reach objectives | Upland prescriptions | Riparian prescriptions |
|---|---|---|---|
| **Alternative 1** | • Continue revenue production for beneficiaries;<br>• Increase both early and late succession habitat and extent; and<br>• Improve ecosystem processes in uplands and riparian buffers | • A complex early-seral post VRH approach to allow natural regeneration and increase habitat structures then growing conifers after PCT; and<br>• Accelerated thinning relative to traditional VDT, risking some windthrow to speed diverse habitat development | • Riparian thinning, gap creation, and in-stream wood additions |
| **Alternative 2** | • Continue revenue production for beneficiaries;<br>• Increase elk, fish, alder, and cedar production; and<br>• Listen more to stakeholders for objectives and innovations | • Post-VRH management with variable-density plantings to apply ethnoforestry (elk forage and other early-seral species) then growing conifers at a crop spacing after age 20<br>• Post-VRH management to grow variable cedar and alder mixtures over longer or mixed rotations[1] | • Variable-width stream buffers; and<br>• Very wide conifer thinning in buffers with repeated short-rotation alder |
| **Standard** | • Continue revenue production for beneficiaries;<br>• Meet requirements of the FLP and the HCP. | • OESF management as anticipated for the next decade with VRH, planting, and tending to produce repeated conifer crops[2] | • A fixed 30-m buffer on type 3 stream sections, increased to account for unstable slopes, wind throw or wetlands* |
| **Control** | • Delay revenue production for beneficiaries for one decade;<br>• Track background changes; and<br>• Sequester C as much as possible. | • Allow natural processes to unfold including C sequestration | • Allow natural processes to unfold including C sequestration |

* For the purposes of this experiment, the Standard strategy (OESF Management) is defined as a treatment without riparian entry. In reality, this is a narrow interpretation of what is currently permitted, and sometimes practiced, in the OESF. Standard OESF riparian implementation procedure allows limited riparian entry in the form of thinning to relative density of 35 or several acres regeneration harvest in some basins (Appendix 1). Those entries are expected outside the study watersheds. We excluded riparian entry because riparian entries have been and may be implemented in limited number of OESF watersheds at least in near-term, the riparian harvest type and acreage vary across watersheds, and it is not possible to capture this variability

through the four replicates of the Standard strategy. We will maintain this disclaimer in the analyses for this experiment to avoid misrepresenting the OESF current practices. If OESF riparian management becomes more widespread than expected, results will be interpreted accordingly (whatever prescription fits actual activity will be compared to those that did not).

## Riparian Prescriptions

Five riparian prescriptions will be evaluated within the four management strategies. One in the Alternative 1, Standard, and Control strategies and two in the Alternative 2 strategy (Figure 2). In all strategies (except the Control) the riparian prescriptions (with manipulations or no-entry) will be implemented directly below upland variable-retention harvests (VRH; which is defined as type of stand-replacement harvest in which elements of the existing stand, such as down wood, snags, and a minimum of eight leave trees per acre, are left for incorporation into the new stand). This proximity allows access for economical harvesting in riparian buffers where done. Having the same type of upland harvest (in this case VRH) reduces confounding in the interpretation of the effects of different riparian prescriptions. Untreated riparian buffers in the Standard strategy will be monitored where they are adjacent to harvested upland areas to correspond to how riparian buffers will be monitored in the Alternative 1 and Alternative 2 strategy watersheds

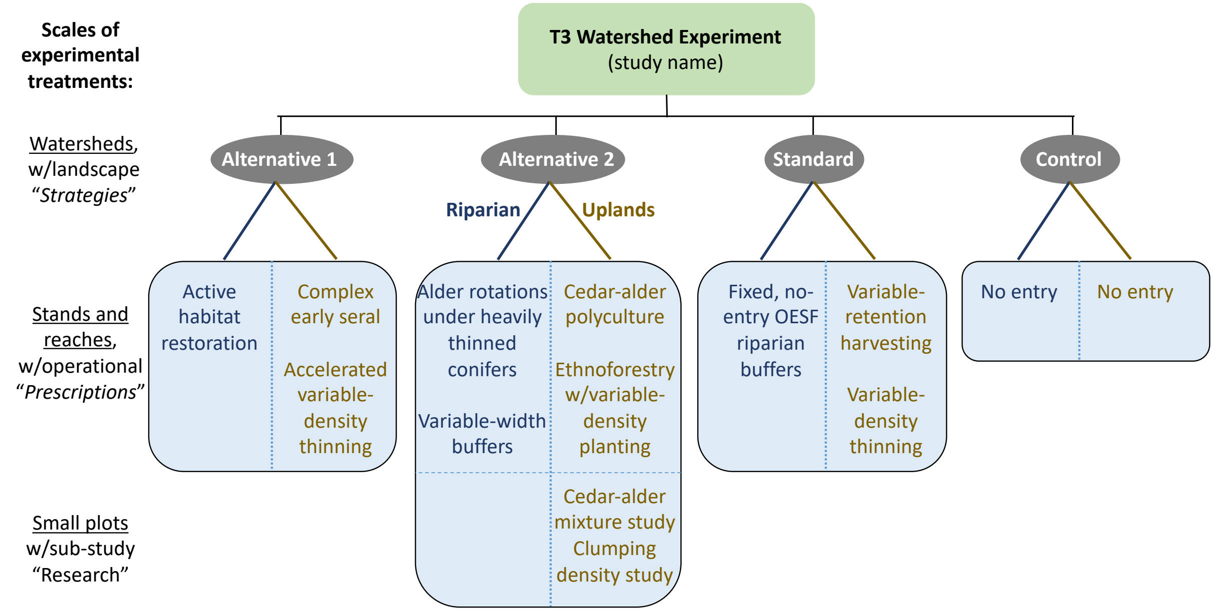

**Figure 2. The T3 watershed experiment design with different scales of experimental treatments. Note that small-plot treatments are nested in prescription treatments which in turn comprise landscape-management strategy treatments across watersheds.**

## Alternative 1 Prescription

The active habitat restoration prescription in the four watersheds representing the Alternative 1 strategy is designed to address existing habitat concerns for aquatic species, primarily salmon, and to accelerate the successional development of mid-successional forests (Figure 3). Recent analyses on the OESF have identified reduced levels of instream wood and high levels of canopy shading throughout the OESF (Martens et al. 2019). It has also been hypothesized that these conditions are not likely to improve until riparian trees grow and recruit as down wood into streams and uniform canopies diversify creating gaps that allow light into streams, which typically occur after forests are older than 200 years (Martens 2019). Given this long timeline for recovery under existing regulations, greater integration of revenue and ecological values seems possible by including riparian manipulations, designed primarily to improve species' habitat conditions, that could also increase revenue or at a minimum pay for the improvements. Treatments will only be applied to riparian forests between 30-100 years (100 years is the beginning age of mature forest in Martens et al. 2020) in age. Forest stands between 0-30 years or older than 100 years in age will be left untreated to continue developing through a 30-m no-harvest riparian buffer. All entered riparian buffers in Alternative 1 will be adjacent to an upland VRH as described above.

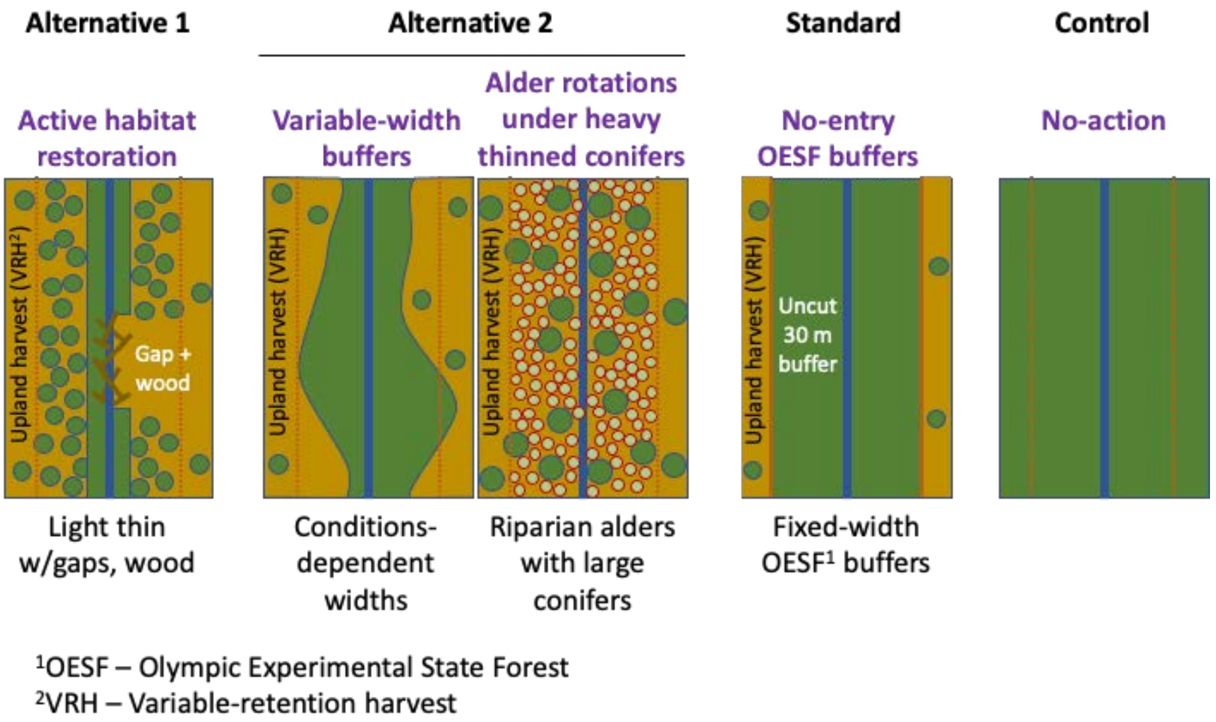

**Figure 3. The five operational-scale riparian-management prescriptions to be compared under the four watershed strategies in the T3 watershed experiment.**

Activities in the habitat restoration prescription include light thinning in the outer 22 m of the 30 m riparian buffer, 30 m x 30 m (0.22-acre) gaps that extend to the stream, and direct additions of conifer trees into the streams (Figure 3). Thinning and gaps are expected to speed growth of conifers, add sunlight to increase stream productivity, create more canopy diversity, and deliver larger pieces of wood to streams over time. Thinning will not happen within 8 m of the floodplain (to lessen the impact of increased sunlight over the reach and prevent or reduce stream temperature increases) but will take place in the outer edge of the buffer. After consultation with Oregon State University and USGS scientists, we decided to add one 30-m-long gap per every 100 m of stream (the gap will be placed toward the upper end of each 100 m segment). The gap will extend away from the stream for 30 m (the width of the riparian buffer), to the VRH located upslope. Enough trees to create multiple wood jams (2-3) will be taken from the gap and will either be cut towards or pushed into the stream (if operationally feasible).

Some economic gains are expected to come from trees harvested during thinning and gaps. The latter will be designed for both operational ease and revenue production. In the active habitat restoration prescription, about 25% of the buffer adjacent to a VRH unit (which otherwise will be uncut in Standard and Control) would have a gap and more than 50% would be thinned. The remaining 25% (near the stream) would be left unharvested. The exact amount of volume harvested through this strategy will be determined by conditions on the ground.

## Alternative 2 Prescriptions

Riparian activities under this strategy will be designed to meet broad environmental goals of the OESF Forest Land Plan (WADNR 2016), but to do so in ways that also clearly increase community wellbeing and possibly address other environment wellbeing concerns (e.g., stream productivity and instream wood). Two different riparian prescriptions will take place within each of the four Alternative 2 strategy watersheds: (1) grow rotations of red alder underneath heavily thinned conifers; and (2) apply variable-width riparian buffers (as envisioned in the 1997 state lands HCP, but rarely tried). These two prescriptions will be spatially separated within each watershed so that they can be evaluated independently at sub-watershed scales with the alder underneath conifer prescription evaluated on a sub-catchment downstream of the variable-width buffer treatment.

The alder rotation under wide thinning prescription[4] will grow repeated rotations of red alder between widely spaced large conifers (<74 trees ha$^{-1}$; <30 tpa). Red alder is valued for its high market value and fast growth rates and therefore is expected to produce revenue and value-added manufacturing benefits, helping to maintain critical hardwood mill infrastructure on the

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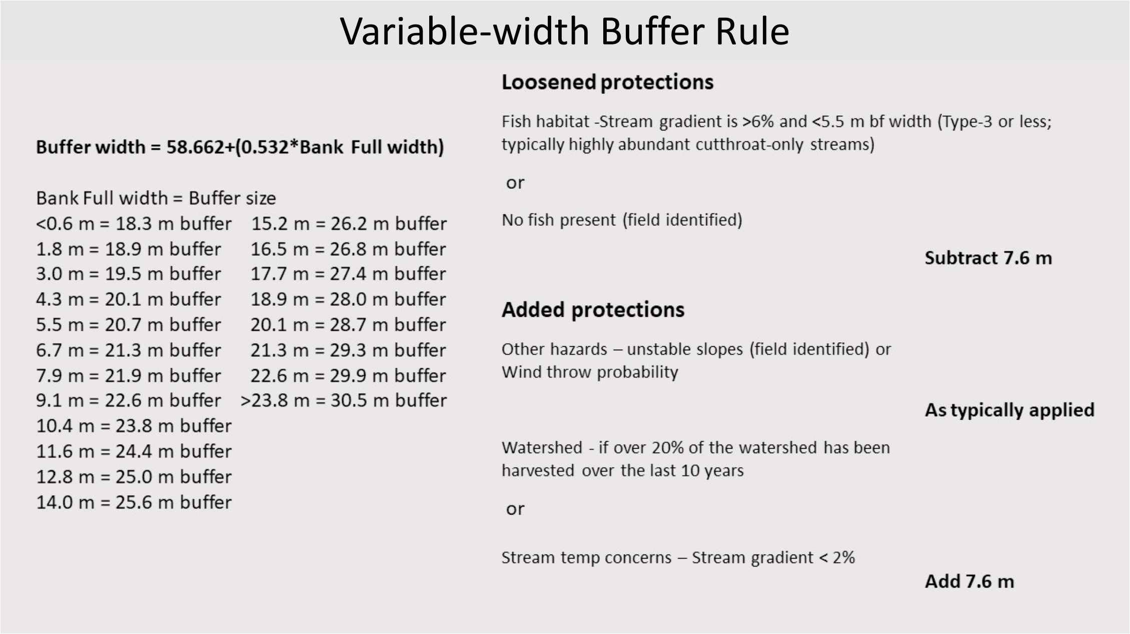
[4] This approach is being evaluated on a Siuslaw National Forest experiment (now 23 years old), where basal area growth of Douglas-fir residuals (thinned plantation at 60 years old) was doubled over controls in years 15-20 of measurement ($p<0.05$; Bormann unpub. data.)

Peninsula. Riparian benefits are expected to include faster production of large stream logs and increased food supply to fish through more nutrients (alder is a $N_2$-fixing species), higher quality litter (leaves vs needles) and terrestrial insects (due to increases in deciduous plants). This treatment will be applied to 100% of the riparian buffer in the designated sub-catchment of each of the four watersheds representing the Alternative 2 strategy. Positive or negative effects of these treatments, however they turn out, have a strong potential to inform both state and federal regulations, some that currently do not recognize the importance of alder and other deciduous trees and shrubs to the terrestrial or aquatic food web, increasing conifer growth, or providing nutrients to streams. These treatments will take place in a lower catchment of the watershed (typically smaller streams with limited or no fish presence).

The variable-width riparian buffer prescription recognizes that overly simplistic regulations with fixed-width buffers are inefficient and counter to integrating community and environment wellbeing. The ecologically appropriate buffer widths are likely to vary by stream size and condition (such as gradient, fish species composition, and other factors). We will use a variable-width riparian buffer based on the bankfull width of a stream and will add or subtract to the overall buffer width based on fish species present, the amount of watershed harvested in the past 10 years, and stream temperature (by targeting lower gradient streams that are more susceptible to higher stream temperatures; Figure 4). These riparian buffers will be applied to both Type-3 and Type-4 streams starting at the 100-year floodplain. Initial riparian buffer width will be determined by a linear regression formula (Buffer Width = 58.662 + [0.532*Bankfull Width]) with an 18.3-m riparian buffer on all streams with a bankfull width less than 0.6 m and a 30-m riparian buffer on all streams with a bankfull width greater than 23.8 m. 7.6 m of riparian buffer width will be subtracted if no fish are present or if cutthroat trout are likely to be the only species present (the most common and abundant salmonid species on the OESF). An additional riparian 7.6 m of buffer width will be applied if over 20% of the watershed has been harvested within the last 10 years or in lower gradient streams where there is a higher likelihood of increased water temperature. The linear regression was conceptualized by the authors as a scalable method for balancing the desire to harvest more while still providing adequate protections to streams. Existing riparian and wetland implementation procedures will be applied to protect unstable slopes, wetlands, and windthrow-prone edges, and the riparian buffer will be expanded accordingly in these situations (Appendix 1). When compared with the Standard (typical OESF management) strategy, the variable-width buffer would reduce riparian buffer widths by 63% in small (<1.8 m bankfull width) non-fish bearing streams and by 33% in the average Type-3 stream.



## Variable-width Buffer Rule

**Buffer width = 58.662+(0.532*Bank Full width)**

Bank Full width = Buffer size
<0.6 m = 18.3 m buffer
1.8 m = 18.9 m buffer
3.0 m = 19.5 m buffer
4.3 m = 20.1 m buffer
5.5 m = 20.7 m buffer
6.7 m = 21.3 m buffer
7.9 m = 21.9 m buffer
9.1 m = 22.6 m buffer
10.4 m = 23.8 m buffer
11.6 m = 24.4 m buffer
12.8 m = 25.0 m buffer
14.0 m = 25.6 m buffer
15.2 m = 26.2 m buffer
16.5 m = 26.8 m buffer
17.7 m = 27.4 m buffer
18.9 m = 28.0 m buffer
20.1 m = 28.7 m buffer
21.3 m = 29.3 m buffer
22.6 m = 29.9 m buffer
>23.8 m = 30.5 m buffer

**Loosened protections**

Fish habitat -Stream gradient is >6% and <5.5 m bf width (Type-3 or less; typically highly abundant cutthroat-only streams)

or

No fish present (field identified)

**Subtract 7.6 m**

**Added protections**

Other hazards – unstable slopes (field identified) or Wind throw probability

**As typically applied**

Watershed - if over 20% of the watershed has been harvested over the last 10 years

or

Stream temp concerns – Stream gradient < 2%

**Add 7.6 m**

**Figure 4. The rules for determining the variable-width riparian buffer to be used as part of the Alternative-2 type integration strategy in the riparian portion of the T3 Watershed Experiment.**

## Standard Prescription

Current OESF riparian management, guided by the implementation procedure in the 2016 OESF Forest Land Plan (refer to Appendix 1), can result in a range of different prescriptions often based on the stability of slopes, the threat of windthrow, or need/availability of the riparian area for thinning or limited VRH harvest. However, the most common approach associated with variable-retention harvests starts with a fixed-width 30-m buffer in WADNR Type-3 and 4 streams (non-fish bearing) with additional width added for unstable slopes, wetlands or when there is a high potential for severe endemic windthrow in the riparian buffer. Based on past management performance and current guidance, we believe that this prescription will continue to be the most prevalent in the OESF over the next decade. For this reason, we selected the no-entry OESF management prescription with no harvests or thinning within the 30-m riparian buffer and buffers will be extended for unstable slopes, wetlands, and areas estimated to be highly susceptible to windthrow following the OESF Forest Land Plan (WADNR 2016; Appendix 1). Standardizing the prescription allows for a replicated design across the four watersheds.

## Control Prescription

The no action prescription in the four watersheds representing the Control strategy will be used to quantify natural background variation in conditions that occur over time and in particular, will aid a better understanding of changes resulting from factors beyond our control that may interact with management[5]. This strategy will also be used to compare the other strategies against a "no management" alternative. The upland and riparian portions of the watersheds will be deferred from forest harvests for ten years. However, it should be noted that these watersheds have a previous management history similar to the other watersheds within the experiment. The control is not a currently viable long-term management strategy under WADNR's trust mandate to produce revenue for school and county trusts. We acknowledge that this prescription could become viable if carbon credit markets outcompete the forest product markets in providing revenue to the trusts. To compare to others, control reaches will be established for monitoring purposes that lie below where a VRH that would have been conducted if it had not been in a Control strategy watershed.

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[5] Factors such as wind or other natural disturbance, changes in ocean conditions (e.g., Pacific decadal oscillation) climate change, or changes in fishing regulations.

## Study Area

The study takes place on the western Olympic Peninsula on state lands of the OESF. The prescriptions will be located in 16 Type-3 watersheds (Figure 5). The study watersheds range in size from 215 to 1,077 hectares (1.3 to 6.8 km$^2$; Table 2). Elevation in the watersheds range from a minimum of 41 m to a maximum of 1,034 m. The area is characterized by maritime climate and receives heavy precipitation ranging from 203 to 355 cm per year, with the majority falling as rain during the winter. The watersheds are within the western hemlock climax vegetation zone, which is dominated by hemlock with variable amounts of Sitka spruce, western red cedar, and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco). Silver fir (*Abies amabilis* (Dougl. ex Loud.) Dougl.) can be common at higher elevations and red alder is common at lower elevations and near waterways. Young glacial and sedimentary soils, abundant moisture, and a long growing season result in rapid tree growth. Old-growth forests that once dominated the landscape now occupy about 11% of the OESF. As of 2011, the OESF forest has less than 20% of its forests less than 19 years old, approximately 60% between 20 to 60 years old, and 20% older than 80 years old; WADNR 2016). Upland harvest in this experiment will be conducted in forests mostly between 20-60 years old.

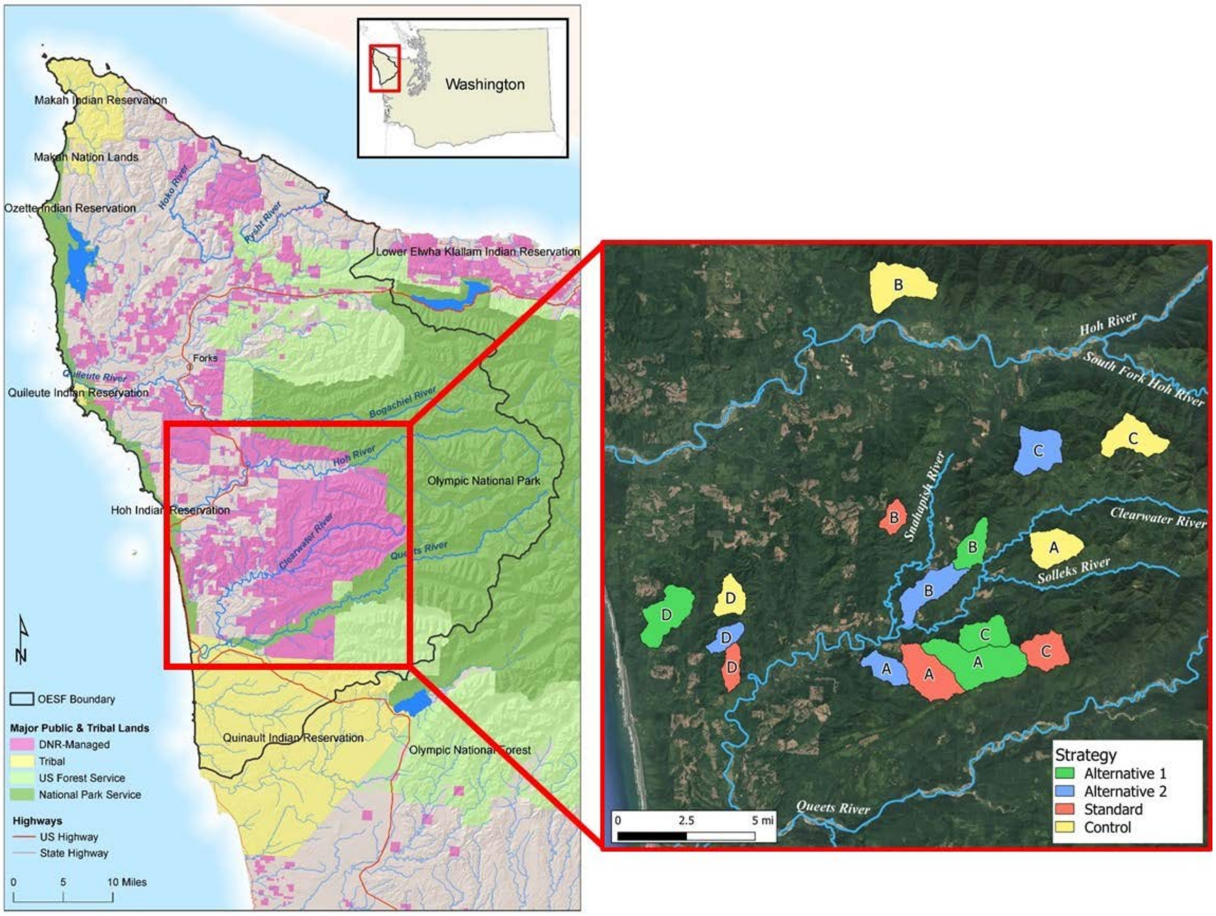


**Figure 5. Map of the Olympic Experimental State Forest (OESF) and 16 experimental watersheds grouped into four blocks with randomly assigned, watershed-scale, strategy treatments.**

**Table 2. Characteristics of the 16 watersheds selected for the T3 watershed experiment**

| Block | Strategy | Watershed Area (ha) | Harvestable acres (ha)[a] | Median Slope (%) | Elevation Min. (m) | Elevation Max. (m) | Managed by WADNR (%) |
|---|---|---|---|---|---|---|---|
| A | **Alternative 1** | 1077 | 219 | 46 | 110 | 652 | 100 |
| | **Alternative 2** | 342 | 99 | 39 | 78 | 387 | 100 |
| | **Standard** | 730 | 147 | 27 | 115 | 468 | 100 |
| | **Control** | 541 | 190 | 46 | 160 | 817 | 100 |
| B | **Alternative 1** | 377 | 112 | 29 | 127 | 754 | 100 |
| | **Alternative 2** | 595 | 214 | 29 | 81 | 425 | 100 |
| | **Standard** | 215 | 80 | 48 | 178 | 570 | 100 |
| | **Control** | 778 | 157 | 52 | 93 | 806 | 97 |
| C | **Alternative 1** | 453 | 169 | 48 | 170 | 644 | 100 |
| | **Alternative 2** | 609 | 235 | 64 | 263 | 883 | 100 |
| | **Standard** | 469 | 167 | 41 | 304 | 764 | 79 |
| | **Control** | 600 | 65 | 54 | 391 | 1034 | 100 |
| D | **Alternative 1** | 672 | 76 | 28 | 41 | 368 | 88 |
| | **Alternative 2** | 227 | 143 | 46 | 68 | 429 | 94 |
| | **Standard** | 243 | 62 | 32 | 66 | 328 | 88 |
| | **Control** | 324 | 130 | 29 | 87 | 451 | 97 |

[a] Harvestable hectares per watershed was taken from the latest available version of the operable acres GIS layer (2/7/2020)

We analyzed watersheds for current operability (upland areas deemed available for possible harvest at this time; Table 2). Operable areas (shown in the harvestable acres column in Table 2) averaged about 20% on watersheds. Currently inoperable areas included stands too young or without road access, old-growth, wetlands, and protected wildlife habitat. Modelled unstable slopes and riparian buffers were also not included in the operable area. The above assessment resulted from a GIS review using WADNR databases. The exact extent and location of the protected areas and the timber harvest activities with experimental prescriptions in each watershed will be determined through a field review conducted when planning individual timber sales.

## Study Design

The study is a randomized block design with four blocks (A-D; Table 3). Each block has four watersheds (one each of the four strategies, randomly assigned) for a total of sixteen watersheds (Table 2; Figure 5). The 16 watersheds were divided into 4 blocks to maximize similarity within block and provide differences between blocks that represent the range of conditions in the larger population of watersheds across the OESF. The larger population of watersheds examined had these characteristics, which define our scope of inference:

- Western Olympic Peninsula, previously managed forest (starting in the 1960s; with some unmanaged stand pockets) within the OESF boundary;
- Areas with larger blocks of WADNR ownership, mainly in the Clearwater and Hoh River drainages; areas north of Forks are too checkerboarded with different landowners;
- Watersheds greater than 200 ha with fish-bearing reaches (Type 3); and
- Modelled operable acres of more than 20% of the watershed, driven by economic considerations including existing road access, stand volumes, and topographic limits on logging systems.

From this population, we identified 16 watersheds and 4 blocks using similarity analyses based on GIS data available at the time (Appendix 2). Driving variables on the grouping of watersheds in blocks were proximity, elevation, and percentages of unmanaged pockets of older forest and modelled unstable slopes. The four strategies were then randomly assigned within each block by an open process, with the WADNR region manager rolling dice. The resulting design is a randomized complete block.

**Table 3. ANOVA design**

| Source | Degrees of freedom |
|---:|---:|
| Treatments | 3 |
| Blocks | 3 |
| Error | 9 |
| Total | 15 |

A variety of more complex models are envisioned for hypothesis building as well but are not developed here because of uncertainty based on evolving additional questions and field realities, only some of which have been revealed at this time. One specific contrast we know we want to evaluate is the hypothesis that there are significant effects from active riparian management compared to riparian buffers with no active management. Both the Control and Standard strategies preclude active management in the riparian buffers and both the Alternative 1 and Alternative 2 strategy treatments include it, so treatment degrees of freedom increase to 7.

Having four strategies replicates provides higher statistical power relative to some other watershed-scale experiments implemented in the Pacific Northwest. This higher level of power is necessary to justify a variety of possible conclusions. Increasing the sample size is important to distinguish small or no strategy effects (either positive or negative) given the amount of variability between watersheds. Determining significant effects or having confidence that effects are not significant will be critical to the acceptance of the results. It will also help to better assess the cause-and-effect relationships between management, stream habitat, and salmonid populations needed to change existing regulations.

After watersheds were grouped into the blocks, it was determined that the Alternative 1 watershed in C block did not have any harvestable acreage along the fish-bearing portion of the watershed due to recently adopted protection of marbled murrelet habitat. In addition, a review of watersheds and organizational support for incorporating new watersheds within the experiment prevented the addition of new watersheds into this experiment. After much debate, we decided to switch the C block watershed originally scheduled for the Alternative 1 strategy with the A block Control watershed. The A block control was selected because the C block control would also provide insufficient harvestable area around the fish bearing portion of the stream. In addition, the former A block Control watershed was selected because of its similar watershed characteristics (watershed size, mouth elevation, and medium stream gradient) with the former C Block Alternative 1 watershed. Although we recognize the negative impacts to the randomization and blocking, we felt that the alternative of eliminating this watershed (or the entire C block) and thus reducing the sample size for the entire experiment would be more problematic for determining differences between the strategies.

We will also attempt to account for environmental variation through pre-treatment monitoring by the multiple replicate, before-After and Control-Impact (BACI) design (Smith 2014). The BACI design is meant to distinguish the effect of an activity (management treatment) from other sources of spatial or temporal variability (Underwood 1992). Work on current biophysical and historical differences in T3 study watersheds continues (see Overview plan [in prep]) to identify possible co-variates to use in subsequent analyses. Note that pre-treatment time-series data only increases power when pre-treatment monitoring is long enough to capture temporal variation or when between-block variation is higher than between-treatment variation (Homann et al. 2001).

The sample design was reviewed by a statistician (Dr. Martin Liermann from NOAA Fisheries) who has joined the project as a PI. His primary concern was the low sample size (four replicates) and that we would need a large effect size and/or low between watershed variability to provide certainty in our results (see Appendix 3). While expressing support for the project, he made seven suggestions including: 1) thinking about experimental treatments as an estimation problem (it will be clear that not rejecting is not the same as no effect, large confidence intervals will reduce the chances of over interpreting a surprisingly large effect size, and we may be able to rule out some treatments), 2) developing an exploratory analysis to generate hypotheses, 3) exploring hypotheses that can be tested at a fine scale resolution, 4) considering a reduced number of treatments to increase the number of replicates, 5) focusing on metrics that are most likely to be directly linked to the treatments, 6) investing in collecting information on implementation effectiveness and cost, and 7) simulating data.

## Riparian Study Questions and Hypotheses

A set of initial research questions are posed below followed by hypotheses that can be evaluated by this study. Other questions and hypotheses may emerge as the study gets underway. Prior to implementation of forest stand treatments, we will use an analytical modeling approach to refine our hypotheses regarding treatment effects on stream ecosystems and salmonids. One option for accomplishing this may be to adapt a previously constructed river food web model (Aquatic Trophic Productivity model (ATP); Bellmore et al. 2017, Whitney et al. 2019) to simulate how expected changes in stream shading, water temperature, and inputs of terrestrial organic matter (i.e., leaf litter and insects) with each treatment influence algal, aquatic insect, and ultimately, fish productivity. Model simulations will help discern how environmental differences among study watersheds (e.g., differences in pre-treatment flow, water temperature, and nutrient regimes) might mediate experimental outcomes. Following the implementation of treatments, measured outcomes will be compared to model predictions to assist in elucidating mechanisms underlying responses. Furthermore, the model will be refined using this empirical data to make broader-scale predictions (i.e., how would other locations respond to similar treatments?).

***Q1*** *- How effective is the current, management of the OESF (Standard) in meeting its riparian conservation objective for "maintaining habitat that is capable of supporting viable populations of salmonid species, as well as for other non-listed and candidate species dependent on in-stream and riparian environments" both currently and in the future?*

Effectiveness of current policy:

$H_0$: Standard OESF management is leading to declining salmonid habitat and populations
or $H_1$: Standard OESF management is maintaining or improving salmonid habitat and populations.

***Q2*** *- Can integrative riparian forest management strategies (environmental and community inspired) maintain or improve salmonid habitat and populations while increasing revenue to the trusts?*

Alternative hypothesis 1:

> $H_0$: No difference in salmonid habitat or salmon populations relative to the other management strategies and no increase in trust revenue; $H_1$: Salmonid habitat or populations decreased relative to the other management strategies; $H_2$: Salmonid habitat or populations increased relative to the other management strategies with an increase or no decrease in trust revenue; $H_3$: No difference in salmonid habitat or populations relative to the other management strategies with an increase in trust revenue.

Alternative hypothesis 2:

> $H_0$: No difference in trust revenue or other measures of wellbeing between management strategies; $H_1$: Trust revenue or other measures of wellbeing decreased relative to the other management strategies; $H_{2:}$ Trust revenue or others measure of wellbeing increased relative to the other management strategies.

***Q3*** *- Will alder planting and wide spacing speed growth of residual conifers (reduce time to get large wood input)?*

> $H_0$: no effect; $H_1$: slows growth; or $H_2$: speeds growth.

***Q4*** *- Will an alder crop (at 35 years) be achieved and harvested that generates net revenue to trusts (as projected at year 10)?*

> $H_0$: no effect; $H_1$: volume or quality too low; or $H_2$: volume and quality acceptable.

***Q5 -*** *When/if significant effects are achieved at sub-catchments/reaches, do they manifest as cumulative spatial contributions?*

> $H_0$: no; $H_1$: yes;

***Q6*** *- Are the alternative management strategies operationally and economically feasible (note that answering this question will be handled in the uplands study, where operational costs and revenues will be tracked)?*

> $H_0$: no; $H_1$: yes, but only because they cover additional costs; $H_2$: yes, and they generate net revenue.

## Monitoring Indicators and Metrics

Environment wellbeing response variables that are possible with current funding include various habitat measures known to indicate stream and riparian health and salmonids population viability (Table 4). Social and economic measures associated with community wellbeing are being developed separately (see Overview Plan [in prep]) but will likely include total operational costs and total and net revenue and numbers and quality of jobs. The sampling for calculating the primary metrics (Table 4) is planned and budgeted as part of the study. The sampling for the secondary and additional metrics will only be added if additional cooperation or resources are added.

**Table 4. Stream and riparian forest monitoring indicators and metrics considered for the T3 watershed experiment; the "Reach" column includes alder sub-catchment pour points in Alternative 2 watersheds; refer to figure 6 for the location of the Reach and Outlet monitoring reaches**

| Indicator | Metric | Reach | Watershed Outlet | Primary | Secondary* |
|---|---|---|---|---|---|
| Stream habitat | Type | X | X | X | |
| | Size | X | X | X | |
| | Pool forming factor | X | X | X | |
| Forest canopy | Percent shade | X | | X | |
| Salmonids | Species composition | X | X | X | |
| | Density (Abundance) | X | X | X | |
| | Biomass | X | X | X | |
| | Fish diet | X | X | | X |
| Macroinvertebrates | Abundance/biomass, species composition (benthic, drift) | X | X | X | |
| | | X | X | X | |
| Periphyton | Amount | X | | | X |
| Stream temperature | 7DMAX | X | X | X | |
| Stream flow | Cubic feet per sec | X | X | | X |
| Stream chemistry | DOC | X | X | X | |
| | Total C, N, P | X | X | | X |
| Detrital inputs | Amount, composition, timing | X | | | X |
| | Terrestrial invertebrates | | | | |
| Instream wood | Density | X | X | X | |
| | Volume | X | X | X | |
| | Movement | X | X | X | |
| Stream substrate | % fine sediment | X | X | X | |
| | % gravel and boulders | X | X | | X |
| Stream geomorphology | Gradient | X | X | X | |
| Riparian forest | Composition | X | | X | |
| | Density | X | | X | |
| | Basal area | X | | X | |
| Groundwater | Pressure | X | | | X |
| Riparian microclimate | Air temperature | X | | | X |
| | Humidity | X | | | X |

*Secondary indicators will only be attempted with additional funding or cooperation.

## Implementation Schedule

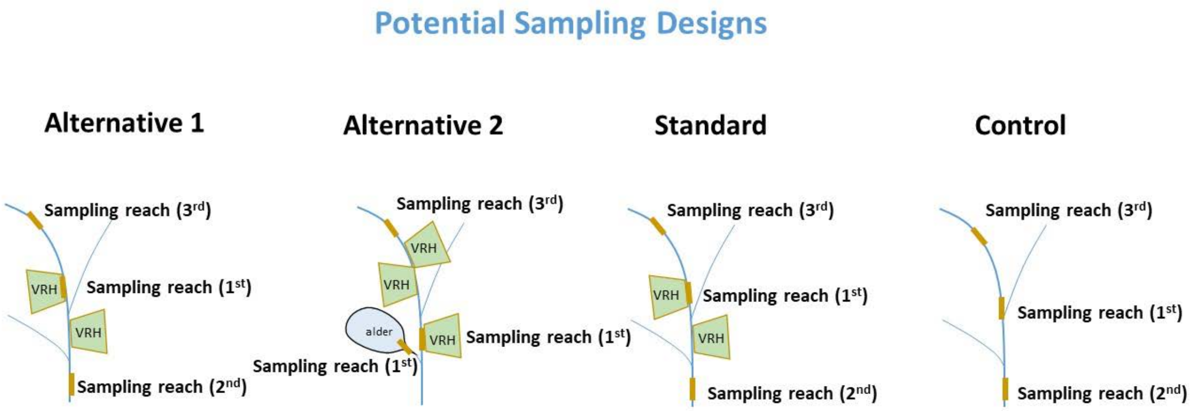
We plan for two years of pre-treatment monitoring in 2020 and 2021. The treatments will be implemented as early as fall 2021 but purchasers are allowed up to two years to implement the forest harvest operation. Treatments will be followed by a minimum of four years of post-treatment monitoring.

| | |
|---|---|
| Pre-treatment monitoring | 2020-Summer 2021 |
| Treatment | Fall 2021-2023 |
| Post-treatment monitoring | 2023-2026 or 2024-2027 |

## Required Resources

The minimum amount of resources to effectively conduct the study is reflected in the Tier 1 sampling design (Figure 6). Additional levels of monitoring are described in the Tier 2 and 3 designs. The amount of work will be scaled to the amount of money or personnel available (Figure 6). The Tier 1 design will prioritize a reach-level response adjacent to one of the treatments in a watershed for a total of 20 sites per year (1 reach per watershed in the Standard, Control, and Science strategies, and 2 reaches per watershed in the Alternative 2 strategy). This design acknowledges that any impacts from changes in forest management are most likely to be identified at the reach level but would change the focus of the study from a watershed study to a reach-level study. The Tier 2 design will incorporate both reach-level and watershed-level responses by sampling at both an adjacent reach as well as substantially below (downstream of) all treatments, likely near the watershed outlet, as conceptualized during the design of the experiment. One exception will be in Alternative 2 watersheds, where there are two alternatives. Monitoring in the Alternative 2 watersheds under the Tier 2 design will include sampling above the lowest sub-watershed (near the lowest forest harvests) to monitor the response of the variable-width riparian buffer and near the bottom of the wide thinning and alder treatment sub-watershed. The Tier 2 design would therefore sample 32 sites per year. The first year of pre-treatment sampling in 2020 followed the Tier 2 design (Figure 7). The Tier 3 design would include all sampling in the Tier 2 design plus an additional reach above all treatments designed as a within watershed control. The Tier 3 design would therefore sample 48 sites per year.

The fish/stream habitat crew will consist of 4+ people and will collect data on the following primary indicators: salmonids, canopy coverage, instream wood, sediment, stream temperature, habitat units, and stream geomorphology. Sampling will be conducted to allow one site to be sampled per day. Another crew of 2-4 people would be needed to collect information on the riparian forests (this could potentially be done by the fish crew once all fish sampling is finished).



**Tier 1 [1st priority sampling]** = (1 control x 4 replicates) + (1 planned x 4 replicates) + (1 active X 4 replicates) + (2 accelerated x 4 replicates) = **20 reaches**
**Tier 2 [1st and 2nd priorities]** = (2 control x 4 replicates) + (2 planned x 4 replicates) + (2 active X 4 replicates) + (2 accelerated x 4 replicates) = **32 reaches**
**Tier 3 [all reaches]** = (3 control x 4 replicates) + (3 planned x 4 replicates) + (3 active X 4 replicates) + (3 accelerated x 4 replicates) = **48 reaches**

**Figure 6. Diagram of the four management strategies and the three different potential sampling designs for the riparian portion of the T3 watershed experiment.**

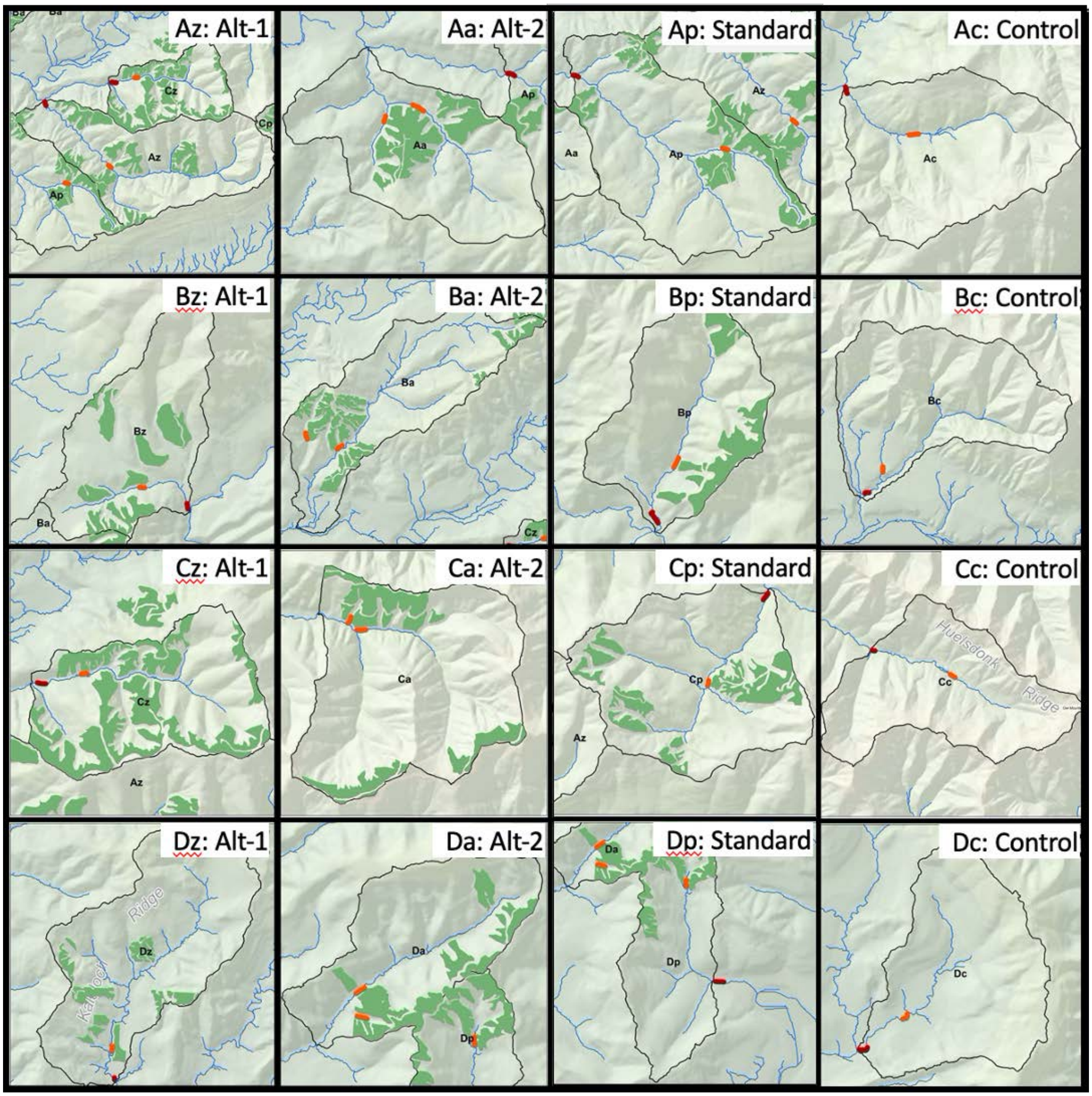


**Figure 7 Map of planned timber harvests (green), near-harvest sampling reaches (orange) and pour point sampling reaches (Red). A = A Block, B = B block, C = C block, D block. The timber harvest units as planned in GIS and subject to modifications after field review and layout.**

Fish/stream habitat sampling crew per year:

Tier 1 - 20 sites X 4 people = 80 crew days per season

**Tier 2 (2020 sampling level) - 32 sites X 4 people = 128 crew days per season**

Tier 3 - 48 sites X 4 people = 192 crew day per season

Riparian vegetation crew:

Tier 1 - 20 sites X 2 people = 40 crew days per season
Tier 2 - 32 sites X 2 people = 64 crew days per season
Tier 3 - 48 sites X 2 people = 96 crew days per season

The experimental treatments will be implemented through the WADNR Olympic Region timber sale program. The timber sales' planning is expected to accrue additional costs associated with the research design. At a minimum, a part-time WADNR forester is required to layout the experimental units and to coordinate with the research teams.

## Sampling Methods

Protocols for field sampling, laboratory analyses, and data management will be written prior to the summer of 2021 field season.

# References

Allouche, S. 2002. Nature and functions of cover for riverine fish. Bulletin Français de la Pêche et de la Pisciculture, (365-366): 297-324.

Anderson, P.D. and M.A. Meleason. 2009. Discerning responses of down wood and understory vegetation abundance to riparian buffer width and thinning treatments: an equivalence–inequivalence approach. Canadian Journal of Forest Research, 39(12): 2470-2485.

Anderson, P.D., D. J. Larson, and S.S. Chan. 2007. Riparian buffer and density management influences on microclimate in young headwater forests of western Oregon. Forest Science, 53(2): 254–269.

Bateman, D.S., R.E. Gresswell, D. Warren, D.P. Hockman-Wert, D.W. Leer, J.T. Light, and J.D. Stednick. 2018. Fish response to contemporary timber harvest practices in a second-growth forest from the central Coast Range of Oregon. Forest Ecology and Management, 411: 142-157.

Beechie, T.J., G. Pess, P. Kennard, R.E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in northwestern Washington streams. North American Journal of Fisheries Management, 20(2): 436-452.

Benda, L. and P. Bigelow. 2014. On the patterns and processes of wood in northern California streams. Geomorphology, 209: 79-97.

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003. Wood recruitment processes and wood budgeting. American Fisheries Society Symposium. American Fisheries Society, pp 49-74.

Benda, L.E., S.E. Litschert, G. Reeves, and R. Pabst. 2016. Thinning and in-stream wood recruitment in riparian second growth forests in coastal Oregon and the use of buffers and tree tipping as mitigation. Journal of Forestry Research, 27(4): 821-836.

Bilby, R.E. and P.A. Bisson. 1987. Emigration and production of hatchery Coho salmon (Oncorhynchus kisutch) stocked in streams draining an old-growth and a clear-cut watershed. Canadian Journal of Fisheries and Aquatic Sciences, 44(8): 1397-1407.

Bilby, R.E. and L.A. Mollot. 2008. Effect of changing land use patterns on the distribution of Coho salmon (*Oncorhynchus kisutch*) in the Puget Sound region. Canadian Journal of Fisheries and Aquatic Sciences, 65(10): 2138-2148.

Bilby, R.E. and J.W. Ward. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences, 48(12): 2499-2508.

Bilby, R.E., J.T. Heffner, B.R. Fransen, J.W. Ward, and P.A. Bisson. 1999. Effects of immersion in water on deterioration of wood from five species of trees used for habitat enhancement projects. North American Journal of Fisheries Management, 19(3): 687-695.

Binkley, D. 1983. Ecosystem production in Douglas-fir plantations: interactions of red alder and site fertility. Forest Ecology and Management, 5: 215-227.

Bisson, P.A. and J.R. Sedell. 1984. Salmonid populations in streams in clearcut vs. old-growth forests of western Washington. Fish and Wildlife Relationships in Old-growth Forests, pp 121-129.

Bisson, P.A., R.E. Bilby, M.D. Bryant, C.A. Dolloff, G.B. Grette, R.A. House, M.L. Murphy, K.V. Koski, and J.R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In: Salo E.O., and T.W. Cundy (eds) Streamside management forestry and fishery interactions. College of Forest Resources, University of Washington.pp 143-190.

Bisson, P.A., J.B. Dunham, and G.H. Reeves. 2009. Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. Ecology and Society, 14(1).

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

Bormann, B.T., D.C. Lee, A.R. Kiester, T.A. Spies, R.W. Haynes, G.H. Reeves, and M.G. Raphael. 2006. Synthesis—interpreting the Northwest Forest Plan as more than the sum of its parts. Chapter 3 in: Haynes, R.W., B.T. Bormann, and J.R. Martin, editors. Northwest Forest Plan—the first ten years (1994-2003): Synthesis of monitoring and research results. PNW GTR 651. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon.

Bormann, B.T., R.W. Haynes, and J.R. Martin. 2007. Adaptive management of forest ecosystems: did some rubber hit the road? BioScience, 57: 187-192

Bormann, BT, K. Cromack, Jr., and W.O. Russell, III. 1994. Influences of red alder on soils and long-term ecosystem productivity. Pp 47-56 in Hibbs, D., DS DeBell, and RF Tarrant (eds). The biology & management of red alder. Oregon State University Press, Corvallis, OR.

Bormann, B.T., R.L. Darbyshire, P.S. Homann, B.A. Morrissette, and S.N. Little. 2015. Managing early succession for biodiversity and long-term productivity of conifer forests in southwestern Oregon. Forest Ecology and Management, 340: 114–125.

Bormann, B.T., B.K. Williams, and T.M. Minkova. 2017. Learning to Learn: The best available science of adaptive management. In, Olson, DH and B Van Horne, Eds. (2017) People, forests, and change: Lessons from the Pacific Northwest. Island Press

Brown, G.W. and J.T. Krygier. 1971. Clear-cut logging and sediment production in the Oregon Coast Range. Water Resources Research, 7(5): 1189-1198.

Burnett, K.M., G.H. Reeves, D.J. Miller, S. Clarke, K. Vance-Borland, and K. Christiansen. 2007. Distribution of salmon-habitat potential relative to landscape characteristics and implications for conservation. Ecological Applications, 17(1): 66-80.

Burton, J.I., D.H. Olson, and K.J. Puettmann. 2016. Effects of riparian buffer width on wood loading in headwater streams after repeated forest thinning. Forest Ecology and Management, 372: 247-257.

Caissie, D. 2006. The thermal regime of rivers: a review. Freshwater Biology, 51(8): 1389-1406.

Cederholm C.J., and L.M. Reid. 1987. Impact of forest management on Coho salmon (Oncorhynchus kisutch) populations of the Clearwater River, Washington: a project summary. In: Salo E.O., and T.W. Cundy (eds) Streamside management forestry and fishery interactions. College of Forest Resources, University of Washington, pp 373–398

Clarke, A., R. Mac Nally, N. Bond, and P.S. Lake. 2008. Macroinvertebrate diversity in headwater streams: a review. Freshwater Biology, 53: 1707–1721.

Coe, H.J., P.M. Kiffney, G.R. Pess, K.K. Kloehn, and M.L. McHenry. 2009. Periphyton and invertebrate response to wood placement in large Pacific coastal rivers. River Research and Applications, 25(8): 1025-1035.

Connolly, P.J. and J.D. Hall. 1999. Biomass of coastal cutthroat trout in unlogged and previously clear-cut basins in the central Coast Range of Oregon. Transactions of the American Fisheries Society, 128(5): 890-899.

Davies, P.E. and M. Nelson. 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Marine and Freshwater Research, 45(7): 1289-1305.

Davis, L.J., M. Reiter, and J.D. Groom. 2016. Modelling temperature change downstream of forest harvest using Newton's law of cooling. Hydrological Processes, 30(6): 959-971.

Dijkstra, F.A. and M.M. Smits 2002. Tree Species effects on calcium cycling: the role of calcium uptake in deep soils. Ecosystems, 5: 385-398.

Doak D. (1989) Spotted owls and old growth logging in the Pacific Northwest. Conservation Biology, 3(4):389–396

Donato D.C., J.S. Halofsky, and M.J. Reilly. 2020. Corralling a black swan: natural range of variation in a forest landscape driven by rare, extreme events. Ecological Applications Jan;30(1):e02013. https://doi.org/10.1002/eap.2013

Doyle, M.W. and D.F. Shields. 2012. Compensatory Mitigation for Streams Under the Clean Water Act: Reassessing Science and Redirecting Policy 1. JAWRA Journal of the American Water Resources Association, 48(3): 494-509.

Eichman, H., G.L. Hunt, J. Kerkvliet, and A.J. Plantinga. 2010. Local employment growth, migration, and public land policy: evidence from the Northwest Forest Plan. Journal of Agricultural and Resource Economics, 316-333.

Feller, M.C. 1981. Effects of clearcutting and slashburning on stream temperature in southwestern British Columbia. JAWRA Journal of the American Water Resources Association, 17(5): 863-867.

FEMAT (Forest Ecosystem Management Assessment Team). 1993. Forest ecosystem management: an ecological, economic, and social assessment: report of the forest ecosystem management assessment team. USDA Forest Service. Portland OR

Franklin, J.F., T.A. Spies, R. Van Pelt, A.B. Carey, D.A. Thornburgh, D.R. Berg, D.B. Lindenmayer, M.E. Harmon, W.S. Keeton, D.C. Shaw, and K. Bible. 2002. Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example. Forest Ecology and Management, 155(1-3): 399-423.

Fraser, D.J., L.K. Weir, L.. Bernatchez, M.M. Hansen, and E.B. Taylor. 2011. Extent and scale of local adaptation in salmonid fishes: review and meta-analysis. Heredity, 106(3): 404-420.

Gomi, T., D.R. Moore, and M.A. Hassan. 2005. Suspended sediment dynamics in small forest streams of the Pacific Northwest 1. JAWRA Journal of the American Water Resources Association, 41(4):877-898.

Hall, J.D., C.J. Cederholm, M.L. Murphy, and K.V. Koski. 2004. Fish-Forestry Interactions in Oregon, Washington and Alaska, USA. Fishes and Forestry: Worldwide Watershed Interactions and Management, 363-388.

Hanley, T.A.; B.T. Bormann, J.C. Barnard, and S.M. Nay. 2014. Responses of southeast Alaska understory species to variation in light and soil environments. Res. Pap. PNW-RP-598. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Hare, S.R., N.J. Mantua, and R.C. Francis. 1999. Inverse production regimes: Alaska and west coast Pacific salmon. Fisheries, 24(1): 6-14.

Hatten, J.A., C. Segura, K.D. Bladon, V.C. Hale, G.G. Ice, and J.D. Stednick. 2018. Effects of contemporary forest harvesting on suspended sediment in the Oregon Coast Range: Alsea Watershed Study Revisited. Forest Ecology and Management, 408: 238-248.

Haynes, R.W., C.A. Montgomery, and S.J. Alexander,. 2017. Wood-products markets, communities, and regional economies. In People, forests, and change. Island Press, Washington DC, pp 47-61.

Hicks, B.J., J.D. Hall, P.A. Bisson, and J.R. Sedell. 1991. Responses of salmonids to habitat changes. In: Meehan, W.R. (ed) Influences of Forest and Rangeland Management on salmonid fishes and their habitats. American Fisheries Society, Bethesda, Maryland, pp 483-518.

Homann, P.S., B.T. Bormann, and J.R. Boyle. 2001. Detecting treatment differences in soil carbon and nitrogen resulting from forest manipulations. Soil Science Society of America Journal, 65: 463–469.

Johnson, S.L. and J.A. Jones. 2000. Stream temperature responses to forest harvest and debris flows in western Cascades, Oregon. Canadian Journal of Fisheries and Aquatic Sciences, 57(S2): 30-39.

Johnson, S.W., J. Heifetz, and K.V. Koski. 1986. Effects of logging on the abundance and seasonal distribution of juvenile steelhead in some southeastern Alaska streams. North American Journal of Fisheries Management, 6(4): 532-537.

Kaeriyama, M., H. Seo, and H. Kudo. 2009. Trends in run size and carrying capacity of Pacific salmon in the North Pacific Ocean. North Pacific Anadromous Fish Commission Bulletin, 5: 293-302.

Kauffman, J.B., R.L. Beschta, N. Otting, and D. Lytjen. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries, 22(5): 12-24.

Kaylor, M.J. and D.R. Warren. 2018. Canopy closure after four decades of postlogging riparian forest regeneration reduces cutthroat trout biomass in headwater streams through bottom-up pathways. Canadian Journal of Fisheries and Aquatic Sciences, 75(4): 513-524.

Kaylor, M.J., D.R. Warren, and P.M. Kiffney. 2017. Long-term effects of riparian forest harvest on light in Pacific Northwest (USA) streams. Freshwater Science, 36(1): 1-13.

Kemp, P., D. Sear, A. Collins, P. Naden, and I. Jones. 2011. The impacts of fine sediment on riverine fish. Hydrological Processes, 25(11): 1800-1821.

Kiffney, P.M., J.S. Richardson, and M.C. Feller. 2000. Fluvial and epilithic organic material dynamics of headwater streams of southwestern British Columbia, Canada. Archive für Hydrobiologie. 148: 109–129.

Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2003. Responses of periphyton and insects to experimental manipulation of riparian buffer width along forest streams. Journal of Applied Ecology 40: 1060-1076.

Kiffney, P.M., J.S. Richardson, and J.P. Bull. 2004. Establishing light as a causal mechanism structuring stream communities in response to experimental manipulation of riparian buffer width. Journal of the North American Benthological Society, 23(3): 542-555.

Kirschner, A.R. 2010. Understanding poverty and unemployment on the Olympic Peninsula after the Spotted Owl. The Social Science Journal, 47(2): 344-358.

Lakel III, W.A., W,M, Aust, M.C. Bolding, C.A. Dolloff, P. Keyser, and R. Feldt. 2010. Sediment trapping by streamside management zones of various widths after forest harvest and site preparation. Forest Science, 56(6): 541-551.

Lawson, P.W., E.A.Logerwell, N.J. Mantua, R.C. Francis, and V.N. Agostini. 2004. Environmental factors influencing freshwater survival and smolt production in Pacific Northwest Coho salmon (Oncorhynchus kisutch). Canadian Journal of Fisheries and Aquatic Sciences, 61(3): 360-373.

Lusardi, R.A., B.G. Hammock, C.A. Jeffres, R.A. Dahlgren, and J.D. Kiernan. 2019. Oversummer growth and survival of juvenile Coho salmon (Oncorhynchus kisutch) across a natural gradient of stream water temperature and prey availability: An in situ enclosure experiment. Canadian Journal of Fisheries and Aquatic Sciences 77:413–424.

Lundström, J., K. Öhman, and H. Laudon. 2018. Comparing buffer zone alternatives in forest planning using a decision support system. Scandinavian Journal of Forest Research, 33(5): 493-501.

MacCracken, J.G. 2002. Response of forest floor vertebrates to riparian hardwood conversion along the Bear River, southwest Washington. Forest Science, 48(2): 299-308.

Macdonald, J.S., E.A. MacIsaac, and H.E. Herunter. 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in subboreal forest ecosystems of British Columbia. Canadian Journal of Forest Research. 33: 1371–1382.

Marshall DB (1988) Status of the marbled murrelet in North America: with special emphasis on populations in California, Oregon, and Washington. U.S. Fish and Wildlife Service, Portland, Oregon. No. FWS-88 (30).

Martens, K.D., W.D. Devine, T.V. Minkova, and A.D. Foster. 2019. Stream conditions after 18 years of passive riparian restoration in small fish-bearing watersheds. Environmental Management, 63(5): 673-690.

Martens, K.D. 2019. Assessment of the Causal Linkages between Forests and Fish: Implications for Management and Monitoring on the Olympic Experimental State Forest. Washington State Department of Natural Resources, Olympia, WA.

Martens, K.D., D.C. Donato, J.S. Halofsky, W.D. Devine, and T.V. Minkova. 2020. Linking instream wood recruitment to adjacent forest development in landscapes driven by stand-replacing disturbances: a conceptual model to inform riparian and stream management. Environmental Reviews, 28(4): 517-527.

Meleason, M.A., S.V. Gregory, and J.P. Bolte. 2003. Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecological Applications, 13(5): 1212-1221.

Mellina, E. and S.G. Hinch. 2009. Influences of riparian logging and in-stream large wood removal on pool habitat and salmonid density and biomass: a meta-analysis. Canadian Journal of Forest Research, 39(7): 1280-1301.

Miller, R.R. 2010. Is the past present? Historical splash-dam mapping and stream disturbance detection in the Oregon Coastal Province. Master thesis Oregon State University.

Miller, S.A., S.N. Gordon, P. Eldred, R.M. Beloin, S. Wilcox, M. Raggon,H. Andersen, and A. Muldoon. 2017. Northwest Forest Plan—the first 20 years (1994–2013): watershed condition status and trends. Gen. Tech. Rep. PNW-GTR-932. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 74 p.

Minkova, T.V. and J.S. Arnold. 2019. A structured framework for adaptive management: bridging theory and practice in the Olympic Experimental State Forest. Forest Science, fxz011.

Montgomery, D.R., B.D. Collins, J.M. Buffington, and T.B. Abbe. 2003. Geomorphic effects of wood in rivers. In American Fisheries Society Symposium, 37: 21-47.

Moore, R.D., D.L. Spittlehouse, and A. Story. 2005. Ripraian microclimte and stream temperature response to forest harvesting: a review. JAWRA Journal of the American Water Resources Association, 41(4): 813-834.

Murphy, M.L. and J.D. Hall. 1981. Vaired effects of clear-cut logging on predators and their habitat in small streams of the Cascade Mountains, Oregon. Canadian Journal of Fisheries and Aquatic Sciences, 38(2): 137-145.

Murphy, M.L. and K.V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management, 9(4): 427-436.

Naiman, R.J., E.V. Balian, K.K. Bartz, R.E. Bilby, and J.J. Latterell. 2002. Dead wood dynamics in stream ecosystems. In Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests. US Department of Agriculture, Forest Service, Pacific Southwest Research Station, pp 23-48.

Nehlsen W., J.E. Williams, and J.A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2): 4–21.

Newbold, J.D., D.C. Erman, and K.B. Roby. 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Canadian Journal of Fisheries and Aquatic Sciences, 37(7): 1076-1085.

Olson, D.H., A.A. Coble, and J.A. Homyack. 2020. Beyond Best Management Practices. American Fisheries Society Symposium.

Olson, D.H., P.D. Anderson, C.A. Frissell, H.H.Jr. Welsh, and D.F. Bradford. 2007. Biodiversity management approaches for stream-riparian areas: perspectives for Pacific Northwest headwater forests, microclimates, and amphibians. Forest Ecology and Management. 246: 81–107.

Olson, D.H., and K.M. Burnett. 2009. Design and management of linkage areas across headwater drainages to conserve biodiversity in forest ecosystems. Forest Ecology and Management. 258S: S117–S126.

Olson, D.H., and K.M. Burnett. 2013. Geometry of forest landscape connectivity: pathways for persistence. In: Anderson, P.D. and K.L. Ronnenberg, eds. Density management in the 21st century: west side story. Gen. Tech. Rep. PNW-GTR-880. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, pp 220–238.

Olson, D.H. and J.I. Burton. 2014. Near-term effects of repeated-thinning with riparian buffers on headwater stream vertebrates and habitats in Oregon, USA. Forests, 5(11): 2703-2729.

Olson, D.H., J.B. Leirness, P.G. Cunningham, and E.A. Steel. 2014. Riparian buffers and forest thinning: effects on headwater vertebrates 10 years after thinning. Forest Ecology and Management, 321: 81-93.

Pess, G.R., T.P. Quinn, S.R. Gephard, and R. Saunders. 2014. Re-colonization of Atlantic and Pacific rivers by anadromous fishes: linkages between life history and the benefits of barrier removal. Reviews in Fish Biology and Fisheries, 24(3): 881-900.

Piccolo, J.J. and M.S. Wipfli. 2002. Does red alder (*Alnus rubra*) in upland riparian forests elevate macroinvertebrate and detritus export from headwater streams to downstream habitats in southeastern Alaska? Canadian Journal of Fisheries and Aquatic Sciences, 59(3): 503-513.

Pisano, S. 2012. Water temperature thresholds for Coho salmon in a spring fed river, Siskiyou County, California. California Fish and Game, 98(1): 19Y37.

Poage, N., and J.C. Tappeiner. 2002. Long-term patterns of diameter and basal area growth of old-growth Douglas-fir trees in western Oregon. Canadian Journal of Forest Resources. 32: 1232–1243.

Pollock, M.M. and T.J. Beechie. 2014. Does riparian forest restoration thinning enhance biodiversity? The ecological importance of large wood. JAWRA Journal of the American Water Resources Association, 50(3): 543-559.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. In American Fisheries Society Symposium. 17: 334-349.

Reeves, G.H., D.H. Olson, S.M. Wondzell, P.A. Bisson, S. Gordon, S.A. Miller, J.W. Long, and M.J. Furniss. 2018. Chapter 7: The aquatic conservation strategy of the Northwest Forest Plan—a review of the relevant science after 23 years. In Synthesis of Science to Inform Land Management Within the Northwest Forest Plan Area. General Technical Report, PNW-GTR-966.

Richardson, J.S., M.C. Feller, P.M. Kiffney, R.D. Moor, S. Mitchell, and S.G. Hinch. 2010. Riparian management of small streams: an experimental trial at the Malcolm Knapp Research Forest. Streamline Watershed Management Bulletin, 13(2): 1-16.

Richardson, J.S. and S. Béraud. 2014. Effects of riparian forest harvest on streams: a meta-analysis. Journal of Applied Ecology, 51(6): 1712-1721.

Richardson, J.S., R.J. Naiman, and P.A. Bisson. 2012. How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices? Freshwater Science, 31(1): 232-238.

Romero, N., R.E. Gresswell, and J.L. Li. 2005. Changing patterns in coastal cutthroat trout (Oncorhynchus clarki clarki) diet and prey in a gradient of deciduous canopies. Canadian Journal of Fisheries and Aquatic Sciences, 62(8): 1797-1807.

Roni, P., T. Beechie, G. Pess, and K. Hanson. 2015. Wood placement in river restoration: fact, fiction, and future direction. Canadian Journal of Fisheries and Aquatic Sciences, 72(3): 466-478.

Roon D.A., J.B. Dunham, and J.D, Groom. 2021. Shade, light, and stream temperature responses to riparian thinning in second-growth redwood forests of northern California. PLoS ONE 16(2): e0246822.

Ruzicka, K.J., K.J. Puettmann, and D.H. Olson, D.H. 2014. Management of riparian buffers: upslope thinning with downslope impacts. Forest Science. 60(5): 881–892.

Sauter, S.T., J. McMillan, and J.B. Dunham. 2001. Salmonid behavior and water temperature. Seattle, WA: United States, Environmental Protection Agency, Region 10 Office of Water. Final Report to the Policy workgroup of the EPA Region 10 Water Temperature Criteria Guidance Project. EPA 910-D-01-001. 36 p.

Sedell, J.R., G.H. Reeves, and K.M. Burnett. 1994. Development and evaluation of aquatic conservation strategies. Journal of Forestry. 92(4): 28–31.

Segura, C., K.D. Bladon, J.A. Hatten, J.A. Jones, V.C. Hale, and G.G. Ice. 2020. Long-term effects of forest harvesting on summer low flow deficits in the Coast Range of Oregon. Journal of Hydrology, 585, p.124749.

Sheer, M.B. and E.A. Steel. 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River basins. Transactions of the American Fisheries Society, 135(6): 1654-1669.

Smith, E.P. 2014. BACI Design. Wiley Stats Ref: Statistics Reference Online.

Spies, T.A., J.F. Franklin, and T.B. Thomas. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology, 69(6): 1689-1702.

Steel, E.A., A. Muldoon, R.L. Flitcroft, J.C. Firman, K.J. Anlauf-Dunn, K.M. Burnett and R.J. Danehy. 2017. Current landscapes and legacies of land-use past: understanding the distribution of juvenile Coho salmon (Oncorhynchus kisutch) and their habitats along the Oregon Coast, USA. Canadian Journal of Fisheries and Aquatic Sciences, 74(4): 546-561.

Stenhouse, S.A., C.E. Bean, W.R. Chesney, and A.S. Pisano. 2012. Water temperature thresholds for Coho salmon in a spring fed river, Siskiyou County, California. California Fish and Game, 98(1): 19-37.

Stewart, G.B., H.R. Bayliss, D.A. Showler, W.J. Sutherland, and A.S. Pullin. 2009. Effectiveness of engineered in-stream structure mitigation measures to increase salmonid abundance: a systematic review. Ecological Applications, 19(4): 931-941.

Suttle, K.B., M.E. Power, J. M. Levine, and C. McNeely. 2004. How fine sediment in riverbeds impairs growth and survival of juvenile salmonids. Ecological Applications, 14(4): 969-974.

Swanson, M.E., N.M. Studevant, J.L. Campbell and D.C. Donato. 2014. Biological associates of early-seral pre-forest in the Pacific Northwest. Forest Ecology and Management, 324: 160-171

Swartz, A., D. Roon, M. Reiter, and D. Warren, 2020. Stream temperature responses to experimental riparian canopy gaps along forested headwaters in western Oregon. Forest Ecology and Management, 474, p.118354.

Sweeney, B.W. and J.D. Newbold. 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. JAWRA Journal of the American Water Resources Association, 50(3): 560-584.

Tiwari, T., J. Lundström, L. Kuglerová, H. Laudon, K. Öhman, and A.M. Ågren. 2016. Cost of riparian buffer zones: A comparison of hydrologically adapted site-specific riparian buffers with traditional fixed widths. Water Resources Research, 52(2): 1056-1069.

Thomas, K.D., and C.E. Prescott. 2000. Nitrogen availability in forest floors of three tree species on the same site: the role of litter quality. Canadian Journal of Forest Research, 30: 1698-1706.

Tschaplinski, P.J. and R.G. Pike. 2017. Carnation Creek watershed experiment—long-term responses of Coho salmon populations to historic forest harvest practices. Ecohydrology, 10(2): 1812.

Tuchmann, E.T., M.H. Brookes, and M. Daterman, M. 1996. The Northwest Forest Plan: a report to the President and Congress. US Dept. of Agriculture, Office of Forestry and Economic Assistance.

Underwood, A.J. 1992. Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. Journal of Experimental Marine Biology and Ecology, 161(2): 145-178.

U.S. Fish and Wildlife Service (USFWS) (1990) Endangered and threatened wildlife and plants; determination of threatened status for the Northern Spotted Owl. Fed. Register 55: 26114–26194.

U.S. Fish and Wildlife Service (USFWS) (1992) Endangered and threatened wildlife and plants; determination of threatened status for the Washington, Oregon and California population of the Marbled Murrelet. Fed Register 57(191): 45328–45337.

Van Pelt, R., T.C. O'Keefe, J.J. Latterell, and R.J. Naiman. 2006. Riparian forest stand development along the Queets river in Olympic National Park, Washington. Ecological Monographs, 76(2): 277-298.

Walters, C. 1997. Challenges in adaptive management of riparian and coastal ecosystems. Conservation Ecology, [online]1(2):1. Available from the Internet. URL: http://www.consecol.org/vol1/iss2/art1/

Warren, D.R., W.S. Keeton, P.M. Kiffney, M.J. Kaylor, H.A. Bechtold, and J. Magee. 2016. Changing forests—changing streams: riparian forest stand development and ecosystem function in temperate headwaters. Ecosphere, 7(8): 1435.

WADNR (Washington State Department of Natural Resources). 1997. Final habitat conservation plan. Washington State Department of Natural Resources, Olympia, Washington.

WADNR (Washington State Department of Natural Resources). 2016. Olympic Experimental State Forest: forest land plan. Olympia, Washington.

Wedemeyer, G. 1973. Some physiological aspects of sublethal heat stress in the juvenile steelhead trout (Salmo gairdneri) and Coho salmon (Oncorhynchus kisutch). Journal of the Fisheries Board of Canada, 30(6): 831-834.

Wilhere, G.F. and T. Quinn. 2018. How wide is wide enough? Science, values, and law in riparian habitat conservation. Natural Resources Journal, 58(2): 279-318.

Wilzbach, M.A., B.C. Harvey, J.L. White, and R.J. Nakamoto. 2005. Effects of riparian canopy opening and salmon carcass addition on the abundance and growth of resident salmonids. Canadian Journal of Fisheries and Aquatic Sciences, 62(1): 58-67.

Wipfli, M.S., and C.V. Baxter. 2010. Linking ecosystems, food webs, and fish production: subsidies in salmonid watersheds. Fisheries. 35: 373–387.

Yamanaka, T., C.Y. Li, B.T. Bormann, and H. Okabe. 2003. Tripartate associations in an alder: effects of Frankia and Alpova on the growth, nitrogen fixation and mineral acquisition of *Alnus tenuifolia*. Plant and Soil, 254: 179–186.

Young, K.A., S.G. Hinch, and T.G. Northcote. 1999. Status of resident coastal cutthroat trout and their habitat twenty-five years after riparian logging. North American Journal of Fisheries Management, 19(4): 901-911.

# Appendix 1. Procedure (PR-14-004-160) for Riparian Management in the Olympic Experimental State Forest (OESF) Habitat Conservation Plan (HCP) planning unit.

Riparian Management in the Olympic Experimental State Forest (OESF) Habitat Conservation Plan (HCP) Planning Unit

Cancels: This procedure replaces the interim procedure (PR 14-004-160 [twelve-step watershed assessment], dated May, 2000). Implement immediately.

**Date:** November 4, 2016

**Application: All HCP-covered lands within the OESF HCP planning unit**

## DISCUSSION

The vision of the HCP riparian conservation strategy for the OESF is to protect, maintain, and restore habitat capable of supporting viable populations of salmonid and other species dependent on in-stream and riparian environments. This vision is achieved in part by applying riparian management zones to all Type 1 through 4 streams and Type 5 streams on potentially unstable slopes or landforms. The riparian management zone consists of an interior-core buffer adjacent to the stream and an exterior buffer (when applied) adjacent to the interior-core buffer.

In the OESF, riparian management zones are tailored to watershed and site-specific conditions. On Type 1 through 4 streams, the starting point for applying riparian management zones is the basic or "default" width of the interior-core buffer per the HCP. The default width of the interior core buffer is then adjusted for potentially unstable slopes or landforms with the potential to deliver sediment or debris to the stream network, wetlands, and a limited amount of regeneration harvest within the interior-core buffer. Exterior buffers are applied as needed based on an assessment of severe endemic windthrow risk (severe endemic windthrow will be defined later in this procedure).

Through a watershed assessment process, Forest Resources Division (Division) staff calculate the maximum number of acres of regeneration harvest ("allotted acres") that may occur each decade without impeding riparian function within the interior-core buffers of Type 1 through 4 streams in each Type 3 watershed. Allotted acres are based on the current and projected ecological conditions of each Type 3 watershed. Division staff periodically update the number of allotted acres as harvests are performed, forest stand conditions change, land is acquired or transferred, new scientific information becomes available, or other changes occur. Refer to the OESF HCP Planning Unit Forest Land Plan for information on how the number of allotted acres is determined and updated, and for a more complete explanation of the OESF riparian conservation strategy.

Allotted acres are set for the overall Type 3 watershed, not for individual streams. Allotted acres can be used on one stream or split across two or more streams, so long as the number of allotted acres is not exceeded for the watershed. Thinning in the riparian management zone also is allowed, as described in this procedure.

On all streams regardless of type, DNR also applies a 30-foot equipment limitation zone measured outward horizontally from the outer edge of the 100-year floodplain.

# ACTION

## For all regeneration harvests:

A) Using DNR's corporate GIS data layers, identify the Type 3 watershed (s) in which the timber harvest unit is located.

B) Identify the location and stream type of all waters located within and adjacent to the boundary of the timber harvest unit using the water typing information in PR 14-004-150 (available in the Forestry Handbook). [6] Consult the region biologist or other specialist if needed for additional guidance on this or any other step of this procedure.

C) Apply the interior-core buffer to Type 1 through 4 streams, using the following default widths:

   i. Type 1 and 2 streams:
      150 feet
   ii. Type 3 and 4 streams:
      100 feet

   Default widths are based on the average widths listed in Tables IV.5 (p. IV .58) and IV. 10 (p. 1\/.123) of the HCP,

   Measure the default width of the interior-core buffer outward horizontally from the outer edge of the 100-year floodplain. To identify the edge of the 100-year floodplain, use the guidance in PR 14-004-150 (available in the Forestry Handbook).

D) Per the forest harvest practices rules, identify and field-verify potentially unstable slopes or landforms that can contribute debris or sediment to the stream network. Incorporate the potentially unstable slope or landform into the interior-core buffer even if the slope or landform extends beyond the default width of the interior-core buffer (refer to Figure 1).

E) For all wetlands associated with typed waters, extend the interior-core buffer outward as necessary to encompass the wetland and its wetland management zone.

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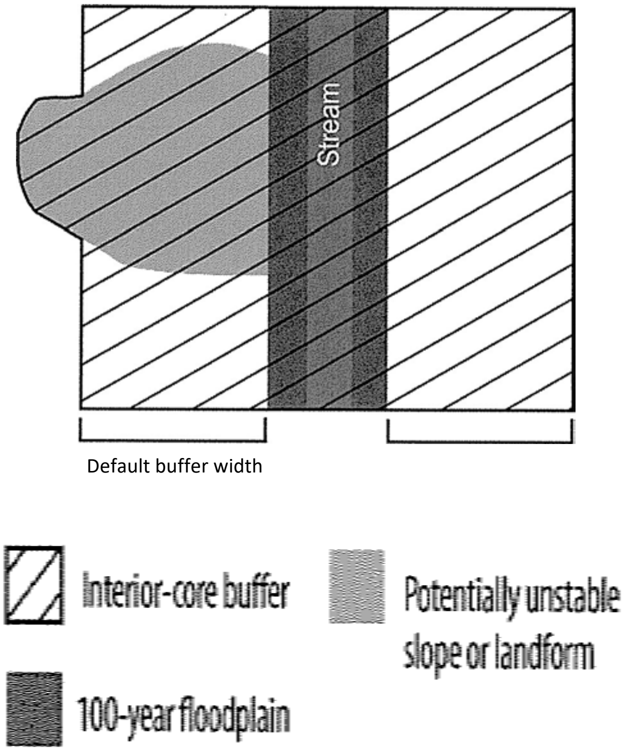
[6] DNR is using the same State Lands stream typing system in the OESF that is used in all other west side planning units.

Figure 1. Interior-core buffer with a potentially unstable slope or landform



F) Assess the potential for severe endemic windthrow in the interior-core buffer of Type 1 through 4 streams. Endemic windthrow results from peak winds that occur fairly frequently (every five years or less) and is considered severe when it causes a significant loss of riparian function.

  i. Run the OESF windthrow probability model, or a future model as developed, using the "severe endemic windthrow" setting. This setting identifies areas with a 5 percent or greater chance of severe endemic windthrow, which is defined in the model as 90 percent of the area experiencing 50 percent or greater canopy loss, Run the model at both the watershed and stream-reach scale. Use of the model can be combined with field assessments or the methods described in Step Eii, below.

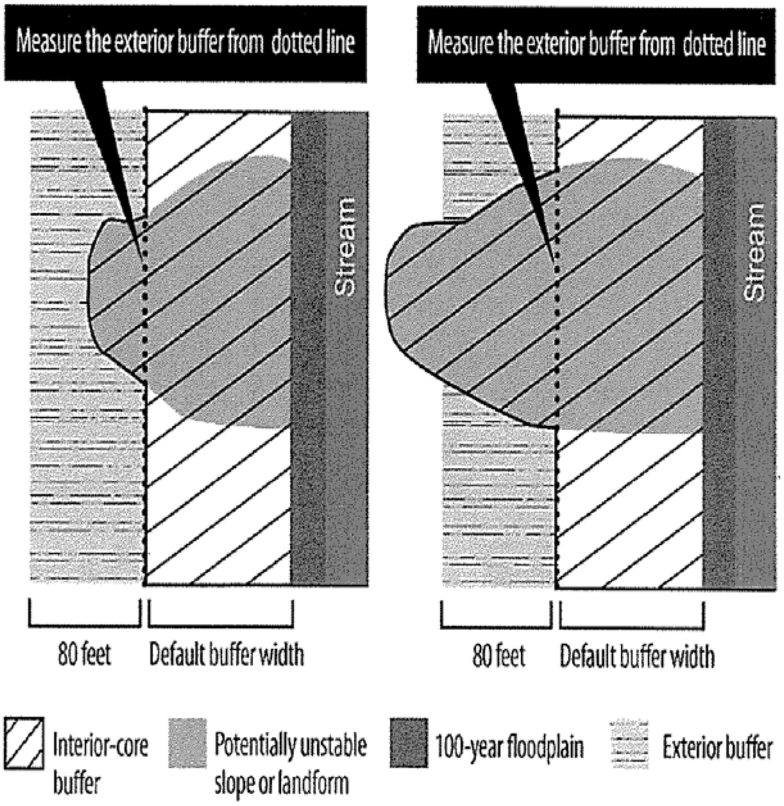
  ii. If the model is not available, use other, qualitative methods to determine severe endemic windthrow risk. Those methods include but are not limited to review of aerial photos and other information (to understand windthrow trends in the area) or completion of the "Buffer Strip Survival Rate Worksheet" in "Designing Stable Buffer Strips for Stream Protection" in the Forestry Handbook.

G) If there is potential for severe endemic windthrow in the interior core buffer of Type 1 through 4 streams, select one or both of the following options:

i. Reconfigure the shape and orientation of the harvested edge, distribution of leave trees, or both to reduce severe endemic windthrow risk and rerun the OESF windthrow probability model on the reconfigured sale to ensure that the risk has been reduced (if not, an exterior buffer will be required).

ii. Apply an 80-foot-wide exterior buffer along areas of the interior-core buffer identified as having potential for severe endemic windthrow. Measure the exterior buffer outward horizontally from the default width of the interior-core buffer (refer to Figure 2).

**Figure 2. Measuring the exterior buffer when the exterior buffer is applied (drawing is not to scale)**



H) Write an activity prescription for the riparian management zones of Type 1 through 4 streams.

i. Identify the current allotted acres (refer to introduction of this procedure) for the Type 3 watershed in which the timber harvest unit is located. A list of allotted acres by watershed is located in the Forestry Handbook.

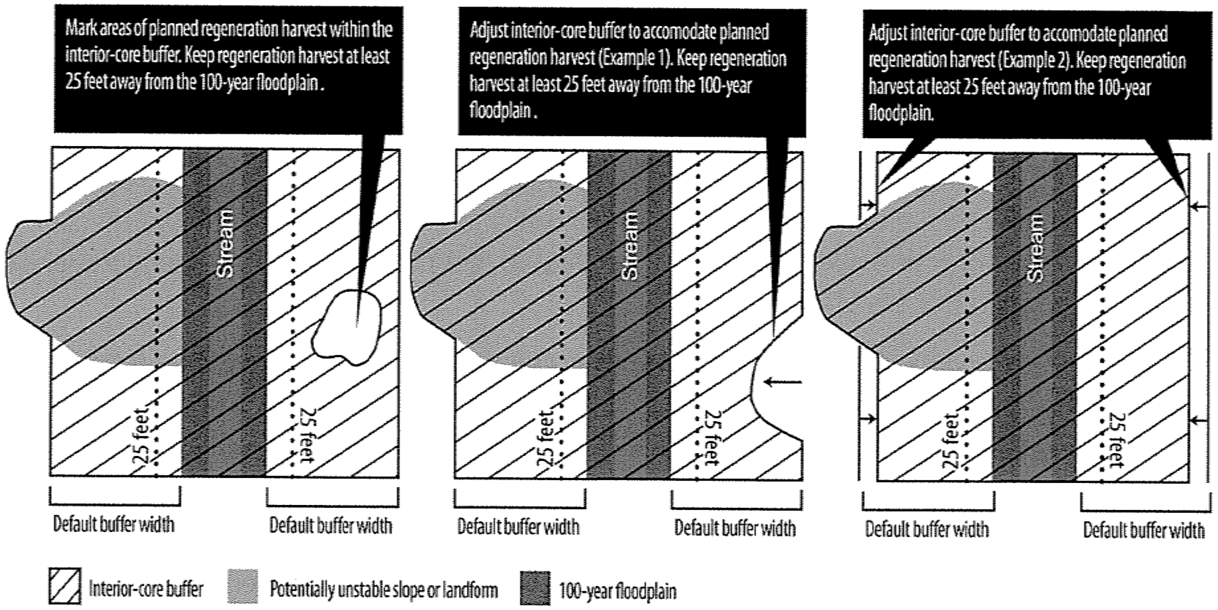
ii. Adjust outer edge of the interior-core buffer as necessary to accommodate planned regeneration harvest (if any) or mark any areas of regeneration harvest that are within the interior-core buffer but not located along the outer edge of the buffer (refer to Figure 3 for examples). In determining where to place allotted acres:

a) Do not exceed the number of allotted acres for the watershed. Harvest on any portion of the interior-core buffer that extends beyond the default width of the buffer is not counted against the allotted acres.

b) Place regeneration harvest at least 25 feet away from the outer edge of the 100-year floodplain.

c) Consider windthrow risk.

**Figure 3. Examples of regeneration harvest placed within the interior-core buffer**



Mark areas of planned regeneration harvest within the interior-core buffer. Keep regeneration harvest at least 25 feet away from the 100-year floodplain.

Adjust interior-core buffer to accomodate planned regeneration harvest (Example 1). Keep regeneration harvest at least 25 feet away from the 100-year floodplain.

Adjust interior-core buffer to accomodate planned regeneration harvest (Example 2). Keep regeneration harvest at least 25 feet away from the 100-year floodplain.

d) For harvest on potentially unstable slopes, follow the guidance in Chapter 16 of the Forest harvest practices Board Manual.

iii. Document the decisions made in this step in the activity prescription.

I) Apply and mark an interior-core buffer on all Type 5 streams located on field-verified, potentially unstable slopes or landforms. The interior-core buffer includes the stream and the identified potentially unstable slope or landform. Do not apply an exterior buffer to Type 5 streams that receive an interior-core buffer.

J) Mark the final edge of the riparian management zones for all streams in or adjacent to the timber harvest unit.

## Other management activities within the riparian management zone

Activities that may occur in the riparian management zone include but are not limited to the following:

- Thinning harvest.
  - "Thinning harvest" refers to both pre-commercial thinning and commercial thinning, including variable density thinning.
  - Thinning harvests are allowed in all areas of the interior-core buffer (up to the last row of trees adjacent to typed waters) except any 100-year floodplain that has been designated by the Federal Emergency Management Agency (FEMA) on flood insurance rate maps; these floodplains are typically associated with Type 1 and 2 streams (DNR 1997 p.IV. 110). Follow forest harvest practices rules for thinning on any potentially unstable slopes or landforms that have been incorporated into the interior-core buffer. To maintain shade, do not thin any area of the interior-core buffer below an average of RD 35. For variable density thinning, gaps larger than $^1/4$ acre located inside the interior-core buffer count against allotted acres of regeneration harvest.
  - Thinning is allowed in exterior buffers. Determine the spacing of tree removal at the time of thinning based on an assessment of the physical and biological condition of the site. The OESF windthrow probability model can be used to test different thinning configurations to ensure wind firmness after thinning.
  - It is not necessary to mark the boundaries of the riparian management zone for a thinning unless the thinning prescription for the riparian management zone is different from that of the uplands. In that case, mark the boundary where the prescription changes.
- Selective harvest of a small number of hardwood trees (hardwood conversion) and/or removal of single hardwood trees. Hardwood conversions count against the allotted acres of regeneration harvest.
- Restoration efforts, including habitat-enhancement projects such as the creation of snags, down wood, and in-stream large woody debris.
- Peer-reviewed research projects designed to improve the integration of revenue and ecological values or operational trials.

- Application of herbicides in accordance with WAC 222-38-020, Handling, Storage, and Application of Pesticides and PR 14-006-040, Site Preparation and Vegetation Management.
- Road construction and road crossings over streams. Per Section 3 of the Forest harvest practices Board Manual, roads within 200 feet of typed waters should be avoided where possible. Refer to Section 3 of the manual for more information. To minimize cumulative impacts associated with roads, design roads to take the most direct route over streams that is operationally feasible.
- Yarding corridors.
- Salvage in the case of a natural disturbance. Salvage that involves regeneration harvest counts against the allotted acres Refer to PR 14-004-520 for more information on natural disturbance.
- Brush and bough harvest.
- Pruning.
- Construction of recreational trail crossings.

## Exceptions

For exceptions to the guidelines in this procedure, attain approval from Region Manager and consult with the Forest Resources Division Manager.

APPROVED BY: ______________________ Date: 12/8/16

Policy Director and State Forester

# Appendix 2. Similarity analysis used to develop blocking

Background on the process.

Phase 1. Initial screen

We found 33 T3 watersheds that passed an initial screen based on:

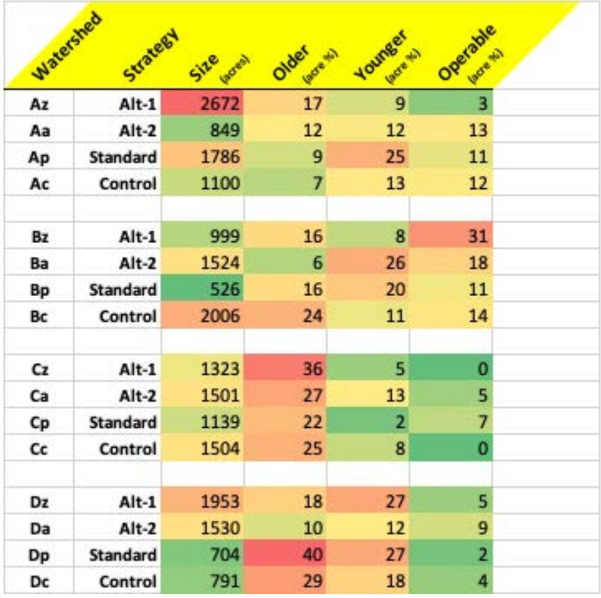
- A predominance of WADNR ownership (issue: control over treatment);
- 500 to 2000 acres (issue: landscape scale with fish above pour point);
- Some amount of older forest and modelled unstable slopes in riparian areas (issue: we wanted to examine in some treatments, the effects of entry into these generally avoided portions of the landscape—to see if the sustainable harvest calculations might be altered);
- Minimal recent harvest activity (issue: given random allocation, all watersheds should be able to perform as a control); and
- Operational difficulties (Issue: mainly road access and harvestable timber in the near term to make the study implementable trough WADNR timber sale program).

Phase 2. Block building

From this pool, we then examined similarity based on four traits (not in priority order):

- Size (acres);
- Older (proportional area of forest patches designated for either for Northern Spotted Owl or Marbled Murrelet habitat);
- Younger (proportional area of stands modeled as too young to be harvested within the first decade); and
- Operable (acre% model in the OESF Forest Land Plan (WADNR 2016).).

A number of iterations and compromises resulted in this block array, with a late emphasis on proximity to each other, given variation in other variables that precluded a very clean array across all variables (Figure A2-1). Proximity was assumed to have positive additional but previously unconsidered similarity such as in harvest timing and techniques and elevation.



| Watershed | Strategy | Size (acres) | Older (acre %) | Younger (acre %) | Operable (acre %) |
|---|---|---|---|---|---|
| Az | Alt-1 | 2672 | 17 | 9 | 3 |
| Aa | Alt-2 | 849 | 12 | 12 | 13 |
| Ap | Standard | 1786 | 9 | 25 | 11 |
| Ac | Control | 1100 | 7 | 13 | 12 |
| | | | | | |
| Bz | Alt-1 | 999 | 16 | 8 | 31 |
| Ba | Alt-2 | 1524 | 6 | 26 | 18 |
| Bp | Standard | 526 | 16 | 20 | 11 |
| Bc | Control | 2006 | 24 | 11 | 14 |
| | | | | | |
| Cz | Alt-1 | 1323 | 36 | 5 | 0 |
| Ca | Alt-2 | 1501 | 27 | 13 | 5 |
| Cp | Standard | 1139 | 22 | 2 | 7 |
| Cc | Control | 1504 | 25 | 8 | 0 |
| | | | | | |
| Dz | Alt-1 | 1953 | 18 | 27 | 5 |
| Da | Alt-2 | 1530 | 10 | 12 | 9 |
| Dp | Standard | 704 | 40 | 27 | 2 |
| Dc | Control | 791 | 29 | 18 | 4 |

**Figure A2-1. Similarity analysis result.**

Resulting block characteristics

In general, the watersheds in Block A have a low % of older forest and high proximity (they are adjacent—

see map next page). Fortunately, the low operable rating turned out not to be true. This block remains variable in sizes, but we may be able to reduce the Block A, Alternative 1 watershed (Az).

The watersheds in Block B has moderate proximity, located to the north and central of the study area, but extending to the N side of the Hoh River (See map next page). These are generally lower elevation and generally highly operable (by the model).

The watersheds in Block C are primarily similar by being higher elevation with reasonable proximity, low operable and containing large patches of older forest. Field examination found more young forest than the model indicated. This block has extreme pre-treatment access problems (discussed later), and one was not sampled given time and difficulty.

Block D is tightly proximal, close to the Ocean, smaller, and with larger inclusions of non-WADNR lands (looking at phase 1 data). There is variability in Older, and modelled younger data may not be accurate?

The process of randomizing within blocks was challenging and institutionally difficult.
We set up a process where the Regional manager rolled the dice to assign treatments in front of UW, managerial, and OESF staff. Everyone realized that this was not a process that could be easily undone or redone.

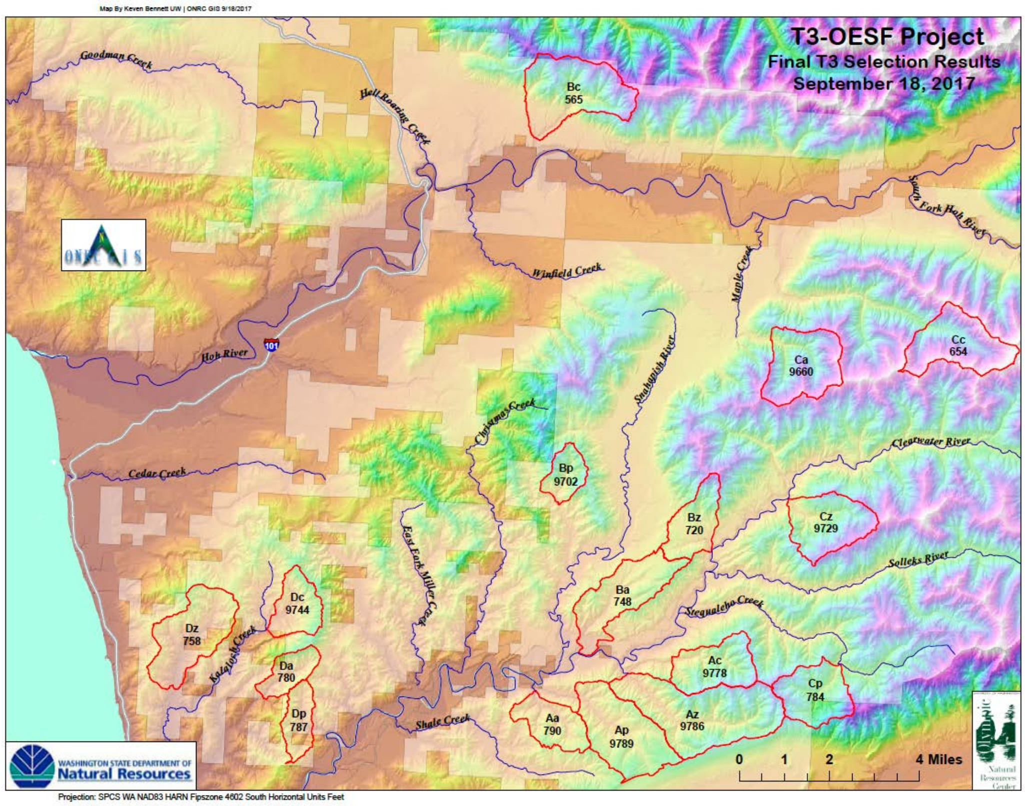


**Figure A2-2. Resulting array of experimental units.**

# Appendix 3. Implications of the T3 study design

## Implications of the T3 study design

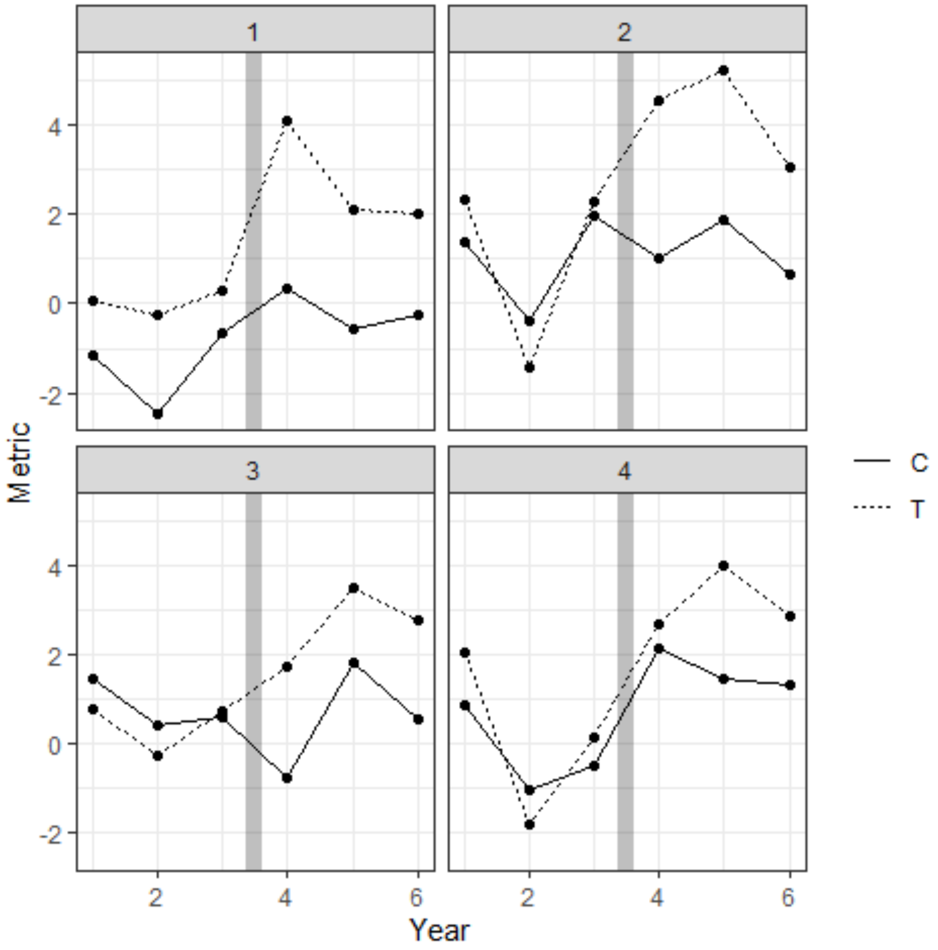
Martin Liermann, Statistician (Biology), NOAA Fisheries

2021-03-05

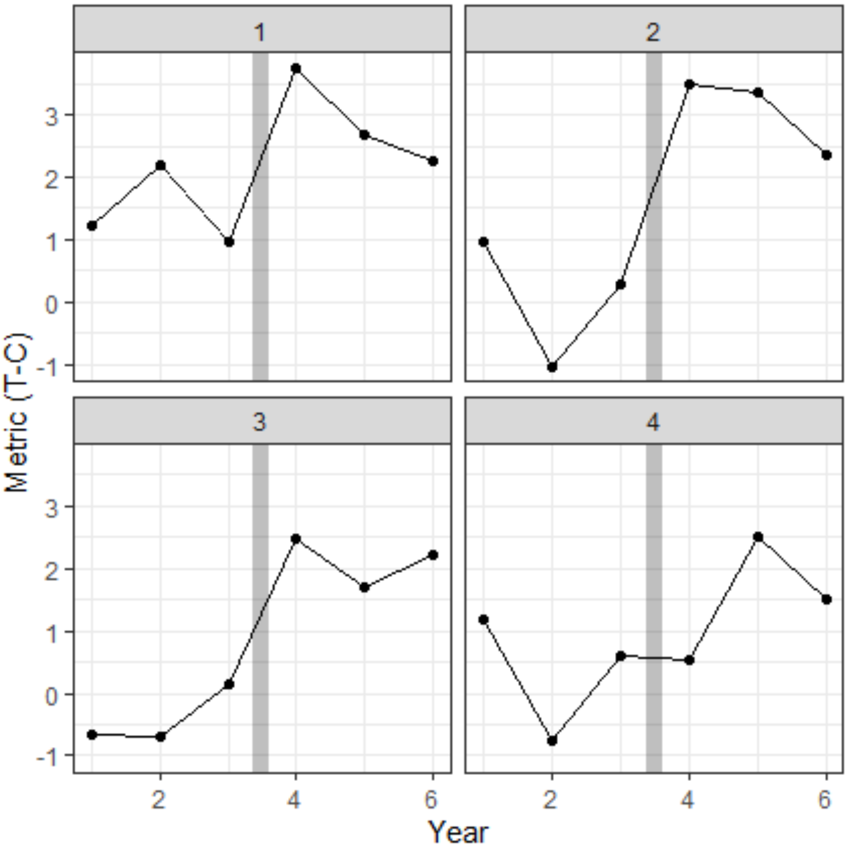
### Summary

The T3 study design includes 4 basins nested within 4 blocks where each block has a control basin and 3 treatments (common to all blocks). Each of the 4 x 4 = 16 basins will be monitored for 2-3 years before and 2-3 years after treatments have been implemented in the treatment basins. Assuming 3 years before and 3 years after, this would result in 4 x 4 x 6 = 96 measurements for each metric of interest (However, notice that some metrics will be collected for a subset of years. And, monitoring will likely extend beyond the initial 3 years of post treatment data).

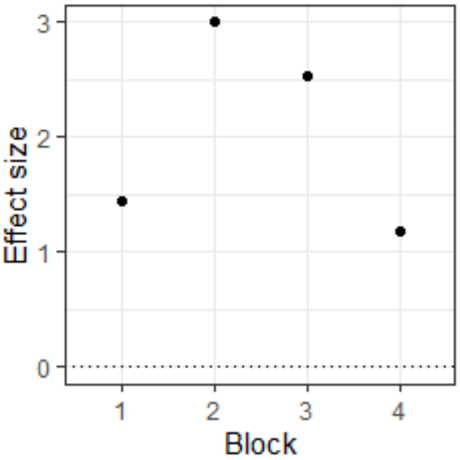
Here's what the data might look like for the control and 1 treatment basin.



Subtracting the control from the treatment values allows us to see the change in the treatment reach post treatment, relative to the control reach.



Finally we can subtract the average of the before values from the average of the after values to get 4 effect sizes, one for each basin.



We can analyze the data as summarized in any of the 3 plots above. In each case, we will get comparable results. So, ultimately, we are looking at a one-sample t-test with a sample size of 4.

When you look at the first plot, it seems like you have a lot of data (96 individual points). However, if you are looking at basin scale effects, it ends up boiling down to N=4 (as summarized in the 3rd plot).

With N=4, it is very difficult to make statistical inference unless the variability in your effect sizes is very small. This seems unlikely for the types of environmental variables that will be measured in the T3 study.

With small sample size, you have low power which means (e.g. Button et al., 2013):

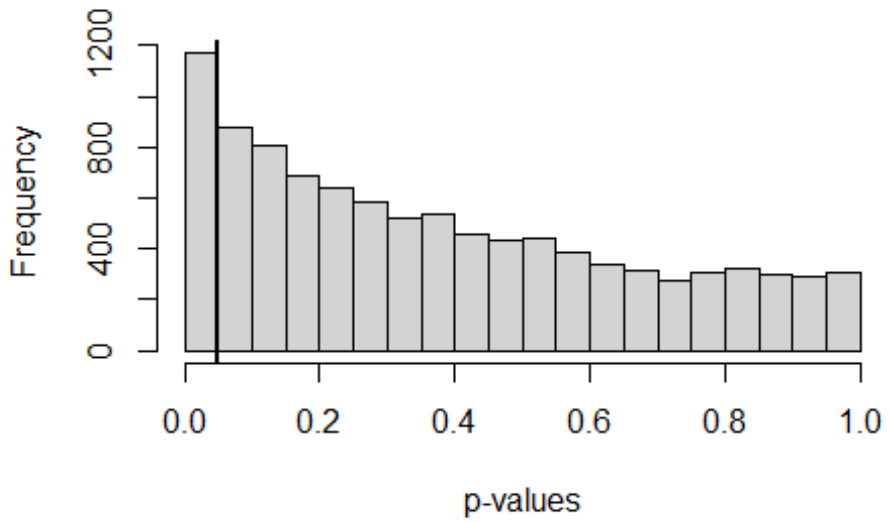
1) You are less likely to detect an effect.
2) If you reject (e.g. $p < 0.05$) it is more likely that you are rejecting in error (no actual effect or wrong direction).
3) If you reject it is very likely that the effect size is over-estimated by a substantial amount or is in the wrong direction.

Here is a simple example to illustrate the problem. I will simulate many different data sets where the true effect size is about 50% of the standard deviation between effect sizes. This is in line with what was found in (Richardson and Béraud, 2014) for example.

I will take 10,000 samples of size 4 and analyze each to produce a p-value and an effect size. In the real world we only get one sample. Here, by repeating the experiment many times (through simulation), we can get a sense of how to interpret a single result. Here's the code:

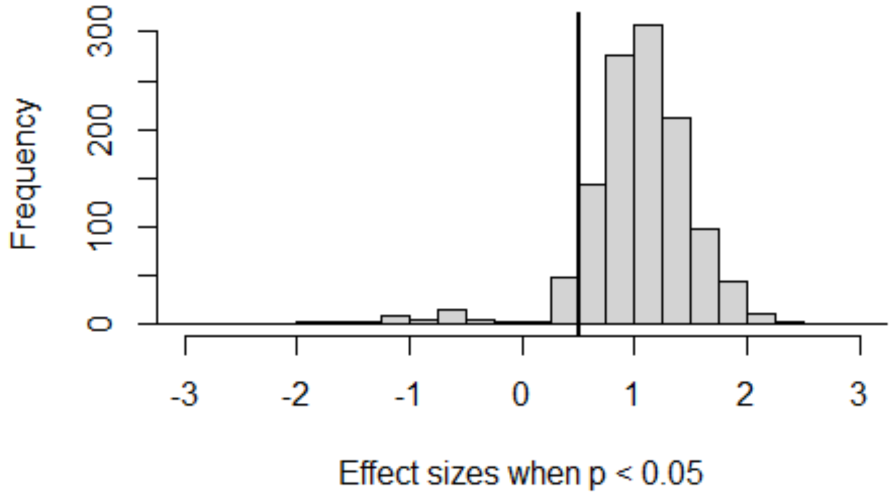
```r
effSize <- numeric(10000)
pVals <- numeric(10000)
for(i in 1:10000){
  samp <- rnorm(4,0.5,1)
  effSize[i] <- mean(samp)
  pVals[i] <- t.test(samp)$p.value
}
```

First let's look at the p-values. Here's a histogram of the p-values with a vertical line at 0.05.



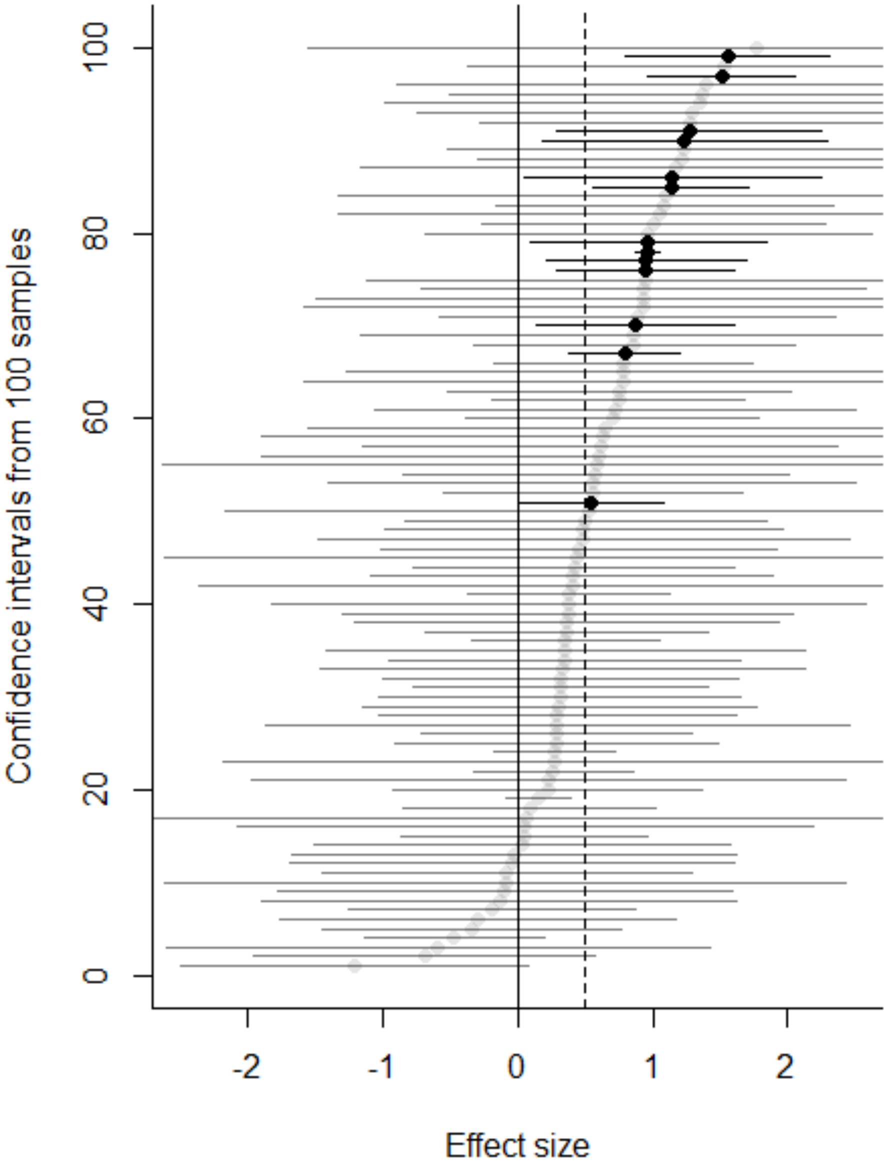
If we only reject when the p-value is less than 0.05, then we reject less than 12% of the time. This value is also called the power of the test. Here the power is low!

Now let's look at the effect sizes. Here is a histogram of the effect sizes for samples with $p < 0.05$. I added a vertical line at the true effect size (0.5) for reference.



Notice that estimated effect sizes tend to be much to big (about 2 times larger) or negative. This situation is referred to as magnitude and sign errors (type M and type S errors). This is very common when you have low powered designs (Gelman and Carlin, 2014).

It's easy to understand why this happens if you look at the confidence intervals for the estimated effect sizes. Here, I have generated random 100 samples of size 4 and plotted the estimated effect size (the mean) along with the 95% confidence interval.



Notice that because the confidence intervals are on average quite wide, in most cases the estimate has to be bigger than the true effect size in order for the confidence interval to exclude 0 (i.e. $p < 0.05$, the filled in points).

Another problem is that when you reject, there is a decent chance that there is actually no (or a negligible) effect. To illustrate this, consider a situation where you believe ahead of time that there is about a 50/50 chance that your hypothesis is true (or the effect size is non-negligible). We can represent that by considering 20,000 experiments where in half of the cases we have the scenario above (i.e. effect size = 0.5) and for the other half we have an effect size of 0.

| | Reject | Don't reject | %(reject) |
|---|---|---|---|
| Effect size = 0 | 480 | 9520 | 5 |
| Effect size = 0.5 | 1088 | 8912 | 11 |
| %(H0=true) | 31 | 52 | NA |

The table above summarizes the results of the 20,000 simulated data sets. As you can see, in 31% of the cases where you rejected, the null hypothesis was true (i.e. effect size=0), even though the probability of rejecting when then null hypothesis was true was only 5%.

To summarize, if you have an effect size that is 50% of the standard deviation between effect sizes (i.e. between block variability in effect size), and N=4, then:

- You have a 11% chance of rejecting with $p < 0.05$.
- If you reject there is a 31% chance that there is no effect (assuming 50/50 prior belief that there is an effect).
- If you reject, the estimated effect size will likely be over twice the true effect size.

There is a growing consensus in statistics that these types of problems are pervasive and need to be addressed (Amrhein et al., 2019a, 2019b; Button et al., 2013; Gelman and Carlin, 2014; Leek et al., 2017; Nuzzo, 2015).

This problems described above are just exacerbated when you have more than one treatment and many potential metrics to look at. Adding covariates or using more complex models is unlikely to help since the sacrificed degrees of freedom are unlikely to be paid back with sufficient explanatory power.

So, what does this mean?

Unless you have a large effect and/or low between basin variability in the effect size, your results will be uncertain (ambiguous). It will be very difficult to detect differences between treatments, because a) all include modern forest practices designed to avoid the large effects seen in historic clear cuts to the stream banks, b) most metrics are quite variable, and c) you have N=4. This means that you will likely end up in an ambiguous situation where a non-statistically significant result could mean anything from a large important difference to no effective difference.

## Recommendations

1) I would avoid thinking about things **dichotomously** (true/false). Instead, I would think of this as an estimation problem. This will do a couple things.
    a) It will be clearer that not rejecting is not the same as no-effect. By seeing the estimate and large confidence interval you can talk about the biological relevance of the observed effect size and the plausible range of values.
    b) If you do reject, you will likely see a large confidence interval which will include values close to zero. This will reduce the chances of over interpreting a surprisingly large effect size.
    c) You may be able to rule out certain situations. For example, you may be able to say with some confidence that the effect sizes is less a certain value.
2) In addition to the formal effects that you would like to estimate, I would include an exploratory analysis where you can look at many different questions without worrying about inflating your alpha (i.e. lot's of tests means more chances of a false positive). These results would then be presented as more hypothesis generating.
3) Examine hypotheses that can be asked at a more fine scale spatial resolution. For example, if there are multiple clearings in the new treatment, you can look at light/periphyton/etc… adjacent to and above each site and use this replication to estimate uncertainty in the effect size at the reach scale.
4) Consider reducing the number of treatments. This will increase replication for the remaining treatments.
5) Focus on metrics that are likely to be more directly linked to the treatments. For example, looking at changes in the number of spawning Coho would be futile! However, looking at light reaching the stream, or tree density (for thinning treatments) seems much more feasible. Things like invertebrate drift, or pool depths are less directly affected and will likely have more muted and variable responses.

6) Invest effort into collecting detailed information on implementation effectiveness and cost. For example, did the thinning achieve the desired density and spatial pattern. How profitable were the different treatments.
7) Simulate data. Choose a handful of metrics that represent the different types of things that will be measured. Then simulate, exactly the type of data you expect to collect (e.g. for each reach). Use results from other studies to get an idea of how large the effect size might be and how variable the measurements might be. Then, repeat an analysis similar to the one above.

I know that this all comes off as very negative. That's not the message I want to leave you with. I really like this project. I just want to create realistic expectations. When you have N=4, and the effect sizes for a given metric will likely be small and variable, it is unlikely that you will be able to say much about the relative merits of the different treatments.

## References

Amrhein, V., Greenland, S., McShane, B., 2019a. Scientists rise up against statistical significance. Nature 567, 305–307.

Amrhein, V., Trafimow, D., Greenland, S., 2019b. Inferential statistics as descriptive statistics: There is no replication crisis if we don't expect replication. The American Statistician 73, 262–270.

Button, K.S., Ioannidis, J.P., Mokrysz, C., Nosek, B.A., Flint, J., Robinson, E.S., Munafò, M.R., 2013. Power failure: Why small sample size undermines the reliability of neuroscience. Nature reviews neuroscience 14, 365–376.

Gelman, A., Carlin, J., 2014. Beyond power calculations: Assessing type s (sign) and type m (magnitude) errors. Perspectives on Psychological Science 9, 641–651.

Leek, J., McShane, B.B., Gelman, A., Colquhoun, D., Nuijten, M.B., Goodman, S.N., 2017. Five ways to fix statistics. Nature 551, 557–559.

Nuzzo, R., 2015. How scientists fool themselves–and how they can stop. Nature News 526, 182.

Richardson, J.S., Béraud, S., 2014. Effects of riparian forest harvest on streams: A meta-analysis. Journal of Applied Ecology 51, 1712–1721.