Riparian Function Literature Synthesis

Prepared for the Riparian Scientific Advisory Group (RSAG) of Washington State

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Background

Washington State Forest Practices rules and management guidelines covered by the FPHCP (Forest Practices Habitat Conservation Plan, 2006) are strongly influenced by the science of riparian processes articulated in the FPHCP Environmental Impact Statement (EIS Chapter 6 References, Appendix A Regional Summaries, Appendix B Riparian Modeling, 2005). The EIS references include the Forest Ecosystem Management Assessment Team (FEMAT) report, "Forest Ecosystem Management: an ecological, economic, and social assessment. Section V: Aquatic Ecosystem Assessment (1993)." Although the Forests and Fish Report and FPHCP and the rules derived from it considered many sources, our scientific understanding of riparian processes has evolved based on additional research that has been completed since then. More recent science has affirmed some aspects of the then-current state of knowledge on riparian processes and the effects of timber harvest on them. Still, some of the scientific conclusions are changing. In addition, riparian management strategies have evolved to address resource objectives. This synthesis will look at literature that has been completed since the FEMAT and Forests and Fish report, and the FPHCP EIS. It will inform the Adaptive Management Program (AMP) committees and the Forest Practices Board (FPB) regarding the effects of forest harvest and other management practices on riparian functions and processes.

This review will follow a similar but modified format of the riparian literature review developed by Schuett-Hames et al. (2015) for the Cooperative Monitoring Evaluation and Research Committee (CMER) under the Westside Type F Prescription Effectiveness Monitoring project. However, this review will not focus only on Type F (fish-bearing streams) but on the response of riparian functions following harvest in all forests adjacent to rivers and streams. Priority will be given to studies conducted in areas with similar habitat and landscape characteristics as those found in the state of Washington. Further, data extracted from these studies will include the experimental design and the variables measured, the metrics used to quantify these variables, and the methods used for their collection and analysis.

A synthesis of the reviewed literature will summarize the overall findings by key riparian function, and related physical processes, that will provide recommendations for future research. The riparian functions specified in the FPHCP include "large woody debris recruitment, sediment filtration, stream bank stability, shade, litterfall and nutrients, in addition to other processes important to riparian and aquatic systems." (FPHCP, 2006).

This literature review and synthesis will address specific questions (listed below) and identify appropriate variables and associated metrics that can be used to quantify and assess timber harvest effects on the riparian functions.

Focal Questions

1. What are the effects of timber harvest intensities and extent on the riparian functions, with an emphasis on the five key functions listed above, in comparison to conditions before harvest?

    a. What are the effects of thinning (intensity, extent) on the riparian functions, over the short and long-term compared to untreated stands?
    b. How do buffer widths and adjacent upland timber harvest prescriptions influence impacts of riparian thinning treatments?
    c. What are the effects of clearcut gaps in riparian stands (intensity, extent) on the riparian functions, over the short and long-term, compared to untreated stands
    d. How do buffer widths and upland timber harvest influence impacts of clearcut gaps treatments?
    e. What are the effects of any combinations of the above treatments?
2. How and to what degree do specific site conditions (e.g., topography, channel width and orientation, riparian stand age and composition) influence the response of the riparian functions?
3. What is the frequency of weather-related effects (e.g., windthrow, ice storms, excessive heat, flood and drought events) on riparian areas? What are the weather-related effects (positive and negative) on the riparian functions, and how are they distinguished from harvest effects? How do these effects differ between treated and untreated riparian forests?
4. How do various treatments within riparian buffers relate to forest health and resilience to fire, disease, and other forest disturbances?
5. How do the functions provided by riparian stands change over time (e.g., large woody debris recruitment from farther away from the stream)?
6. Are there feedback mechanisms (e.g., microclimate changes within the riparian buffer) related to forest management that affect the recovery rates of riparian functions?
7. What major data gaps and uncertainties exist relative to effects of timber harvest (both riparian and adjacent upland) on the riparian functions?

Methods

The riparian function literature synthesis includes literature pertinent to the effects of timber harvest, management, natural disturbances (e.g., fire, disease, insect infestation, etc.), and channel geomorphology in riparian areas on the "five key riparian functions" as defined in the Forest Practices Habitat Conservation Plan (FPHCP, 2006). Literature searches were primarily conducted using the Web of Science and Google Scholar. Sources were also gathered via personal communication with employees and members of the Washington State Department of Natural Resources' Cooperative Monitoring Evaluation and Research (CMER) scientific advisory groups. Technical reports on the United States Forest Service website were also investigated for their potential use. Finally, we also considered studies and manuscripts unpublished in formal scientific journals available on ResearchGate and ProQuest, including Ph.D. dissertations and master's theses. Papers returned from the keyword searches were initially screened by title and abstract. Papers were deemed appropriate for inclusion if they fit 3 criteria: (1) utilize experimental designs such as before-after-control-impact (BACI), after-control-impact (ACI), before-after-impact (BAI), after-impact (AI), simulation modeling, or meta-analysis to quantify the effect of riparian forest treatment, harvest, disturbance, site characteristics and conditions, etc. on riparian functions with an emphasis on the five key functions, (2) have been published or completed since the Forest and Fish report, i.e., 1999, (3) have been conducted in western North America including coastal Alaska, southern and coastal British Columbia, southern Alberta, the Pacific Northwest, the Intermountain West, and the Great Basin regions. Studies from outside these areas were included if they contained generalizable information about riparian functions (e.g., the relationship of canopy cover with shade and temperature).

A list of search terms was developed to capture any studies relevant to the topics of the seven focal questions (Table. 1). A master list of all returned study titles and abstracts from Web of Science was also compiled for further analysis of keyword popularity and combinations (Figure 1).

Table 1. List of terms used in search of keywords and titles of literature sourced from Web of Science. Terms in **bold** were used in all searches. Terms were grouped by topic (e.g., management, physiography, disturbance, etc.). Results show the number of publications returned for each combination of search terms.

Key Words/title	Results
(Riparian OR stream OR headwater Or Watershed) AND	
(Function OR sediment OR nutrient OR woody debris OR large wood OR LWD OR woody debris recruitment OR shade OR temperature OR light OR litter OR water quality OR diversity OR wood*) AND/OR	15,138
(Manag* OR harvest OR thin* OR forest* OR forest operation OR buffer OR buffer strips OR gap* OR treat* OR clearcut OR clearcut gap)	12,602
(Topograph* OR physiograph* OR channel width OR stream width OR bankfull width OR valley constraint OR morphology OR diversity OR distance to stream OR Parent material OR soil OR litholo* OR geolog*)	12,381
(Disturbance OR fire OR windthrow OR ice storms OR drought OR flood* OR resilience OR resistance OR microclimate OR site conditions)	12,725
(Climate)	12,588
(feedback OR long-term OR short-term OR time)	12,150
(Forest health OR recovery OR regeneration OR disease OR insect OR fung* OR patho*)	12,328
(Stand structure OR stand age OR composition OR density OR structure OR species OR species composition)	12,214
Total titles and abstracts searched, excluding duplicates	**16,750**

From the initial title and topic review of the 16,516 papers sourced in our search, we refined the list to 528 papers for consideration based on the 3 criteria listed above (e.g., utilize experimental design with results focusing on at least one of the five key functions; published after 1999; were conducted in western North America). From these 528 papers we further refined our list to 105 articles based on information gleaned from the abstract, introduction and methods sections regarding study design and relevant geography. Of these 105 articles 91 provided information on at least one of the five key functions and were thoroughly read and used to develop an annotated bibliography (Appendix). The other 14 articles provided information and experimental results about fire frequency and fire behavior in riparian areas, or effects of fire on one of the five key functions. These 14 papers about fire were not included in the literature review but were reviewed and discussed in focal questions 3 and 7. Frequency of the top 8 keywords were represented in a histogram to express the popularity of topics in the literature since the year 2000 (Figure 1). We organized our review of the relevant literature by (1) FPHCP objective and (2) focal question. A table was submitted along with this report that gives a more thorough description of details used to categorize publications in supplemental materials (supplemental table of references; S1).

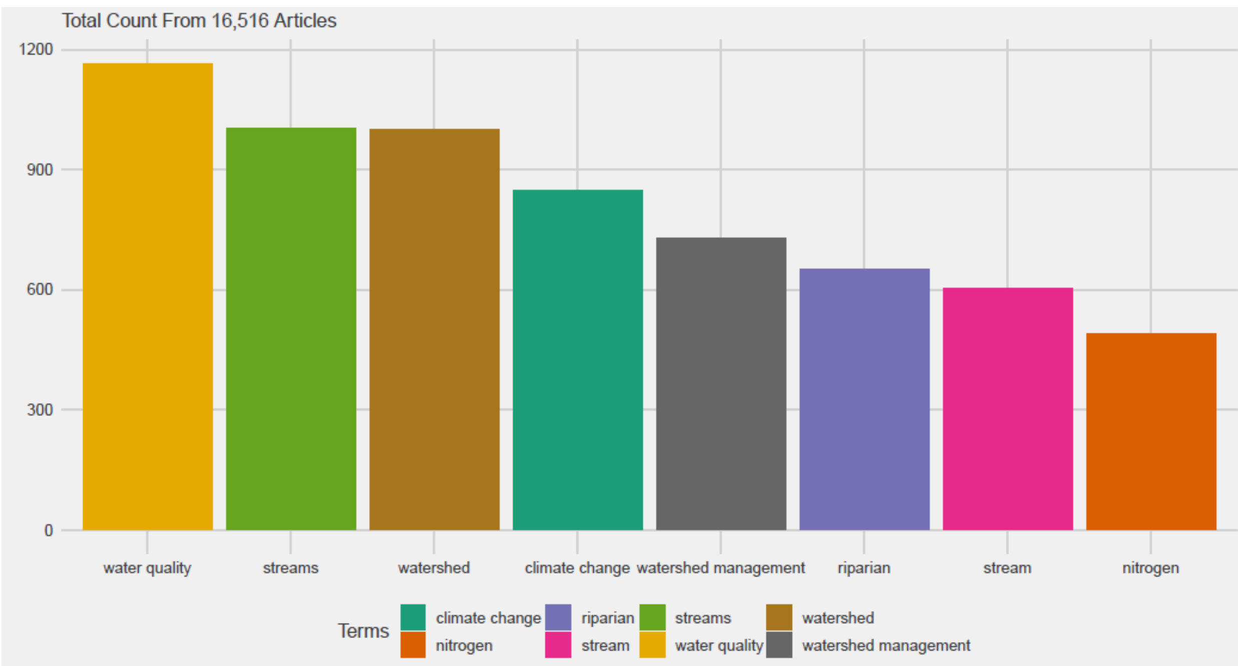

Figure 1. Frequency of keywords in the original 16,516 publications sourced from Web of Science

Results/Summary of Review

We conducted our review of the 72 relevant publications to (1) summarize the most current state of knowledge of how timber harvest affects riparian function and related processes with a focus on the five key riparian functions defined in the FPHCP, and (2) extract information that has the potential to provide answers to, or methods and experimental designs that could be used to answer the 7 focal questions. Our review focused primarily on peer-reviewed journal publications but included 3 CMER reports and 1 report from the United States Forest Service website. Of these 72 studies, 33 were conducted on headwater or non-fish-bearing streams, 16 on fish-bearing streams, and 23 on a combination of fish and non-fish-bearing streams or hypothetical streams in a model simulation. Most of the studies reviewed were conducted in the Pacific Northwest region but several from just outside this region (British Columbia, Alberta, Idaho, Montana, Wyoming, Colorado) were also included (Figure 2.). Few studies could be found that quantify how riparian area treatments directly affect bank stability. Several CMER studies, however, have investigated the effects of riparian timber management on soil and streambank disturbance and erosion (Ehinger et al., 2021; McIntyre et al., 2018; Schuett-Hames et al. 2011). In these studies, soil/bank disturbance and erosion were further analyzed for their contribution to sediment export and delivery to streams. Because of this relationship between bank erosion and sediment delivery, bank stability is discussed and reviewed in the section with sediment. Further, because of the paucity of studies in the literature that provide experimental evidence of how riparian area treatments affect bank stability, studies that investigate bank stability or bank erosion based on other factors (e.g., vegetation type, vegetation coverage) have been included and reviewed in question 7. These studies are provided as recommendations for methods that could be used in an experimental design comparing changes in bank stability before and after treatment or between treated and untreated riparian stands.

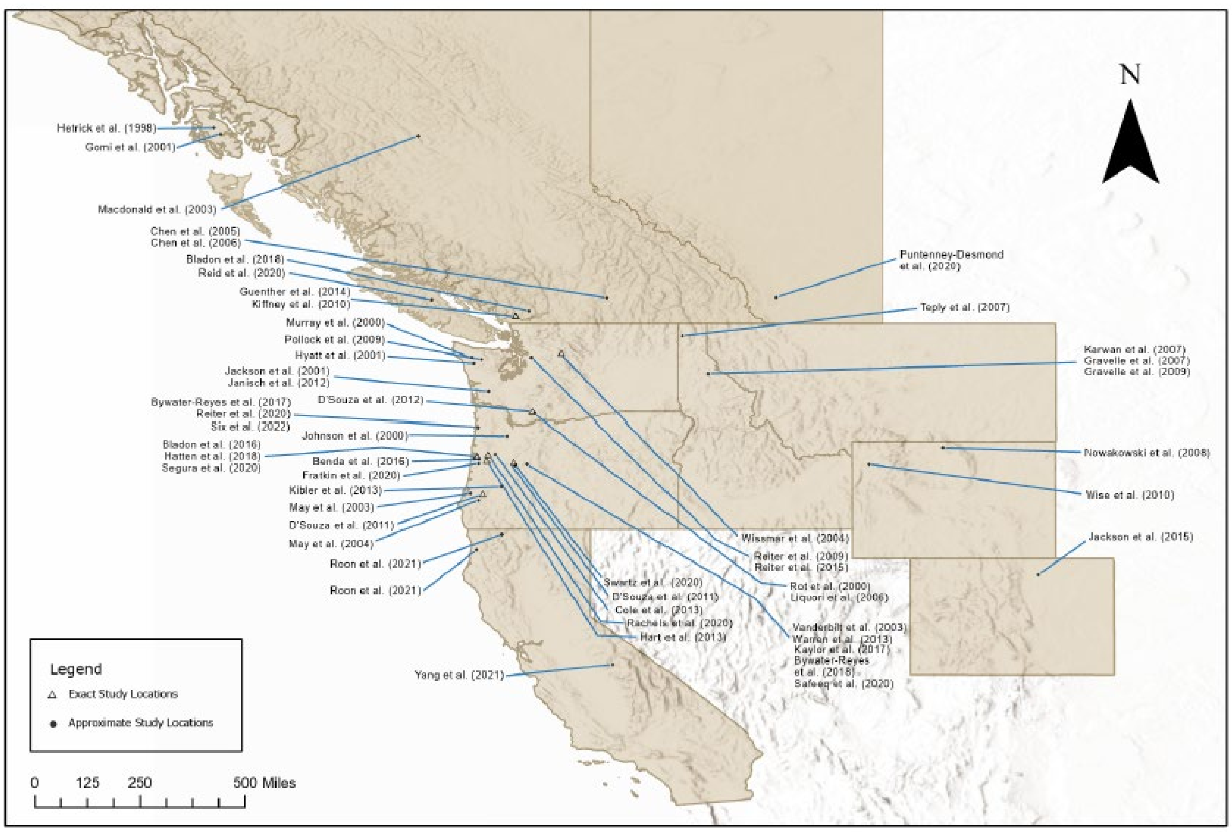

Figure 2. Locations where studies were conducted. References not listed include studies that sourced data from multiple locations.

Discussion of findings relative to FPHCP objectives

Litter/Organic matter inputs/Nutrients

Prior to the Forest and Fish Report (1999), studies that directly quantify the effects of timber harvest within riparian areas on litter and organic matter (OM) input into streams in managed watersheds of western north America are sparse. Two seminal studies, one from the H.J. Andrews experimental watershed studies (Gregory et al., 1987) and one from the Carnation Creek experimental watershed (Hartman & Scrivener, 1990) present results that estimate loss of litter input following harvest. Gregory et al., (1987) which was part of the Streamside Management: Forestry and Fishery Management collection produced by Salo & Cundy (1987) noted that removal of the forest canopy from timber harvesting resulted in decreases in annual litter fall from 300-400 g/m^2 in the mature forests to less than 100 g/m^2. Further, they posit that decreased litter inputs after logging can persist for 10 – 20 years before recovering. Results from Hartman & Scrivener, (1990) showed that litter inputs post-logging were 25-50% of pre-logging levels with about 50% of the loss recovering within a decade (note: buffer widths varied from 1-70 m, litter input loss was not analyzed by buffer width).

Experimental studies published after 1999 that investigate the factors affecting litter and organic matter (OM) input (not including LW) into streams in western North America are still relatively few. In our search we found six papers that quantify the effects of timber harvest or the effects of site factors (e.g., topography, vegetation characteristics) Four of these studies focus on headwater streams and two of the studies reviewed here extend into larger fish-bearing streams (Bilby & Heffner, 2016; Hart et al., 2013; Kiffney & Richardson, 2010; McIntyre et al., 2018; Six et al., 2022; Yeung et al., 2019).

Studies specifically investigating controls on litter inputs used litter traps for sample collection and quantify changes in litter delivery from dry weight. Before litter quantification, it is commonly separated by type (e.g., leaves, twigs, cones, etc.), species (e.g., hardwood, conifer), season, and distance from stream. Litter weights are usually compared with treatment (e.g., harvest intensities, buffer widths), site factors (e.g., slope, species composition, stand density, distance to stream), and local weather conditions (e.g., precipitation, wind speed) with statistical or simulation modeling.

In terms of site factors, Bilby & Heffner (2016) used a combination of field experiments, literature review, and modeling to estimate the relative importance of factors affecting litter delivery from riparian areas into streams of western Washington in the Cascade mountains at high and low elevations. Their results showed that under the wind conditions recorded at Humphrey Creek, most litter recruited into the stream originated from within 10 m of the stream regardless of litter or stand type. No difference was found in delivery distance and litter type (needles or broadleaf) at young sites. However, needles released at mature sites had a higher proportion of cumulative input from greater distances than needles or alder leaves released at younger sites. Litter travel distance was linearly related to wind speed ($p < 0.0001$). Doubling wind speed at one site led to a 67-87% expansion of the riparian litter contribution zone in the study area. The results also reveal a trend that suggests slope affects the width of the litter contributing area. However, the authors did not apply statistical analysis to these values and only speculate that increasing the slope from 0-45% would increase the width of the litter contributing area by up to 71% for needles and 95% for leaves. From these results, Bilby & Heffner (2016) suggest that wind speed has a strong effect on the width of litter delivery areas within riparian areas, but that relationship is also affected by stand age (suggesting that tree height was a factor) and litter type (deciduous vs. conifer). Other than stand structure and topography, another study shows evidence of species composition affecting litter delivery into streams. Hart et al. (2013) compared litter delivery into streams between riparian zones dominated by deciduous (red alder) and coniferous (Douglas-fir) tree species in western Oregon. Results from this study show that deciduous forests dominated by red alder delivered significantly greater vertical and lateral inputs (g m^{-2} y^{-1}) to adjacent streams than did coniferous forests dominated by Douglas-fir. Deciduous-site vertical litter input (mean = 504 g m-2 y-1) exceeded that from coniferous sites (394 g m-2 y-1) by 110 g/m2 over the full year. Annual lateral inputs at deciduous sites (109 g m-2 y-1) were 46 g m-2 y-1 more than at coniferous sites (63 g m-2 y-1). The timing of the inputs also differed, with the greatest differences occurring in November during autumn peak inputs for the deciduous forests. Further, annual lateral litter input increased with slope at deciduous sites (R2 = 0.4073, p = 0.0771), but showed no strong relationship at coniferous sites (R2 = 0.1863, p = 0.2855). These results were partially consistent with Bilby & Heffner (2016) in that they suggest litter type, and topography (slope) can affect the litter input rates. Lateral litter movement in the riparian area increased with slope for deciduous riparian forests throughout the year and for coniferous forests only in the spring and summer months.

In terms of the effects of timber harvest on litter and OM quantity in streams, 4 studies in our review were found that provide experimental results that have been conducted since 2000 and focus on western North America. Of these 4 studies, 1 used simulation modeling (Yeung et al., 2019), and the other 3 (Kiffney & Richardson, 2010; McIntyre et al., 2018; Six et al., 2022) used field-based experiments to estimate the effects of timber harvest within riparian forests on OM inputs and dynamics in streams. Yeung et al. (2019) simulated post-harvest responses to leaf-litter derived coarse particulate organic matter (CPOM) quantity in a coastal rainforest stream in British Columbia, Canada. For this study, Yeung et al. (2019) used published empirical data from representative small, forested streams in coastal British Columbia to calibrate and set parameters for their CPOM model. The model compared the effects litterfall reduction, increase in peak flows, and increase in stream temperature (estimated for 4 harvesting intensities based on available data) on in stream CPOM standing stocks. Results showed evidence that litterfall reductions from timber harvest was the strongest control on in-stream CPOM quantity for 4 years post-harvest. However, when litterfall reductions were below 30%, the effect size varied with relative changes to peak flows and stream temperature. Stream temperature increases specifically showed a significant interaction with litterfall reductions. The authors propose that the decreased activity of CPOM consumers caused by increasing stream temperatures by 4 ^{0}C or more, may be enough to offset the loss of litterfall inputs of CPOM stocks. This speculation was made based on the temperature dependent function of leaf litter consumption by common shredder species and temperature ranges modeled by Stenroth et al. (2014).This model predicts shredder activity is optimized at ~15 ^{0}C but begins to quickly decline at temperatures above 16 ^{0}C. The caveat of this study is that it did not include LW dynamics in preserving CPOM post-harvest.

All four studies that applied an experimental design to assess the changes in litter and OM delivery into streams used a Before-After Impact-Control (BACI) design. Also, all these studies compared changes in litter and OM inputs into streams for two or more riparian forest harvest prescriptions (Table 2). Kiffney & Richardson (2010) compared changes in litter input between riparian harvest prescriptions that included clear-cut to stream edge, 10 m wide buffer reserve, 30 m buffer reserves, and an uncut control over the course of 8 years. No thinning was applied within the reserves. Upland treatment at all sites applied clearcut. Results showed differences in litter flux relative to riparian treatment persisted through year 7, while a positive trend between reserve width and litter flux remained through year 8. Needle inputs remained 6x higher in the buffer and control sites through year 7, and 3-6x higher in year 8 than in the clearcut sites. Twig inputs into the control and buffered sites were ~25x higher than in the clearcut sites in the first year after treatment. The linear relationship between reserve width and litter inputs was strongest in the first year after treatment, explaining ~57% of the variation, but the relationship could only explain ~17% of the variation in litter input by buffer width by year 8 (i.e., the relationship degraded over time). The authors interpret these results as evidence that litter flux from riparian plants to streams, was affected by riparian reserve width and time since logging.

McIntyre et al. (2018) also assessed the difference in the changes in litterfall inputs into streams following three experimental treatments: an unharvested control (Reference), current Forest Practices that apply a two-sided 50-ft riparian buffer along at least 50% of the stream (FP; with clearcut to stream's edge outside of the buffer), a two sided 50-ft buffer along the entire stream (100%), and a clearcut to stream without a buffer (0%). The upland forests of all treatments were clearcut harvested. Results for litterfall input showed a significant decrease in total litterfall (includes leaves/needles, twigs, cones etc.) input in the FP and 0% treatments between pre- and post-treatment periods (2 years of pre-, and 2 years of post-harvest data). However, compared to the Reference streams, only the 0% treatment (unbuffered) showed a significantly lower litterfall input post-harvest and only for deciduous leaves, and combined total of deciduous leaves and conifer needles. The 100% buffer showed a non-significant increase in litterfall inputs relative to the reference streams. The authors interpret these results as evidence that the riparian vegetation community in the unbuffered treatment had not recovered by the end of year 2 post-harvest.

Six et al. (2022) also investigated the effects of timber harvest on litter inputs. However, this study had no replication in their design for each treatment and only 2 control sites (i.e., n = 1 for each treatment). The results are presented here because there is a general lack of studies available in the literature after 2000 that provide experimental evidence of the effects of riparian timber harvest on litterfall inputs into streams. Six et al. (2022) compared changes in litterfall pre- and post-treatment between sites with a complete clearcut to stream, a clear cut with leave trees (retention of 5 trees per hectare), clearcut with a 15 m no-cut retention buffer, and an uncut control. Because of the small sample sizes, no tests for significance could be applied. However, the authors interpreted the data with descriptive statistics and graphical summaries. Their results showed post-harvest litter delivery decreased for the clearcut with no leave trees but increased for both the clearcut with leave tree and clear cut with retention buffer. These results are somewhat consistent with those of McIntyre et al., (2018) which showed significant decreases in litter delivery only in sites with no retention buffer.

The objective of the study from Wooton (2012) was to assess how riparian area treatments impact river food webs with an emphasis on economically important salmonid species in an Olympic Peninsula River in Washington state. However, they present results and statistical analysis for differences in litter inputs (g m^{-1} hr^{-1}) between treated and untreated reaches. Because of the lack of litter input studies in literature, their results are presented here. Wooton (2012) removed the dominant tree species, red alder (Alnus rubra), from one bank along five treatment reaches ranging from 100-300 m long and replaced them with conifer seedlings. Paired control reaches were interspersed between treated reaches along the stream. Specific methods for tree removal or width of buffer in treatment reaches were not reported. Leaf litter decreased significantly ($p = 0.04$) in the treatment reaches compared to the control reaches (4.92 + 2.55 vs. 14.12 + 5.70 g m^{-1} hr^{-1}).

Nutrients

Riparian timber management practices in the 1970s were developed for water quality standards with the development of the Clean Water Act of 1972, based on nutrient concentrations and water clarity. Before implementing these BMPs, timber harvest practices included clearcut to the stream edge, burning of slash, and application of pesticides which resulted in large and immediate increases in stream water nutrient concentrations that remained higher than pre-harvest or reference stream values for months and even years (Brown, 1973; Fredriksen, 1975). However, BMP development and implementation over the past several decades have shown evidence of their effectiveness in minimizing these effects both in magnitude and across time (Deval et al., 2021; Shah et al., 2022; Stednick, 2008). For example, Shah et al. (2022) in their global review of the effects of forest management on water quality under contemporary management practices concluded that the development of BMPs across the world has resulted in reduced or in some cases, undetectable impacts on water quality. However, they also report that harvest impacts on nutrient concentrations can be complex and depending on the management practices implemented, their effects may manifest many years after the work has been completed (e.g., slow decomposition of slash, regrowth of vegetation, changes in land use). Indeed, Sweeney & Newbold (2014) in their literature review and synthesis on the efficacy of forest buffers in protecting water quality based on buffer width, remark on the high variability of responses across studies. They report that removal of nitrogen from upland sources per unit width of a forested buffer varied inversely with subsurface water flux. This suggests factors that influence water flux through the buffer (e.g., hillslope gradient, soil porosity, vegetation type and composition, precipitation) also impact buffer efficacy in removing nutrients and pollutants.

Zhang et al. (2010) in a review and meta-analysis of the effectiveness of buffers in reducing nonpoint source pollution found comparable results. They reported slope (hillslope gradient) as having a linear relationship with buffer pollutant removal efficacy that switched from positive to negative when slope increased beyond 10% (i.e., hillslope gradients of ~10% were optimal for buffer efficacy in removing pollutants). However, there may be some variation in these relationships based on the nutrient or pollutant observed (e.g. form of nitrogen, phosphorus, etc.). For example, Vanderbilt et al. (2003) analyzed long-term datasets (ranging 20-30 years for each watershed) to investigate patterns in dissolved organic nitrogen (DON) and dissolved inorganic nitrogen (DIN) export with watershed hydrology. Their results showed that total annual discharge was a positive predictor of annual DON export in all watersheds with R^2 values ranging between 0.42 to 0.79. In contrast, relationships between total annual discharge and annual export of nitrate (NO3-N), ammonium (NH4-N), and particulate organic nitrogen (PON) were variable and inconsistent across watersheds. The authors speculate that different factors may control organic vs. inorganic N export.

In our search of the literature, four studies were found that provide experimental evidence of the effects of riparian timber harvest on nutrient flux in western north America and were published since 2000. Gravelle et al., 2009 compared the effects of contemporary forest harvesting practices in Idaho on nutrient cycling and in stream concentrations. This study followed the BACI design and featured a pre-treatment measurement phase (5 years), a post-road construction phase (5 years), and a post-harvest phase (5 years). Treatments imposed included a clearcut to stream with 30-foot equipment exclusion zone (non-fish-bearing), a target reduction of 50% of the canopy removal over 50% of the area, equating to 25% removal of existing shade (fish-bearing streams), and was compared to an uncut reference. Results for the post-road construction period showed no significant changes in any analyzed nutrient concentrations. Results for the post-harvest period showed significant increases in monthly mean nitrate and nitrite (NO^3 and NO^2) at sites immediately downstream from the clearcut, the partial harvest, and at sites downstream from both treatments in the stream network (cumulative). The changes in monthly mean NO3 and NO^2 during the five years post-harvest were greatest for the clearcut treatment (+0.29 mg L^{-1}), followed by the cumulative (+0.07 and +0.05 mg L^{-1}) and partial harvest (+0.03 mg L^{-1}). NO^3 showed progressively increasing monthly concentrations for 3 years after harvest before declining. None of the other nutrients analyzed in this study (Kjeldahl nitrogen (TKN), total phosphorus (TP), total ammonia nitrogen (TAN) consisting of un-ionized (NH^3) and ionized (NH^{4+}) ammonia, and unfiltered orthophosphate (OP) samples) showed significant changes during the post-harvest period.

In a follow up study, Deval et al. (2021) compared changes to nutrient concentrations 8 years after Gravelle et al. (2009) completed their study. During these 8 years (extended harvest period) the extent and frequency of harvest operations increased. Treatments consisted of additional road construction and timber harvest (clearcut), with site management operations including pile burning and competition release herbicide application. Following these treatments, streams in all harvested watersheds again experienced significant increases in NO^3 + NO^2 concentrations of even higher magnitude than during the first post-harvest period. Further, there were also small but significant increases in mean monthly total phosphorus (TP) concentrations at all treatment sites, including the downstream cumulative site. Cumulative NO^3 +NO^2 concentrations increased throughout the study but showed signs of recovery in one watershed approximately 3 years after the last treatment (clearcut, broadcast burn, herbicide). The authors attribute the increase in NO^3+NO^2 and TP during the extended harvest periods (i.e., beyond what was observed in the first post-harvest period) to the application of herbicides and broadcast burning.

In general, the authors of both these studies (Deval et al 2021; Gravelle et al., 2009) concluded that Idaho BMPs for riparian forest harvest are effective in reducing sediment and pollutants into streams. While there were significant increases in nitrate and nitrite concentrations following management operations, levels never increased above acceptable values for water quality standards and there was evidence of nitrogen recovery to pre-harvest (or unharvested) levels after 3 years.

Considering the interaction between climate and forest harvest on nutrient transport, Yang et al. (2021) investigated the effects of drought and forest thinning operations (independently and combined) on stream and soil water chemistry in the Mediterranean climate headwater basins of the Sierra National Forest. Data on water chemistry were taken 2 years prior and 3 years following drought and thinning operations in two watersheds, each with thinned and control stands. Young stands with high shrub cover (> 50%) were masticated to < 10% shrub cover. The thinning prescription in mature stands removed trees across all diameter classes to a target basal area range of 27–55 m^2 ha^{-1} with target basal areas varying based on tree density. Thinning extended into the riparian management zone. Trees within 15 m of the stream could be chainsaw-felled and skidded, but mechanical equipment was excluded within 30 m of the stream. Results showed that drought alone altered dissolved organic carbon (DOC) in stream water, as well as altered the proportion of dissolved organic carbon to nitrogen (DOC: DON) in soil solution in unthinned (control) watersheds. Volume-weighted concentration of DOC was 62% lower ($p < 0.01$) and DOC:DON was 82% lower ($p = 0.004$) in stream water and soil solution, respectively, during years of drought than in years prior to drought. Drought combined with thinning altered DOC and dissolved inorganic nitrogen (DIN) in stream water, and DON and total dissolved nitrogen (TDN) in soil solution. For stream water, volume-weighted concentrations of DOC were 66- 94% higher in thinned watersheds than in control watersheds for all three consecutive drought years following thinning. No differences in DOC concentrations were found between thinned and control watersheds before thinning. The authors conclude that their results provide evidence that the influences of drought and thinning are more pronounced for DOC than for nitrogen in streams. They also speculate that the periodic changes in climate (e.g., seasonal, drought) contribute to the high variability in carbon and nitrogen concentration in streams in Mediterranean climates following harvest.

Specific to Washington, the Hard Rock (McIntyre et al., 2021) and the Soft Rock (Ehinger et al., 2021) studies also reported on changes in nutrient concentrations and nutrient export in streams following riparian timber harvest along headwater streams of western Washington. Treatments included a 50 ft buffer along both sides of the stream for the entire RMZ (“100%”), 50 ft buffer along at least 50% of the RMZ (“FP”), clearcut to stream (“0%”), and an unharvested reference (Ref). Results for nitrogen and phosphorus concentrations in streams showed that post-harvest changes for total-N or total-P were not significant for any of the treatments relative to the Reference. The only significant difference detected post-harvest was for nitrate-N concentration between the 0% buffer treatment and all other treatments. However, for annual export (kg ha-1 yr-1), total-N and nitrate-N export increased post-harvest at all sites, with the smallest increase in the 100% treatment and the largest in the 0% treatment. Compared to the reference sites, analysis showed an increase in total-N export of 5.52 ($P = 0.051$), 11.52 ($P = 0.0007$), and 17.16 ($P < 0.0001$) kg ha-1 yr-1 in the 100%, FP, and 0% treatments, respectively, in the first 2 years post-harvest. In the extended period (7-8 years post-harvest) export for total-N remained higher in all treatments compared to the reference by 6.20 (P = 0.095), 5.34 (P = 0.147), and 8.49 (P = 0.026) kg ha-1 yr-1 for the 100%, FP, and 0% treatments, respectively. Nitrate-N showed the same pattern with slightly lower values than total-N. The increase in total-N and nitrate-N export from the treatment watersheds post-harvest was strongly correlated with the increase in annual runoff (R2 = 0.970 and 0.971; P = 0.001 and 0.001) and with the proportion of the basin harvested (R2 = 0.854 and 0.852; P = 0.031 and 0.031). The authors note that there was high variability in the data for the extended period and nitrate-N export only returned to pre-harvest levels in one watershed. Total-P export increased post-harvest by a similar magnitude in all treatments: 0.10 (P = 0.006), 0.13 (P = 0.001), and 0.09 (P = 0.010) kg ha-1 yr-1 in the 100%, FP, and 0% treatments (only analyzed during the 2-year post-harvest period). The authors conclude that the 100% treatment was generally the most effective in minimizing changes from pre-harvest conditions, the FP was intermediate, and the 0% treatment was least effective. Thus, similar to the results of other studies reviewed, these results provide evidence that the effects of timber harvest on nutrient export is proportional to the intensity of the treatment (e.g. percent of basin harvested, presence of protective buffer).

Summary of Factors Impacting Nutrient Concentrations and Export

Similar to instream sediment concentrations and export, there is evidence from the studies reviewed that nutrient dynamics are affected by the intensity of riparian timber harvest (e.g., presence of buffer widths, percent of basin harvested), changes in streamflow (either seasonally or from harvest), climatic events (e.g., drought, heavy precipitation), physiography (e.g., hillslope gradient), and soil disturbance. The Soft Rock study (Ehinger et al., 2021) did analyze changes in both sediment and nutrient flux following harvest for comparison with the Hard Rock study. While the authors of this study report that the softer lithologies were more erodible than the sites sampled for the Hard Rock study and that nutrient flux was within the range of results for the Hard Rock study, effects of treatment and significant differences between studies could not be detected because of limited sample sizes, inconsistent buffer widths, and timing of harvest.

In contrast to the results for sediment, there is evidence that changes in nutrient flux following harvest can persist for considerably longer periods. This has been attributed to management operations such as slash burning, herbicide or fertilizer application that directly affect nutrient loads, and from decomposition of unburned downed wood and litter (Deval et al., 2021: Shah et al., 2022). Results showed that instream dissolved organic carbon (DOC) concentrations of un-thinned stands during drought years were lower, and aromatic DOC was higher than in non-drought years. In-stream DOC concentrations were higher for three consecutive years following thinning, than un-thinned stands.

Table 2. List of treatments, variables, metrics, and results from publications reviewed for information on litter, organic matter, and nutrient inputs.

Reference	Treatment	Variables	Metrics	Notes	Results
Anderson et al., 2007	Upland stands either thinned to 198 TPA or unthinned and ranged from 500-865 TPA. Within thinned stands, 10% of the area was harvested to create patch openings. streamside buffers ranged in width from <5 m to 150 m.	Microsite, microclimate, stand structure, canopy cover	Microsite and microclimate data (humidity, temperature sensors). Stand basal area. Canopy cover was estimated through photographic techniques.	Many of the reported differences in temperature and humidity were considerable but not significant. Results for changes in upland areas not reported here.	Subtle microclimatic changes as mean temperature maxima in treated stands were 1 to 4°C higher than in untreated stands. Buffer widths greater than or equal to 15 m experienced a daily maximum air temperature above stream center of less than 1°C greater than untreated stands. Daily minimum relative humidity for buffers 15 m or greater was less than 5 percent lower than for unthinned stands. Air temperatures were significantly higher in patch openings (+6 to +9°C), and within buffers adjacent to patch openings (+3.5°C), than in untreated stands.
Bilby & Heffner, 2016	Various wind speeds for young and old-growth conifer and deciduous forests. Distance of litter delivery.	Litter input	Models were developed with site characteristics and litter release experiments from sites along Humphrey Creek in the cascade mountains of western Washington. .	Wind speeds, direction, and litter release data were collected for only one year in one area of western Washington.	The results of the linear mixed model developed by the authors showed the strongest relationship for recruitment distance was with wind speed ($p<0.0001$). Using this relationship the authors estimated that the effective delivery area could be increased by 67-81% by doubling wind speed. The other significant relationship was with stand age for needles (not alder leaves). Needles released from mature stands traveled further distances. This is likely due to the higher height of the canopy in the mature stands.
Deval et al., 2021	clearcut to stream, 50% shade retention, with site management operations including pile burning and competition release herbicide application.	Changes in nitrogen and phosphorus compounds.	monthly grab samples from multiple flume sites pre- and post-harvest, laboratory chemical analysis	Data was compared from pre-harvest to post experimental harvest (PH-I), and post operational harvest (PH-II)	The response in NO3 + NO2 concentrations was negligible at all treatment sites following the road construction activities. However, NO3 + NO2 concentrations during the PH-I period increased significantly ($p < 0.001$) at all treatment sites. Similar to the PH-I period, all watersheds experienced significant increases in NO3 + NO2 concentration during the PH-II treatment period. Overall, the cumulative mean NO3 + NO2 load from all watersheds followed an increasing trend with initial signs of recovery in one treatment watershed after 2014. Mean monthly TP concentrations showed no significant changes in the concentrations during the post-road and PH-I treatment periods. However, a statistically significant increase in TP concentrations ($p < 0.001$) occurred at all sites, including the downstream cumulative sites, during PH-II. Generally, OP concentrations throughout the study remained near the minimum detectable concentrations

Gravelle et al., 2009	clearcut to stream, 50% shade retention, uncut reference	Changes in nitrogen and phosphorus compounds.	monthly grab samples from multiple flume sites pre- and post-harvest, laboratory chemical analysis	Data was compared in three treatment periods: pre-harvest, under road construction, post-harvest.	Results showed significant increases in monthly mean NO3 and NO2 following clear-cut harvest treatments relative to the pre-harvest, and road construction periods. Monthly nitrate responses showed progressively increasing concentrations for 3 years after harvest before declining. Significant increases in NO3 and NO2 concentrations were also found further downstream but at values lower than those immediately downstream from harvest treatments. No significant changes of in-stream concentration of any other nutrient recorded were found between time periods and treatments except for one downstream site that showed a small increase in orthophosphate by 0.01 mg P L –1.
Hart et al., 2013	(1) a no cut or fence control; (2) cut and remove a 5 x 8 m section adjacent to stream for plants < 10 cm DBH and >12 cm; and (3) 5 m fence extending underground and parallel to the stream to block litter moving downslope from reaching stream	Litter inputs, vegetation composition, topography, litter chemistry	Litter collected with lateral and vertical traps. Litter was sorted by type, time of fall, spatial source, and quantified by weight. Vegetation, LW, and Site characteristics were quantified for each plot.	This study took place within 5 contiguous watersheds located in the central Coast Range of Oregon.	Deciduous forests dominated by red alder delivered greater vertical and lateral inputs to streams than did coniferous forests dominated by Douglas-fir by 110 g/m2 (28.6–191.6) and 46 g/m (1.2-94.5), respectively. Annual lateral litter input increased with slope at deciduous sites (R2 = 0.4073, p = 0.0771) but not at coniferous sites (R2 = 0.1863, p = 0.2855). Total nitrogen flux to streams at deciduous sites was twice as much as recorded at coniferous sites. However, the nitrogen flux had a seasonal effect with the majority of N flux occurring in autumn at the deciduous sites. The authors of this study conclude by suggesting management in riparian areas consider utilizing deciduous species such as red alder for greater total N input to aquatic and terrestrial ecosystems with increased shade and large woody debris provided by coniferous species.
Kiffney & Richardson, 2010	clearcut to stream, 10 m buffer, 30 m buffer, uncut control	Litter inputs.	Litter was separated into broadleaf deciduous, twig, needles, and other (seeds, cones, and moss) categories following collection and subsequently dried and weighed using a microbalance.	Sites were measured over an 8-year period and included clear-cut (n=3), 10-m buffered reserve (n=3), 30-m buffered reserve (n=2), and uncut control (n=2) treatments.	Inputs consisting of needles and twigs were significantly lower adjacent to clearcuts compared to other treatments, while deciduous inputs were higher in clearcuts compared to other treatments. For example, one year post-treatment, needle inputs were 56x higher during the Fall into control and buffered treatments than into the clearcut. Needle inputs remained 6x higher in the buffer and control sites through year 7, and 3-6x higher in year 8 than in the clearcut sites. Twig inputs into the control and buffered sites were ~25x higher than in the clearcut sites in the first year after treatment. There was no significant difference in treatment for deciduous litter but a trend of increasing deciduous litter input in the clear cut was observed in the data. The linear relationship between reserve width and litter inputs was strongest in the first year after treatment, explaining ~57% of the variation, but the relationship could only explain ~17% of the variation in litter input by buffer width by year 8 (i.e., the relationship degraded over time).

McIntyre et al., 2018	(1) unharvested reference, (2) 100% treatment, a two-sided 50-ft riparian buffer along the entire Riparian Management Zone (RMZ), (3) FP treatment, a two-sided 50-ft riparian buffer along at least 50% of the RMZ (4) 0% treatment, clearcut to stream edge (no-buffer).	Litter inputs from litter traps situated along channel	Sorted by litter type (conifer needles, deciduous leaves, woody components, etc.). Compared between treatments by dry weight.	Authors of the study identify a lack of information on local meteorology as a primary limitation to the study. This, the authors suggest, would have allowed for a more detailed analysis including information on hydrologic mass balance.	Showed a decrease in TOTAL litterfall input in the FP ($P = 0.0034$) and 0% ($P = 0.0001$) treatments between pre- and post-treatment periods. LEAF litterfall (deciduous and conifer leaves combined) input decreased in the FP ($P = 0.0114$) and 0% ($P < 0.0001$) treatments in the post-treatment period. In addition, CONIF (conifer needles and scales) litterfall input decreased in the FP ($P = 0.0437$) and 0% ($P < 0.0001$) treatments, DECID (deciduous leaves) in the 0% ($P < 0.0001$) treatment, WOOD (twigs and cones) in the FP ($P = 0.0044$) and 0% ($P = 0.0153$) treatments, and MISC (e.g., moss and flowers) in the 0% ($P = 0.0422$) treatment. Results for comparison of the post-harvest effects between treatments showed LEAF litterfall input decreased in the 0% treatment relative to the reference ($P = 0.0040$), 100% ($P = 0.0008$), and FP ($P = 0.0267$) treatments. Likewise, there was a decrease in DECID litterfall input in the 0% treatment relative to the Reference ($P = 0.0001$), 100% ($P < 0.0001$), and FP ($P = 0.0015$) treatments. Statistical differences were only detected for deciduous inputs between the 0% treatment and the other treatments.
McIntyre et al., 2021	1) unharvested reference, 2) 100% treatment, a two-sided 50-ft riparian buffer along the entire RMZ, 3) FP treatment a two-sided 50-ft riparian buffer along at least 50% of the RMZ, (4) 0% treatment, clearcut to stream edge (no-buffer).	stream discharge, nitrogen export		Type N (non-fish-bearing streams). Hard-Rock study.	Discharge increased by 5-7% on average in the 100% treatments while increasing between 26-66% in the FP and 0% treatments Results for harvest effects on total Nitrogen export showed significant ($P < 0.05$) treatment effects were present in the FP treatment and in the 0% treatment in the post-harvest (2-years immediately following harvest) and extended periods (7 and 8 years post-harvest) relative to the reference sites, Analysis showed an increase in total-N export of 5.73 ($P = 0.121$), 10.85 ($P = 0.006$), and 15.94 ($P = 0.000$) kg/ha/yr post-harvest in the 100%, FP, and 0% treatments, respectively, and of 6.20 ($P = 0.095$), 5.34 ($P = 0.147$), and 8.49 ($P = 0.026$) kg/ha/yr in the extended period. The authors conclude that the 100% treatment was generally the most effective in minimizing changes in total-N from pre-harvest conditions, the FP was intermediate, and the 0% treatment was least effective. At the end of the study (8 years), only one site had recovered to pre-harvest nitrate-N levels.
Murray et al., 2000	7% and 33% watershed upland harvest. Harvest extended to stream channel.	stream chemistry, stream temperatures , sediment input	Chemistry and pH tested on water grab samples; Daily max, min, and average temperatures collected with Stowaway dataloggers; Sediment change	Results reflect differences in stream conditions 11-15 years post-harvest only. No data collected in first decade following treatment.	10-15 years post-harvest mean maximum daily summer temperatures were still significantly higher (15.4 °C) and mean maximum daily winter temperatures were lower (3.7 °C) than in the reference streams (12.1 °C and 6.0 °C) respectively. Also, winter minimum temperatures for one of the harvested watersheds reached 1.2 °C compared to a winter minimum of 6 °C There were no significant differences in stream chemistry with the exception of calcium and magnesium being consistently higher in the unharvested reference watersheds. No detectable difference in turbidity between treatment and reference watershed streams 10-5 years post-treatment. The stream temperature

			detected with turbidity meters.		changes were significant but did not exceed the 16 ^{o}C threshold used as a standard for salmonid habitat.
Six et al., 2022	Clearcut with no leave trees or retention buffer (CC), clearcut with leave trees (CC w/LT; retention of 5 trees per hectare/2 trees per acre), and clearcut with 15 m wide retention buffer (CC c/B) and two uncut references (REF 1, and 2) along headwater streams	Litter input, LW recruitment	litter traps, In-stream LW volume, weight, and counts.	No replication of treatment sites. Data was analyzed with descriptive and graphical representation only.	Results showed a reduction of canopy cover from 91.4% to 34.4% in the clearcut treatment with no leave trees, from 89.8% to 76.1% in the clearcut treatment with leave trees, and from 89.5% to 86.9% in the clearcut treatment with the 15 m retention buffer. Post harvest litter delivery decreased for the clearcut with no leave trees but increased for both the clearcut with leave tree and clear cut with retention buffer.
Vanderbilt et al., 2003	Datasets (ranging from 20-30 years) from six watersheds in the H.J. Andrews Experimental Watershed.	Nitrogen concentration in streams, precipitation patterns	regression analysis of annual N inputs and outputs with annual precipitation and stream discharge to analyze patterns.	These results come from a coastal climate of western Oregon. The authors warn that the controls on in stream N concentrations will likely differ in different regions.	Total annual discharge was a positive predictor of annual DON export in all watersheds with r2 values ranging from 0.42 to 0.79. In contrast, significant relationships between total annual discharge and annual export of NO3-N, NH4-N, and PON were not found in all watersheds. DON concentrations increased in the fall in every watershed. The increase in concentration began in July or August with the earliest rain events, and peak DON concentrations occurred in October through December. DON concentrations then declined during the winter months. The authors conclude that total annual stream discharge was a positive predictor of DON output suggesting a relationship to precipitation.
Yang et al., 2021	Young stands with high shrub cover (> 50%) masticated to < 10% shrub cover. trees removed to a target basal area range of 27–55 m2 ha-1.	Drought, nutrients, dissolved organic carbon	Stream water samples grab samples and chemical analysis	Because of difficulties with accessibility due to weather-related phenomena (particularly during winter months), snowmelt and soil samples were restricted to the lower elevation site.	Drought alone altered DOC in stream water, and DOC:DON in soil solution in unthinned (control) watersheds. The volume-weighted concentration of DOC was 62% lower, and DOC:DON was 82% lower in stream water in years during drought than in years prior to drought. Drought combined with thinning altered DOC and DIN in stream water, and DON and TDN in soil solution. For stream water, volume-weighted concentrations of DOC were 66- 94% higher in thinned watersheds than in control watersheds for all three consecutive drought years following thinning. No differences in DOC concentrations were found between thinned and control watersheds before thinning. Watershed characteristics inconsistently explained the variation in volume-weighted

					mean annual values of stream water chemistry among different watersheds
Yeung et al., 2019	Range of forest harvest intensities	Litter inputs, CPOM in streams	stream temperature, streamflow, litter traps, CPOM decay rates	Authors point out that model results are primarily applicable to stream reaches similar to those used in the study and may not be suitable for streams where large wood is a dominant structure retaining CPOM.	The simulation predicted that litter input reduction from timber harvest was the strongest control on CPOM in streams relative to streamflow and temperature variability. The effects of litterfall reduction were at least an order of magnitude higher than streamflow increases in depleting in-stream CPOM. Significant CPOM depletions were most likely when there was a 50% or greater reduction in litterfall following harvest. The caveat of this study is that it did not include LW dynamics in preserving CPOM post-harvest. As other studies have shown, harvest can increase in-stream LW, and in-stream LW can act as a catchment for CPOM.

Large Wood (LW)/wood load/wood recruitment

Large wood in streams is essential to create pools, regulate flow, and provide a slow pulse of nutrients that help create and maintain salmonid habitat (Harmon et al., 1986). Sievers et al. (2017), in a global meta-analysis of the effects of riparian alteration on trout populations, found the most positive response of trout populations was with increasing in-stream wood and livestock exclusion from the riparian area. Large woody debris production and recruitment into streams can vary between watersheds, and multiple studies have attempted to identify the drivers of LW production and recruitment with varying results. For example, Benda et al. (2003) present a wood budgeting framework for riparian zones that includes numerical expressions for punctuated forest mortality by important drivers they identify as fire, chronic mortality and tree fall, bank erosion and mass wasting, decay, and stream transport. This framework can be applied to different regions by adjusting parameter values to make predictions of the importance of landscape factors (e.g., climate, topography, basin size) on wood recruitment and abundance in streams for any area. Depending on the region or landscape for which the framework is being applied, less common but more locally important disturbances such as ice storms, ice breakage, and wind throw can also be incorporated. This study and the framework it developed illustrate the diversity of the wood recruitment, transport, and decay processes. The relative importance of each wood recruitment mechanism, and the fate and transport of the in-stream wood depends on the variation observed in the environmental, management, and vegetation factors of a site. Thus, frameworks such as the one developed by Benda et al. (2003) help identify the relative importance of these recruitment processes and their relationship with local landscape factors.

A Review of the Available Literature Related to Wood Loading Dynamics in and around Streams in Eastern Washington Forests, was developed for CMER in October of 2004 (CMER 03-308, 2004). In this review, the researchers sourced 14 references with quantitative and descriptive information relating to the correlation between wood volume and pieces of wood in streams and the adjacent riparian community. The authors conclude that while the literature was incomplete, several significant correlations existed between LW in streams and riparian zone stand characteristics. For unmanaged (defined as unlogged and un-roaded) sites in Washington, researchers reported positive correlations between the volume of LW in streams with adjacent riparian zone mean tree height ($P<0.001$), mean tree diameter ($P<0.001$), and mean basal area ($P<0.001$). For numbers of LW pieces, positive correlations were found with the basal area ($P<0.007$) but no other vegetation characteristic of the adjacent riparian area. However, regression analysis showed a significant positive correlation of LW piece quantity with core zone trees/acre ($P<0.001$, $R^2 = 0.45$) and core zone basal area/acre ($p=0.004$, $R^2=0.29$). Relative to managed riparian areas, streams adjacent to unmanaged riparian areas had significantly higher LW volume. The most relevant sources of these results listed in this review were from Fox (2001), Chesney (2000), Camp et al. (1997), and Knight (1990). Two other studies named in this review (McDade et al., 1990; Fox, 2003) show evidence that as much as half of the wood found in the streams could not be attributed to the adjacent designated riparian areas which indicates the importance of scale when investigating in stream LW source.

In the western United States, several notable studies since 2000 have continued to investigate and refine the factors important for LW recruitment. For example, Wing & Skaugset (2002) investigated the relationships between land use, land ownership, and channel and habitat characteristics with LW quantity and volume in stream reaches in western Oregon. The relevant results (those derived for forested streams only) showed that stream gradient was the most important explanatory variable for in-stream LW volume with the split in the regression analysis occurring at 4.7%. Stream reaches with gradients less than 4.7% had on average less than half the in-stream LW volume (11.3 m^3 vs. 25.2 m^3 per reach) than reaches with gradients >4.7%. Results for LW pieces (logs at least 0.15 m diameter, and 3 m long) per 100 m length showed bankfull width (BFW) as the most important explanatory variable with a split in the regression analysis occurring at 12.2 m BFW. Reaches with a BFW <12.2 m averaged 11.1 LW pieces per 100 m compared to wider streams which averaged 4.9 pieces per 100 m. When the analysis was constrained to "key" LW pieces (logs at least 0.6 m diameter and 10 m long), stream gradient again emerged as the most important explanatory variable with the split in the regression occurring at 4.9% stream gradient (mean key pieces per 100 m were 0,5 and 0.9 for gradients <, and >4.9%, respectively). Following stream gradient and BFW, lithology was also an important explanatory variable showing splits for Mesozoic and sedimentary lithologies (in 3 out of 4 analyses) grouped as containing half the LW quantity (pieces, key pieces, volume) on average than all other geologies (basalt, cascade, and marine sedimentary geologies). Wing & Skaugset (2002) suggests that geomorphic characteristics, in particular stream gradient and bankfull width, but also underlying lithology in forested areas correlate best with LW presence in headwater streams of western Oregon.

Another study from the Oregon Coast Range, May & Gresswell (2003), compared LW recruitment processes between small colluvial channels and larger alluvial channels. Results from this study showed that LW derived from local hillslopes and riparian areas accounted for the majority of pieces (63%) in small colluvial channels. In contrast, the larger alluvial channel received wood from a greater variety of sources, including recruitment from local hillslopes and riparian areas (36%), fluvial redistribution (9%), and debris flow transported wood (33%). Further, distributions of the source distance of wood pieces were significantly different between colluvial and alluvial channels. In colluvial streams, 80% of total wood and 80% of total wood volume recruited to colluvial streams originated from trees rooted within 50 m of the channel. In the alluvial channel, 80% of the pieces of wood and 50% of the total volume originated from trees which came from within 30 m of the channel. Considering the mechanisms responsible for recruitment, for both colluvial and alluvial stream channels, slope instability exhibited the longest source distance (median source distance = 40 m), followed by windthrow (median source distance = 20 m), then natural mortality (median source distance = 18 m), and for obvious reasons, bank erosion had the shortest median source distance (2 m). Compared between channel types (colluvial vs. alluvial), the median source distance of wood recruited by windthrow was significantly greater in colluvial channels than in the alluvial channel ($p < 0.05$). Source distances for all other processes did not differ significantly between channel types. May & Gresswell (2003) interpret these results as evidence that stream size and topographic position strongly influence processes that recruit and redistribute wood in channels. Processes of slope instability were shown to be important conveyors of wood from upland forests to small colluvial channels. In the larger alluvial channels, windthrow was found to be the dominant recruitment process from adjacent riparian area.

Three larger scale studies from Washington (Fox & Bolton, 2007), the northwestern United States (Sobota et al., 2006), and the Columbia River Basin (Hough-Snee et al., 2016) present results from simulation modeling or statistical modeling for site and physiographic factors influencing LW recruitment and in stream loading. Sobota et al. (2006), in a landscape-wide study of factors affecting tree fall direction and LW recruitment in watersheds of the Pacific Northwest (data sourced from Washington, Oregon, Idaho, and Montana), found valley constraint to have the strongest correlation with in-stream woody debris. Outputs from their model showed that riparian areas in channels with >40% valley side slopes had the highest tendency for tree fall towards streams; in these steep slope valleys, recruitment of large wood in streams was 1.5-2.4 times greater than on moderately sloped landforms (< 40%).

Fox & Bolton (2007) modeled LW values from 150 stream segments located in unmanaged watersheds, across Washington, with landscape, reach, and stand characteristics to understand the central tendency of instream LW values in "natural" fish-bearing streams. Outputs from their models show evidence that in-stream wood volume (m^3 per 100 m stream length) and LW piece count for streams up to 20 m in bankfull width (BFW) increased with drainage area and as streams became less confined with BFW being a significantly better predictor of wood parameters than basin size. Also, in-stream wood volume increased with adjacent riparian timber age as determined by the last stand replacing fire. In this study (Fox & Bolton, 2007), the authors noted that other predictor variables (e.g., gradient, bedform) also showed some evidence of an effect but the variability of these variables were too great to evaluate with confidence.

Hough-Snee et al. (2016) reported similar issues with their results using Random Forest (RF) models developed from field data to identify relationships between hydrogeomorphic and ecological attributes that influence instream wood accumulation. Final RF models explained 43.5% of the variance in volume and 42.0% of the variance in frequency of in stream wood loads. Mean annual precipitation, riparian large tree cover, and watershed area were estimated as the most important predictors of in stream wood loads. However, so did individual watershed which showed there was an interaction with site (i.e., site conditions unaccounted for may be affecting the response). Given the heterogeneous results across all sub-basins studied, the authors conclude by emphasizing the importance of incorporating local data and context when building wood models to inform future management decisions.

Multiple studies have also investigated the effects of timber harvest under varying riparian management zone prescriptions on LW recruitment. Specific to Washington, Schuett-Hames and Stewart (2019a) compared in stand structure, tree fall rates, and LW recruitment between riparian management zones harvested under the current standard Shade Rules (SR), the All-Available Shade Rule (AAS), and unharvested references for fish-bearing streams in the mixed conifer habitat type (2500 - 5000 feet elevation) for eastern Washington. Both shade rules have a 30-ft no-cut buffer (core zone) immediately adjacent to the stream. The SR prescription allows thinning in the buffer zone 30-75 feet (inner zone) from the stream while the AAS prescription requires retention of all trees providing shade in this area. Results showed that cumulative wood recruitment from tree fall after the five-year post-harvest interval was highest in the SR group, lower in the AAS group and lowest in the REF group. The SR and AAS LW recruitment rates by volume were nearly 300% and 50% higher than the REF rates, respectively. Wood recruitment in the SR sites was significantly greater than in the AAS and reference sites. Conversely, wood recruitment did not differ significantly between the AAS and reference sites. Considering the source distance of post-harvest recruited LW, most recruited fallen trees originated in the core zone (76%, 72%, and 64% for the REF, AAS and SR groups, respectively), while the proportion from the inner zone (30–75 feet from the stream) was ~10% greater for the SR group compared to the AAS and REF groups. These results suggest that while treatment of SR sites is intended to increase resistance to disturbances such as fire and disease, it also provides evidence that these treatments increase the susceptibility to windthrow and thus increases mortality relative to reference sites five years post-harvest. Further, thinning treatments in the inner zone appeared to change the spatial pattern (source distance) of wood recruitment from fallen trees. It is important to note that this was a short-term study (5 years). The authors remark that LW recruitment is a process that can change over decadal time scales, and follow-up monitoring is recommended.

Four similar studies conducted for non-fish bearing streams in western Washington compared changes in LW recruitment and stand mortality following harvest (Ehinger et al., 2021; McIntyre et al., 2021; Schuett-Hames et al., 2011; Schuett-Hames et al., 2019b. Schuett-Hames et al., (2011) and Schuett-Hames & Stewart(2019b) investigated changes in riparian stand mortality and LW recruitment into the bankfull channel 5- and 10-years post-harvest, respectively. Treatments for riparian forests adjacent to non-fish-bearing streams evaluated in these studies include clearcut to stream edge, upland clearcut with a 50-foot no cut buffer, and these were compared to unharvested reference streams. Results showed that tree fall rates (annual fall rates of live and dead standing stems combined) was over 8 times and 5 times higher in the 50-foot buffers than in the reference buffers 3 years after treatment when compared as a percentage of standing trees and as trees/acre/yr, respectively. These differences were significant for both metrics ($p \leq 0.001$). Total tree-fall rates in the period 4-5 years after treatment, while still higher in the 50-foot buffers was not significant.

Over the entire five-year period, the percentages of standing trees that were uprooted and broken (as well as the combined total) were significantly greater in the 50-foot buffer than in the reference. Differences in mortality followed a similar pattern to tree fall rates. In the 50-foot buffer sites, mortality rates were significantly higher (3.5 times higher) than in the reference sites for the first three years following harvest. However, in years 4-5 mortality rates increased in the reference buffers after high-intensity storms resulting in non- significant differences in mortality during this period. The cumulative percentage of live trees that died over the entire five-year period was 27.3% in the 50-ft buffers compared to 13.6% in the reference reaches, but the difference was not statistically significant. This was likely because of the high variability in mortality between sites in the 50-foot buffers. The data for mortality rates in the 50-foot buffers had a bimodal distribution with most sites exhibiting less than 30% mortality, although three sites (of 13) exhibited mortality rates greater than 50%.

For LW recruitment into the bankfull channel, results showed during the first three years after treatment recruitment rates were 8 times and 14 times higher in the 50-foot buffers than in the reference buffers respectively. The differences in pieces/acre/year and volume/acre/year between reference and 50-foot buffers were significant. In years 4-5 after harvest LW recruitment decreased in the 50-ft buffers and increased in the reference patches, and the number of recruited LW pieces/acre/yr was greater in the reference patches, although the volume of LW recruited was greater in the 50-ft buffers. Differences in recruitment rates between the 50-foor buffer and the reference buffers for the 4–5-year period were not significant. For the entire first 5 years after harvest, the 50-ft buffers recruited about twice the number of LW pieces recruited in the reference patches, and over 3 times the volume; differences were marginally significant.

The results of the 10-year follow-up study for these sites (Schuett-Hames & Stewart, 2019b) showed that stand mortality in the 50-foot buffer sites had stabilized and showed a cumulative 14.1% reduction in live basal area, while the reference stands showed a 2.7% increase in live basal area. The differences in these values were not significant. Cumulative LW recruited into the stream channel over the 10-period was double in the 50-ft treatment streams compared to the reference streams. However, the majority of the LW recruited in the 50-ft treatment streams came to rest above the streams, providing shade but not affecting streamflow, pool formation, or sediment storage. Further, while the 50-ft buffer treatment provided more LW recruitment in the short-term (10-years), the authors speculate there is a reduction in future LW recruitment potential given the removal of trees outside the 50-ft buffer.

Two other studies which evaluated changes in LW following riparian forest harvest along non-fish-bearing streams in western Washington were complimentary studies. Treatment sites in these studies were underlain by either competent (McIntyre et al., 2021; also referred to as Phase 2 of the “Hard Rock” study), or incompetent (easily eroded) marine sedimentary lithologies (Ehinger et al., 2021; also referred to as the “Soft Rock” study). The buffer treatments evaluated for these studies were compared against unharvested reference sites ("REF") and included a two-sided 50-ft wide riparian buffer along the entire reach (“100%”), and the standard Forest Practices treatment (FP), a two-sided 50-ft wide riparian buffer along at least 50% of the RMZ (buffered and unbuffered portions were analyzed separately; hereafter referred to as FPB for the buffered portion, and 0% for the unbuffered portion). However, because of unstable slopes in some of the sites in the Soft Rock study (Ehinger et al., 2021), many of the buffers were required to be wider than 50-feet (ranging from 18 –160% wider than 50-feet). Conversely, some of the sites treated ended up with buffers narrower than 50 feet. Further, there was limited availability of sites that fit the criteria (marine sediment lithology, timing of treatment). Because of these limitations, statistical analysis and comparison of LW response between treatments and references could not be performed. Thus, the results are only descriptive, but they provide useful information for comparison to the Hard Rock study.

Results from the Soft Rock study showed mean cumulative post-harvest mortality during the 3-year post-harvest interval was only 6.5% of live density (trees/ha) in the reference sites. In contrast, mean post-harvest mortality in the full buffer sites and the <50 ft buffer sites were 31 and 25% of density, respectively. However, there was considerable variation in mortality among sites, exceeding 65% in two full buffer treatment sites. Windthrow and physical damage from falling trees accounted for ~75% of mortality in the full and <50 ft buffers. In contrast to the treated sites, <10% of trees died due to wind or physical damage in the reference sites. For LW recruitment, there was an increase in pieces of LW per 100 m length of stream in the full buffers (8%) and the unbuffered treatments (13%) and a decrease in the streams adjacent to buffers < 50 feet wide (-15%) 3 years after harvest. The Hard Rock study did not require changes to the grouping of treatments (i.e., all treatment buffers were harvested as described above; e.g., Reference, 100%, FPB, 0%). Also, the Hard Rock study collected up to 9 years of post-harvest data that allowed for the comparison of LW changes over time pre- to post-harvest, and between treatments.

Results for the Hard Rock study showed that by year 8 post-harvest mortality as a percentage of pre-harvest basal area was lower in the reference (16.1%) than in the 100% (24.3%) and FPB (50.8%) treatments. The FPB–Reference contrast in mortality was not significant 2 years post-harvest, but it was at 5- and 8-years post-harvest as mortality in FPB increased relative to the Reference over time. The contrast in mortality between the 100% and Reference were not significant for any time interval 8 years post-harvest. Wind/physical damage was the primary cause of mortality for all treatments, including the Reference. In the 100% treatment it accounted for 78% and 90% of the loss of basal area and density (trees/ha), respectively; in FPB it accounted for 78% and 65% of the loss. Wind accounted for a smaller proportion of mortality in the Reference RMZ (52% and 43%, respectively). LW recruitment to the channel was greater in the 100% and FPB RMZs than in the reference for each pre- to post-harvest time interval. Eight years post-harvest mean recruitment of large wood volume was two to nearly three times greater in 100% and FPB RMZs than in the references. Annual LW recruitment rates were greatest during the first two years, then decreased. However, there was a great deal of variability in recruitment rates within treatment sites and the differences between treatments were not significant. Mean LW loading into the channel (pieces/m of channel length) differed significantly between treatments in the magnitude of change over time. There was a 66%, 44% and 47% increase in mean large wood density in the 100%, FP and 0% treatments, respectively, in the first 2 years post-harvest compared with the pre-harvest period and after controlling for temporal changes in the references. By year 8, only the FP treatment showed a significantly higher proportional increase (41%) in wood loading when compared to the reference. In the time interval 2-8 years post-harvest wood loading in the 100% treatment stabilized and began to decrease in the 0% treatment.

The Hard Rock and Soft Rock studies showed similar results. Both studies showed an increase in stand mortality that also led to an increase in LW recruitment into the channels adjacent to 50-foot (and greater in the Soft Rock) buffer treatments relative to unharvested reference sites. However, the longer time period of study in the Hard Rock study showed mortality and thus LW recruitment began to stabilize after year five. The results presented by Schuett-Hames (2012, 2019b) showed a similar pattern of an initial increase in mortality rates and LW recruitment rates in treated stands relative to untreated stands within three years of treatment, but stabilization within 5-10 years. Unfortunately, because of the limitations in sample size and buffer width consistency in the Soft Rock study, confident conclusions on the effects of lithological competency on LW recruitment post-harvest cannot be drawn.

All studies reviewed above which investigate the effect of timber harvest with riparian buffers show that the initial increase in mortality within treatment buffers relative to reference buffers is primarily a result of increased windthrow mortality. Liquori (2006) found similar results in an investigation of treefall characteristics within riparian buffer sites ranging in width from 25-100 feet along non-fish bearing and fish bearing streams. Within no-cut buffers, windthrow caused mortality was up to 3 times greater than competition induced mortality for 3 years following treatment with tree fall probability highest in the outer areas (closest to upland clearcuts) of the buffers. Their results showed that treefall was generally highest at the outside edges of buffers (50+ feet), representing about 60% of the total observed treefall, while the 0–25-foot zone represented ~18%, and the 25–50-foot zone represented ~22%. This suggests an increase in windthrow susceptibility within riparian buffers with increasing distance from the stream. Liquori (2006), however, did not differentiate thinning treatments applied to the outer zones of the buffer in their analysis mentioning “very modest” thinning was applied to some buffers. They suggest in their interpretation of the results that buffer thinning may influence the depth to which wind forces can penetrate into the buffer. The results from Schuett-Hames & Stewart (2019a), discussed above, show evidence that thinning in the outer area (30-75 feet from bankfull width) changed the source distance curve of wood recruitment from fallen trees with thinned buffers (SR treatments). The results exhibited statistically higher overall treefall rates with a larger percentage coming from the outer area in the SR treatments than in the reference and more lightly thinned (AAS) treatment buffers.

Outside of Washington, but in areas with similar habitats (Oregon, British Columbia) several experimental studies that have investigated the effects of timber harvest on treefall, mortality, LW recruitment, and LW source distance have found comparable results to those conducted in Washington. For example, Martin & Grotefendt (2007) compared riparian stand mortality and in-stream LW recruitment characteristics between riparian buffer strips with upland timber harvest and riparian stands of unharvested watersheds using aerial photography in the northern and southern portions of Southeast Alaska. All buffer strips in this study were a minimum of 20 m wide and included selective harvest within the 20 m zone (thinning intensity not specified or included in the analyses as an effect). The results from this study showed significantly higher mortality (based on cumulative stand mortality: downed tree counts divided by standing tree counts + downed tree counts), significantly lower stand density (269 trees/ha in buffer units and 328 trees/ha in reference units), and a significantly higher proportion of LW recruitment from the buffer zones of the treatment sites than in the reference sites. Also, results showed that mortality varied with distance to the stream. Differences in mortality for the treatment sites were similar to the reference sites for the first 0-10 m from the stream (only a 22% increase in the treated sites). However, mortality in the outer half of the buffers (10-20 m) from the stream in the treatment sites was more than double (120% increase) what was observed in the reference sites. The authors attribute the difference in cumulative stand mortality to the increase in windthrow susceptibility. Mortality attributed to windthrow was twofold and fivefold greater in the inner and outer halves of the treatment buffers than in the reference buffers, respectively.

Bahuguna et al. (2010) evaluated the difference in windthrow caused mortality between 10 m, 30 m buffer widths (neither had thinning within the buffer and both had upland clear-cuts) and unharvested controls in the Coast Mountains, British Columbia. Following harvest, 11% of initially standing timber was blown down in the first and second years in the 10 m buffer, compared to 4% in the 30 m buffer, and 1% in the unharvested controls. However, after 8 years post-harvest, a significant amount of annual mortality occurred when winter storms brought down multiple trees in the unharvested control at 30%, compared to 15% in both 30 m and 10 m buffers. These results show evidence that timber harvest can increase windthrow caused mortality within protective buffers in the short term but can stabilize within a decade. Further, this study shows evidence that windthrow caused mortality is stochastic and large storm events can cause just as much if not higher mortality within untreated riparian forests.

Burton et al. (2016) examined the relationship between annual in-stream wood loading and riparian buffer widths adjacent to upland thinning operations. No-cut buffer widths were 6, 15, or 70 meters, and upland thinning was to 200 trees per ha (tph), with a second thinning (~10 years later) to ~85 tph, alongside an unthinned reference stand ~400 tph. Their results showed that slightly higher volumes of wood were found in sites with a narrow 6-m buffer, as compared with the 15-m and 70-m buffer sites in the first 5 years after the first harvest and maintained through year 1 of the second harvest (end of study). The authors attributed this difference to a higher likelihood of logging debris and/or windthrow, but these factors were not analyzed. Considering source distance, the authors used a mixed modeling approach to assess the relationship between wood volume and source distance for in-stream wood with an identifiable source. This model was only applied to the 70-meter buffer. The results showed that 82-85% of the wood with discernable sources (90% for wood in early stages of decay; 45% of wood in late stages of decay) came from within 15 m of the stream, and the relative contribution of wood to streams declined rapidly with increasing distance. Still, these results are similar to those presented by Schuett-Hames & Stewart (2019a) which showed the majority of the LW recruited (72-76% for treated stands) into the channel were from within the first 30 feet (~9.1 m) of the stream even though upland harvest prescriptions in this study differed from those evaluated by Burton et al. (2016) (e.g., clearcut vs thinning).

Summary of Factors Impacting LW Loads and Recruitment

In general, the studies reviewed above show evidence that upland timber harvest with riparian retention buffers initially increases stand mortality within the buffers and increases LW recruitment relative to unharvested reference stands in the short-term. This increase in mortality and LW recruitment is attributed to an increase in the susceptibility to windthrow within the riparian buffers relative to the unharvested controls. Further, multiple studies (Liquori, 2006; Martin & Grotefendt, 2007, Schuett-Hames & Stewart 2019a) showed evidence that the increase in windthrow caused mortality is highest in the outer area of the riparian buffers (area closest to upland treatments). There is some evidence that thinning within the buffer can also affect mortality rates, but these studies are few. In the three studies that collected post-harvest data for 8 or more years (Bahuguna et al., 2010; McIntyre et al., 2021; Schuett-Hames & Stewart 2019b), there is indication that mortality in the riparian buffers and annual LW recruitment into adjacent streams stabilizes within 5-10 years. However, in the subsequent decades following treatments with upland clearcuts there is evidence that LW recruitment rates can continue to decrease and in stream wood loads may become depleted before recruitment rates can recover (Nowakowski & Wohl, 2008; Reid & Hassan, 2020) depending on applied management practices (e.g., buffer widths, road construction, etc.). For example, Teply et al. (2007) used simulation modeling to estimate the effectiveness of Idaho Forest Practices for riparian buffers and found no significant difference between predicted LW loads for harvested and unharvested sites 30-, 60-, or 100-years post-harvest.

While the general conclusions of short-term increase in LW and long-term reduction of LW following treatment are similar among studies it is more apparent that LW recruitment dynamics are complex and highly variable even within treatment groups; and local site and landscape factors may interact with treatments making it difficult to generalize the effectiveness of different protective buffer treatments on preserving LW recruitment and in-stream wood loads. Indeed, the LW budget framework created by Benda et al. (2003) emphasizes the importance of including local physiographic, site, and disturbance factors. Additionally, the studies reviewed above present results from experimental studies that vary greatly in their design. Buffer widths, riparian and upland treatment prescriptions differ by region, state, and local regulations that can differ further by stream type and size, and location within the landscape (e.g., elevation). Thus, general global conclusions about the effect of riparian forest treatment on LW dynamics are difficult to discern.

Considering the influence of landscape and site factors on LW dynamics factors such as stand density (stems per unit area), basal area, stand age, stream bankfull width, stream gradient, valley constraint, lateral slope steepness, lithology, and mean annual precipitation have all been shown to influence LW recruitment and instream wood loads. Repeatedly, one or more of these factors have emerged as important predictor variables of LW dynamics in watersheds with and without management.

845 Table 3. List of treatments, variables, metrics, and results from publications reviewed for information on large wood (LW), wood loads, and wood recruitment.

Reference	Treatment	Variables	Metrics	Notes	Results
Anderson & Meleason, 2009	Buffer averaging 69 m adjacent to thinning and a 0.4 patch opening; variable width buffer averaging 22 m adjacent to thinning and a 0.4 patch opening.	Instream wood load, understory vegetation cover	Percent cover of LW in streams and in riparian area, %cover shrubs, herbs, moss.		LW changes were non-significant, decrease in treatment reaches with greatest pre-treatment values 5 years post-treatment caused homogenization of LW. Gaps (patch openings) showed the highest changes increase in herbaceous cover, decrease in shrub cover. Moss cover increased in thinned areas but decreased in gaps. LW and vegetation changes insensitive to treatment buffers > 15 m.
Bahuguna et al., 2010	Two buffer widths on each side of the stream (10 m and 30 m) with upland clearcuts, and an unharvested control.	LW, Stand Structure, mortality	Strip plot sampling method running parallel to the stream to collect data on stand metrics.	Experimental design included 3 replicates of each treatment. Data was collected annually for one year pre- and 8 years post-treatment. Vancouver, B.C.	Following harvest, 11% of initially standing timber was blown down in the first and second years in the 10 m buffer, compared to 4% in the 30 m buffer, and 1% in the unharvested controls. Small diameter trees were significantly more represented in streams - 77% of LW was in the 10 cm - 20 cm diameter class while the mean diameter of standing trees in riparian buffers was 30 cm. By 8 years post-harvest, a significant amount of annual mortality occurred in the unharvested control at 30%, compared to 15% in both 30 m and 10 m buffers.
Benda et al., 2016	Simulated treatments of single or double entry thinning with and without a 10-m no cut buffer, with and without mechanical tipping of stems into streams. Thinning encompassed 5-20 % thinning.	instream LW volume	ORGANON growth models simulated secondary forest growth. The model was run for 100 years in 5-year time steps.	used the reach scale wood model (RSWM) developed for the Alcea watershed in central coastal Oregon. Data was sourced from FIA.	Single entry thinning reduced in-stream wood by 33 and 66% after a century, relative to reference streams when one and both sides of the channel were harvested. Adding a 10 m buffer reduced total loss to 7 an 14%. Mechanical tipping of 14 and 12% of cut stems were sufficient in offsetting the loss of instream wood without and with buffers. Double entry thinning without a buffer resulted in 42 and 84% loss of in stream wood relative to the reference streams when one or both sides of the channel were harvested. Adding a 10 m buffer changed reductions of in stream wood to 11 and 22% for one- and two-sided channel harvest. To offset the total predicted reduction of in stream wood for the double entry thinning would require tipping of 10 and 7% of cut stems without and with 10 m buffers.
Burton et al., 2016	70-m buffer representative of one site potential tree, 15-m buffer, 6-m buffer. Outside	LW recruitment, In-stream wood volume, biomass, and	LW volume, LW characteristics and source evidence, reach	Wood surveys were carried out at four times during the study: (1) prior to the	In-stream wood volume increased significantly with drainage basin area; for every 1-ha increase in drainage basin area, wood volume increased by 0.63%. LW volume was slightly higher in the streams adjacent to 6 m buffers than in streams bordered by 15 and 70 m buffers. The higher volume of wood

	of buffer, all treatment stands were thinned first to 200 trees per hectare (tph), then again to 85 tph ~ 10 years later. Uncut reference was ~400 tph.		and stream characteristics.	first thinning, (2) five years after the first thinning, (3) 9-13 years after the first thinning and just prior to the second thinning, and (4) one year after the second thinning.	in the 6 m buffers began 5 years after the first harvest and maintained through 1 year after the second harvest (end of study). . 82% to 85% of all wood inputs (early- and late-stage decay) were sourced from within 15 m of the streams (90% of early-stage decay wood could be sourced, only 45% of late-stage decay wood could be sourced).
Chen et al., 2005	All harvested streams were clearcut to stream edge. Wildfire streams had no post-fire harvest	Instream wood load, biomass, carbon pool	LW count, volume, decay class, size		LW volume, biomass, and carbon pools were significantly higher in streams adjacent to areas recently disturbed by timber harvest (~10 years) or wildfire (~40 years) than in streams passing through old-growth forests. There was no significant difference in in-stream LW between old-growth riparian areas and areas harvested > 30 years ago. The wildfire sites had significantly higher LW values than both the harvested sites. The authors conclude: (1) LWD input in old growth forested streams was relatively stable based on statistical significance. They also speculate: (1) timber harvesting activities would cause a short-term increase of LWD stocks and might greatly reduce LWD loadings over a long-term, and (2) wildfire disturbance would delay LWD recruitment because not all burnt trees would fall in the stream immediately after the wildfire, based on trends in, and extrapolation of the data.
Chen et al., 2006	A total of 35 sites with stream orders ranging from 1-5 (grouped into 4 stream size categories (I = first order; II = second to third order; III = third to fourth order; IV = fourth to fifth order) were selected to measure spatial distribution and	LW, defined as having a diameter of > 0.1 m and a length > 1.0 m.	LW size, volume, density, and biomass. Multiple stream channel features obtained from readily available physiographic and forest cover data.	Study sites were selected based on the following criteria. (1) the streams were in areas of intact mature riparian forests (>80 years); (2) the stream side forests were not disturbed by human activities, such as harvesting, road	Results from this study show that LW size, volume, and biomass generally increased with increasing stream size. For example, the mean LWD diameter in stream size I (16.4 cm) was lower than that in stream size III (20.6 cm) and IV (20.5 cm), respectively. Mean LW length also increases with stream size from 2.3 m in size I, 2.9 m in size II, 3.1 m in size III, and 3.9 m in size IV. Stream IV had the highest mean volume (0.18 m3), significantly higher than stream size I (0.06 m3). LW density (pieces per 100 m2 of stream area), however, decreased as stream size increased. For example, LW density (defined as piece numbers per 100 m^2) numbers were 19, 17, 12, and 4 for stream size I, II, III, and IV respectively. Increases in channel bank full width (R^2 = 0.52) and stream area (R^2 = 0.58) was found to be strongly inversely correlated with LW density.

	variability of LW characteristics			building; (3) the streams were not salvaged.	
Ehinger et al., 2021	1) Buffers encompassing the full width (50 feet), 2) <50ft buffers, 3) Unbuffered, harvested to the edge of the channel, and 4) Reference sites in unharvested forests.			Soft Rock study. Only descriptive statistics were applied for changes in stand structure and wood loading. Small sample sizes.	There was little post-harvest large wood input in reference sites: an average of 4.3 pieces and 0.34 m3 of combined in- and over-channel volume per 100 m of channel. In contrast, the full buffer sites and <50 ft buffer sites received an average of 23 and 10 pieces/100 m and 2.3 and 0.7 m3/100 m of large wood, respectively. Piece counts remained stable in the reference sites through year 3 post-harvest, increased in the full buffer and unbuffered sites (8 and 13%, respectively), and decreased in the <50 ft buffers (-15%).
Fox & Bolton, 2007	LW values from 150 stream segments located in unmanaged watersheds, across all of Washington State	Instream LW, geomorphology, forest zone, disturbance regimes	Descriptive statistics for LW volume and quantity, channel geomorphology, forest habitat type, disturbance regimes.	the authors warn that these values for reference conditions are only applicable to streams with bank-full widths 1-100 m, gradients 0.1%-47%, elevations 91-1,906 m, drainage areas 0.4-325 km2, glacial and rain- or snow-dominated origins, forest types common to the Pacific Northwest.	Results showed that in-stream wood volume increased with drainage area and as streams became less confined. Bank full width (BFW) was the single greatest predictor of in-stream wood volumes relative to other predictor variables. However, this result comes with the caveat that other processes and geomorphologies (e.g., channel bed form, gradient, confinement) are also important in the mechanisms for wood recruitment, modeling in this study showed too much inconsistency with these predictor variables too draw strong conclusions In-stream wood volume also increased with adjacent riparian timber age as determined by the last stand replacing fire. The authors developed thresholds for expected “key piece volume (m3)” (pieces with independent stability) of wood for three BFW classes (20-30 m, >30 – 50 m, > 50 m width) per 100 m stream length for streams with BFW greater than 20 m. From percentile distributions the authors recommend minimum volumes, defined by the 25th percentiles, of approximately 9.7 m3 for the 20- to 30-m BFW class, 10.5 m3 for the 30- to 50-m3 BFW class, and 10.7 m3 for channels greater than 50 m BFW per 100 m length of stream.

Gomi et al., 2001	Five management or disturbance regimes: old growth (OG), recent clear-cut (CC; 3 years), young conifer forest (YC; 37 years after clear-cut), young alder (YA; 30 years after clear-cut), and recent landslide and debris flow channels (LS)	LW quantity and distribution, sediment quantity and distribution, landslide frequency, harvest intensities	LW counts, LW characteristics, stream characteristics.	Results are highly variable among treatments	in-channel numbers of LW pieces were significantly higher in YC and CC sites when compared to OG, YA, and LS sites. The number of LW pieces was highest in YC streams even though logging concluded 3 decades prior to sampling. LW volume per 100 m of stream length in YC was twice that in OG. The total volume of LW per 100 m associated with CC channels was half that in OG channels. The authors conclude (i) inputs of logging slash and unmerchantable logs significantly increase the abundance of in-channel woody debris; (ii) in the absence of landslides or debris flows, these woody materials remain in the channel 50–100 years after logging.
Hough-Snee et al., 2016	In-stream wood volume and frequency were quantified across multiple sub basins.	LW frequency and volume, hydrologic and geomorphic attributes	Models were calibrated with site characteristics from multiple riparian stands in the Columbia River Basin.	Results show a high level of variability between sub basins studied. The overall model shows site (watershed) was an important predictor.	In stream wood volume and frequency were distinctly different across all seven sub-basins. According to random forest (RF) models, mean annual precipitation, riparian large tree cover, and individual watershed were the three most important predictors of wood volume and frequency, overall. Sinuosity and measures of streamflow and stream power were relatively weak predictors of wood volume and frequency. Final RF models explained 43.5% of the variance in volume and 42.0% of the variance in frequency of in stream wood loads. Depending on the sub basin wood volume and frequency was positively correlated with forest cover, watershed area, large tree cover, 25-year flood event stream power, riparian conifer cover, and precipitation. Negative correlations, depending on sub basin, of wood volume and frequency with baseflow discharge, riparian woody cover, watershed area, and large tree cover. Given the heterogeneous results across all sub-basins studied, the authors conclude by emphasizing the importance of incorporating local data and context when building wood models to inform future management decisions.

Hyatt & Naiman, 2001	LW data was collected from multiple sites in the Queets River Watershed.	LW in stream and in riparian forests.	Increment cores from in-stream LW were cross-dated to estimate the time LW was recruited. LW pieces in decay were dated using carbon-dating. A depletion curve was fitted for LW recruited between 1599 and 1997.	The depletion constant was developed for a large, mostly alluvial river and should probably not be applied to smaller streams	Results from this study indicate that the half-life of stream LW to be approximately 20 years, suggesting that current LW will either be exported, broken down, or buried withing 3 to 5 decades (for conifers). Hardwoods were better represented in riparian forests than as in-stream LW, and conversely, conifers were better represented as in-stream LW than in adjacent forests suggesting that LW originating from hardwoods is depleted faster than conifers.
Jackson & Wohl, 2015	In-stream wood volume and frequency were quantified along 33 pool-riffle or plane-bed stream reaches in the Arapaho and Roosevelt National Forests in Colorado.	Sediment storage, channel geometry, in-stream wood load, and forest stand characteristics	Wood loads, wood jam volumes, log jam frequencies, residual pool volume, and fine sediment storage around wood, stand age, and disturbance history.	Old growth defined as forests ≥ 200 years. Age range of young forests not reported. Sample sizes include 10 old-growth and 23 younger forests.	Results indicated that channel wood load (OG = 304.4 + 161.1; Y = 197.8 + 245.5 m3 /ha), floodplain wood load (OG = 109.4 + 80; Y = 47.1 + 52.8 m3 /ha), and total wood load (OG = 154.7 + 64.1; Y = 87.8 + 100.6 m3 /ha) per 100 m length of stream and per unit surface area were significantly larger in streams of old-growth forests than in young forests. Streams in old-growth forests also had significantly more wood in jams, and more total wood jams per unit length of channel than in younger forests (jam wood volume: OG = 7.10 + 6.9 m3; Y = 1.71 + 2.81 m3). Although wood load in streams draining from pine beetle infested forests did not differ significantly from healthy forests, best subset regression (following principal component analysis) indicated that elevation, stand age, and pine beetle infestation were the best predictors of wood load in channels and on floodplains.
Jackson et al., 2001	3 unthinned riparian buffers; 1 with a partial buffer; 1 with a buffer of non-merchantable trees; and 6 were clearcut to the stream edge. Buffers ranged from 15 to 21 m wide, partial buffers were as thin as 2.3 m.	Instream LW, particle size, surface roughness	LW as functional and nonfunctional (not altering flow hydraulics). Particle size distributions.	Data collected for only 1-year pre- and 1-month post-harvest. These results only describe immediate effects of harvest on stream conditions.	Increased slash debris (LW) provided shade for the harvested streams but trapped sediments and prevented fluvial transport. The percentage of fine particles increased from 12 to 44% because of bank failure and increased surface roughness. This was a short-term study on small headwater streams. Sediment and LW conditions in the unharvested and buffered streams remained relatively unchanged during the study.

Liquori, 2006	Data were collected from 20 riparian buffer sites that had all been clearcut within three years of sampling with standard no-cut 25 ft or 50-100 ft buffers for non-fish-bearing and fish-bearing streams, respectively.	Tree and tree fall characteristics, Site characteristics	Tree characteristic data estimated cause of mortality, and distance to the stream. Tree recruitment probability curves were developed as a function of tree height.		Within no-cut buffers windthrow caused mortality was up to 3 times greater than competition induced mortality for 3 years following treatment Tree fall direction was heavily biased towards the channel regardless of channel or buffer orientation and tree fall probability was highest in the outer areas of the buffers (adjacent to the harvest area). Tree fall rates and direction were also heavily biased by species with western hemlock and Pacific silver fir having the highest fall rates compared to Douglas-fir, western red cedar, and red alder.
Martin & Grotefendt, 2007	Buffer widths a minimum of 20 m. Multiple buffer widths and harvest intensities.	Instream wood load, stand mortality	Counts of downed wood, tree stumps, stand characteristics, instream wood from aerial photographs taken post-logging	Stand and stream characteristic, and LW data was surveyed from aerial photographs.	Results showed significantly higher mortality, significantly lower stand density, and a significantly higher proportion of LW recruitment from the buffer zones of the treatment sites than in the reference sites. Differences in mortality for the treatment sites were similar to the reference sites for the first 0-10 m from the stream (22% increase). However, mortality in the outer half of the buffers (10-20 m) from the stream in the treatment sites was more than double (120% increase) what was observed in the reference sites. This caused a change in the LW recruitment source distance curves, with a larger proportion of LW recruitment coming from greater distances in logged watersheds. LW recruitment based on the proportion of stand recruited (PSR) was significantly higher in the buffered units compared to the reference units. However, PSR from the inner 0-20 m was only 17% greater in the buffer units than in the reference units; while PSR of the outer unit (10 – 20 m) was more than double in the buffered units than in the reference units. The researchers conclude that the increase in mortality was caused by an increased susceptibility to windthrow. They estimate that future recruitment potential from the logged sites diminished by 10% relative to the unlogged reference sites.

May & Gresswell, 2003	Survey of LW in three second-order streams and the mainstem of the North Fork of Cherry creek.	LW, delivery mechanism	LW > 20 cm diameter, and >2 m length was categorized by 4 delivery mechanisms, Delivery process, disturbance type, and channel characteristics.	Although mean age of Douglas-fir trees was identified to be excess of 300 years old, further information on differences in stand structure or development stage between sites are not included.	Processes of slope instability were shown to be important conveyors of wood from upland forests to small colluvial channels. In the larger alluvial channels, windthrow was found to be the dominant recruitment process from adjacent riparian area. 80% of total wood pieces and 80% of total wood volume recruited to colluvial streams originated from trees rooted within 50 m of the channel. In the alluvial channel, 80% of the pieces of wood and 50% of the total volume originated from trees which came from 30 m of the channel. The primary function of wood in colluvial channels was sediment storage (40%) and small wood storage (20%). The primary function of wood in alluvial channels is bank scour (26%), stream bed scour (26%), and sediment storage (14%).
McIntyre et al., 2021	(1) unharvested reference, (2) 100% treatment, a two-sided 50-ft riparian buffer along the entire Riparian Management Zone (RMZ), (2) FP treatment a two-sided 50-ft riparian buffer along at least 50% of the RMZ, (3) 0% treatment, clearcut to stream edge (no-buffer).			Hard Rock Study Physical constraints such as a lack of suitable low gradient reaches and/or issues with accessibility related to weather limited downstream measurements of exports to just eight sites.	Large wood recruitment to the channel was greater in the 100% and FPB RMZs than in the reference for each pre- to post-harvest time interval. Eight years post-harvest mean recruitment of large wood volume was two to nearly three times greater in 100% and FPB RMZs than in the references. Annual LW recruitment rates were greatest during the first two years, then decreased. However, these differences were not significant between any treatment comparisons, likely due to the high variability in the data. Mean LW loading (pieces per meter of stream) differed significantly between treatments in the magnitude of change overtime. Results showed a 66% (P <0.001), 44% (P = 0.05) and 47% (P = 0.01) increase in mean large wood density in the 100%, FP and 0% treatments, respectively, in the first 2 years post-harvest compared with the pre-harvest period and after controlling for temporal changes in the references. Five years post-treatment the FP continued to increase 42% (P = 0.08), and again 8 years post-treatment (41%; P = 0.09). From 2-8 years post-harvest LW density in the 100% treatment stabilized and began to decrease in the 0% treatment.
Meleason et al., 2003	Multiple buffer widths and upland harvest intensities	Change in instream wood load over time	Simulation metrics for forest growth, tree breakage, and in-channel process	A potential limitation of growth models in that they lack the ability to predict responses to novel climatic conditions	Simulation results predicted clear-cut to stream accumulated little LW immediately following treatment and little change over time. Maximum in-stream LW loads were predicted for streams with no-cut buffers >30 m for 500-year-old forests (500 years post treatment). Streams with 6 m wide buffers predicted only 32% of pre-harvest standing LW loads after 240 years. Forest plantations with > 10 m buffer widths contributed minimal LW to the stream from outside the buffer zone.

				different than those of the past.	
Nowakowski & Wohl, 2008	History of regulated and unregulated timber harvest practices.	Instream wood volume	LW volume, LW characteristics source evidence, buffer widths, reach and stream characteristics.		In-stream LW was 2-3 times lower in a watershed with a history (>100 years) of timber harvest (1.1 m3/100 m) when compared to unmanaged reference watersheds (3.3 m3/100 m). Valley characteristics (elevation, forest type, forest stand density, etc.) consistently explained more of the variability in wood load (42-80%) than channel characteristics (21-33%; reach gradient, channel width, etc.). Across all streams, the highest explanatory power of all models tested produced land use (managed vs unmanaged), and basal area as a significant predictor of wood loads (r2 = 0.8048). For the unmanaged watershed the model produced stream valley sideslope gradient as the single best predictor of wood load (r2 = 0.5748). Shear stress was the best predictor of wood load in the managed watersheds (r2 = 0.2403), When the significant valley and channel characteristics of the managed and unmanaged watersheds were controlled for, the significant difference in wood loads between managed and unmanaged watersheds were enhanced (p = 0.0006). Managed watersheds (1.1 m3/100 m) had, on average, 2-3 times lower in-stream wood loads than unmanaged (3.3 m3/100 m) watersheds.
Reid & Hassan, 2020	Clearcut to stream and buffer widths that range from 1-70 m. Models were developed for 3 harvest scenarios (1: no-harvest; 2 partial loss of riparian forests; 3 intensive harvest in the riparian zone)	Instream LW	Models were calibrated with long-term data for site and LW characteristics in treatment reaches dating back to 1973.	One caveat of this model is it doesn't account for as much variability on stream configuration or valley morphologies that are likely to affect LW storage.	Results of the model show evidence that wood storage in streams of harvested reaches its minimum value in 50 years or more following loss of LW input, decay, and export of current stock. Recovery of LW volume in-streams following harvest is estimated to take approximately 150-200 years. The pattern and intensity of the harvesting operation had little effect on LW loss and recovery times but did affect the estimated magnitude of LW volume loss in the first 50 – 80 years. The authors conclude that the results show evidence that timber harvest has a long-term effect on LW storage and loading dynamics even with protective buffers. However, buffers can ameliorate the magnitude of LW loss during the recovery period.

Schuett-Hames & Stewart, 2019a	Buffer prescriptions for standard shade rule (a 30-ft no-cut buffer width, and thinning 30-75 ft from the stream), and all available shade rule (requires retention of all shade providing trees in this area) for eastern Washington.	LW recruitment, instream wood volume, mortality, stand structure	LW volume, LW characteristics, LW source evidence, reach and stream characteristics, basin metrics, stand metrics	Short-term study. Results only for 5 years post-harvest. The authors note that LW recruitment is a process that can change over decadal time scales.	Results showed cumulative wood recruitment from tree fall over the five-year post-harvest interval was highest in the standard shade rule (SR) group, lower in the all-available-shade rule (AAS) group and lowest in the reference (REF) group. The SR and AAS rates by volume were nearly 300% and 50% higher than the REF rates, respectively. Most recruiting fallen trees originated in the first 30 feet (76%, 72%, and 64% for the REF, AAS and SR groups, respectively), while the proportion from the inner zone (30–75 feet from the stream) was ~10% greater for the SR group compared to the AAS and REF groups.
Schuett-Hames et al., 2011; Schuett-Hames & Stewart, 2019b	Clearcut to stream with 30-foot equipment exclusion zone, and 50-foot no-cut buffers	LW, mortality, stand structure, canopy cover	QMD, basal area, tree fall rates, instream LW counts and volume, canopy percentage from densiometer.	1) Substantial variability among sites. 2) Due to scale of study, results only applicable to immediate vicinity of buffer treatment.	10 years post treatment, 50-foot buffer mortality stabilized, cumulative 14.1% reduction in basal area; Reference stands increased in basal area by 2.7% over the 10 years. 10-year cumulative LW recruitment into channels were double that of the reference stands 10-year canopy cover of the 50-foot buffer recovered to similar percentages as the reference stands 10-year cumulative canopy cover of CC was 71.5% due to ingrowth of dense shrubs, saplings and herbaceous plants.
Sobota et al., 2006	Data was collected at 15 riparian sites throughout the pacific northwest and the Intermountain West	Tree characteristics, forest structural variables and topographic features	Stand density, basal area, and dominant tree species by basal area; Active channel width and valley floor width.	Bias in landform types between slope categories. Effects of catastrophic disturbance regimes in large rivers not included in model.	The strongest correlations of tree fall direction were with valley constraint. When grouped by species, the individual trees showed a stronger tendency to fall towards the stream when hillslopes were >40%. When field data was integrated into the recruitment model, results showed that stream reaches with steep side slopes (>40%) were 1.5 to 2.4 times more likely to recruit LW into streams than in moderately sloped (< 40%) reaches. The authors warn that while side slope categories (>40%, <40%) was the strongest predictor of tree fall direction in this study, they believe the differences in tree fall direction between these categories mainly characterized differences between fluvial (88% of moderate slope sites) and hillslope landforms (71% of steep slope sites). They suggest that the Implications from this study are most applicable to small- to medium-size streams (second- to fourth-order) in mountainous regions where sustained large wood recruitment from riparian forest mortality is the significant management concern.

Teply et al., 2007	25-ft no-cut buffer, with additional 50-feet requiring 88 trees per acre.	Instream wood load	Simulation metrics for forest growth, tree breakage, and in-channel process	The simulation evaluated both a harvest and a no-harvest scenario to predict mean in-stream LW loads after 30, 60, and 100 years	Simulation results predict a 25-foot no-cut buffer, with an additional 50-foot (25 –75 feet from the high watermark) zone requiring retention of 88-trees-per-acre were sufficient in maintaining no significant change in in-stream LW loading relative to unharvested reference streams.
Wing & Skaugset, 2002	LW loads and site characteristics were collected from 3793 stream reaches in western Oregon State (west of Cascade crest).	LW pieces, LW key pieces, LW volume	LW abundance, land use history, land ownership, site level attributes	Results presented here are only for forested streams (“tree 3” in text). Landownership was the strongest predictor in some models, but this included multiple areas of unforested reaches.	For in stream LW volume, stream gradient was the most important explanatory variable with the split occurring for stream reaches with gradients less than 4.7% averaging 11.5 m3 , which was less than half of the average found at higher gradient reaches (25.2 m3); in this model the stream gradient split explained 11% of the variation observed of instream LW volume. For LW pieces in forested stream reaches, bankfull channel width was the most important explanatory variable with the split occurring for streams channels less than 12.2 m wide. LW pieces for streams <12.2 m wide averaged 11.1 LW pieces per reach while larger channels averaged 4.9 pieces per reach; in this model the BFW split explained 7% of the variation in LW pieces found in forested streams. For key LW pieces (logs at least 0.60 m in diameter and 10 m long) in forested reaches, stream gradient was again the most important explanatory variable with the split occurring at a gradient of 4.9%. The streams with a gradient < 4.9% averaged 0.5 key LW pieces per reach while streams with higher gradients averaged 0.9 key LW pieces per reach; in this model stream gradient explained 8% of the variation in key LW pieces found in streams. Lithology caused second, third or fourth level splits after stream gradient or BFW.

Bank Stability and Sediment

Bank Stability

Few studies could be found that quantify how riparian area harvest directly affects bank stability or bank erosion based on our search criteria. Many studies published since 1999 that investigate bank stability and bank erosion compare relative rates of erosion based on the presence/absence of vegetation, type of vegetation (e.g., grassland vs. forest cover), and soil types or lithology (Konsoer et al., 2015; Micheli et al., 2004; Simon & Collision, 2001; Wynn & Mostaghimi, 2006). Also, many studies have investigated the relative effects of different types of land use (e.g., agricultural, urban, forested) as well as cattle grazing intensity (McInnis & McIver, 2009; Zaimes & Schultz, 2014). The only studies that could be found that provide some experimental evidence as to how timber harvest within the riparian area affects bank stability or erosion come from 3 CMER reports (Ehinger et al. 2021; McIntyre et al. 2018, Schuett-Hames et al., 2011; Schuett-Hames & Stewart, 2019).

Schuett-Hames et al. (2011) investigated how soils and streambanks were disturbed following harvest within the riparian area along perennial non-fish bearing streams (Type Np) in western Washington. To evaluate post-harvest soil and stream bank disturbance, Schuett-Hames et al. (2011) first described a soil erosion feature as areas of exposed soil that (1) had a surface area of greater than 10 square feet, and (2) was caused by harvest practice (e.g., felling, bucking, or yarding). If both criteria were met, the length, width, and distance to stream were recorded, and evidence of sediment delivery to the stream was noted. The number of harvest related soil disturbances were grouped by 100 ft lengths of stream, as were the number of features delivering sediment to the stream. Disturbances along stream bank were quantified using the same methods. The surface area (mean width x length) of disturbance features were used to estimate the percent coverage of soil disturbance within 50-feet of bankfull width and in the equipment exclusion zone (ELZ; within 30 feet of the bankfull width). Finally, the percent of harvested patches with a greater than 10% coverage of soil disturbance features in the ELZ were also quantified (performance target for bank stability). These methods were used to collect data for all 3 harvest treatments. These harvest treatments included 1) a 50-foot wide no cut buffer, 2) clearcut, no buffer, and 3) a 56-foot radius no-cut buffer surrounding the perennial initiation point (PIP). A non-parametric, two-sample Mann-Whitney U test was used to test differences in mean soil and stream bank disturbance metrics between the 50-foot buffer patches and the clearcut (no buffer) patches. A Fisher's exact test was used to test for differences in the relative frequency of patches exceeding the performance target (more than 10% of ELZ area disturbed by management related activities) between 50-foot and the clearcut buffer prescriptions.

Results showed that the differences between the mean values of harvest related soil and streambank disturbances for clear-cut patches and the 50-ft buffers were significant for all metrics (e.g., # of bank disturbance features per 100 ft, # of soil disturbance features per 100 feet, # of soil disturbance features, # of soil disturbance features delivering sediment to stream, % of ELZ with soil disturbance; $P \leq 0.082$). Results for soil disturbance performance targets showed that all of the 50-foot buffer and PIP prescriptions met the performance targets (i.e., maintained <10% harvest-related soil disturbance in the ELZ). One clearcut patch exceeded the 10%

coverage performance target. The difference between clearcut patches and 50-foot buffer patches was significant ($p = 0.007$). The average size of harvest related soil disturbances that delivered sediment to streams was 752 ft^2 (range: 31-9060 ft^2). The average size of soil disturbance features that did not deliver sediment to streams was 65 ft^2 (range: 13 – 214 ft^2). Delivery of sediment to streams was best predicted by the horizontal distance between the soil disturbance and the stream channel ($P < 0.0001$). The average distance to the stream for soil disturbance features that delivered sediment was 1 ft (max. = 7.7), while the average distance for non-delivering soil disturbance features was 14 ft (min 3.3). Using distance-to-stream alone, 96% of the observations were correctly predicted based on whether the horizontal distance to the stream was greater or less than 5.4 ft (R^2 U4 = 0.80). The authors concluded there were more harvest-related soil disturbances following harvest in the clear-cut patches than the 50-ft buffers. Further, that the management practices for the 50-foot and PIP buffers were sufficient at maintaining bank stability performance targets. The clearcut patches were mostly sufficient at maintaining performance targets with the exception of one site.

Schuett-Hames et al. (2011) also collected data on soil disturbance associated with post-harvest root pits created from trees being uprooted by wind or other disturbances. Four metrics were used to evaluate soil disturbance associated with uprooted trees: *Root-pits per acre.* Root-pits/acre was calculated by tallying the number of root-pits in each patch and dividing by the patch acreage. *Root-pits per 100 ft of stream length*. Root-pits/100 ft of stream length was calculated by tallying the number of root-pits in each patch (both sides of the stream), dividing by the stream length, and multiplying by 100. *Root-pits with sediment delivery per acre.* Root-pits/acre with evidence of sediment delivery to the channel was calculated by tallying the number of root-pits where evidence of sediment delivery to the stream channel is observed in each patch and dividing by the patch acreage. *Root-pits with sediment delivery per 100 ft of stream length.* Root-pits with sediment delivery/100 ft of stream length were calculated by tallying the number of root-pits with evidence of sediment delivery in each patch (both sides of the stream), dividing by the stream length, and multiplying by 100. These metrics were measured 3 years and 5 years following harvest to give an annual rate of change for each metric at 3 years, from 3-5 years, and for the entire 5 years. These standardized annual rates were compared between each treatment patch type and a unharvested reference patch of the same size.

Results showed that in the first three years after harvest, the mean annual rate of total root-pit formation (all root-pits) in the 50-ft buffers was over 10 times higher than the reference rate. This difference was significant ($p = 0.002$). A similar result was found in the difference between root pits delivering sediment to streams ($p = 0.002$). The mean total root-pit formation rate in the clear-cut patches was much lower than the reference rate (likely because there were less trees to topple). This difference was significant ($P \leq 0.001$). During the second time period (years 4-5 after harvest) the greatest change in the root-pit formation rates was a large increase in the rate for the reference patches and a decrease in rates for the 50-ft buffers. The difference in rates between the reference and the 50-foot buffer were not significant for this time period. The clear-cut patches continued to have the lowest rate and were still significantly lower than the reference patches ($P \leq 0.001$). Over the entire first five years, the rate of total root-pit formation for the 50-ft buffers was nearly double the reference rate, however, this difference was not significant. The pattern was similar for root-pits with sediment delivery, however the difference between the reference and buffer patches was less pronounced due to the higher percentage of root-pits delivering sediment in the reference patches. The percentage of root-pits with evidence of sediment delivery was much higher in the clear-cut patches than in the 50-ft buffers (20.1%) and the reference (26.0%) patches but was not significantly different. Results for the PIP buffers showed a similar trend as the 50-foot buffers with an increase in root pits delivering sediment to the stream in the first three years, but a sharp decline after the third year. Over the course of the full five years Over the entire 5 year period, the percentage of root-pits with evidence of sediment delivery in the PIP buffers (17.6%) was similar to the percentage for the 50-ft buffers (19.8%). These values did not differ significantly from the references.

The authors also investigated the factors affecting whether the post-harvest root pits delivered sediment to streams for 2006 and 2008 (3 and 5 years post-harvest). In both years, sediment delivery to streams was best predicted by the distance of the root-pit from the stream ($P < 0.0001$). Mean horizontal distance to the stream for root-pits that delivered sediment was 8.2 ft compared to 28.0 ft for those that did not deliver. Using horizontal distance to stream, the proportion of the total uncertainty that was attributed to the model fit was 0.39, and 80% of the observations were correctly predicted based on whether the horizontal distance to stream was greater or less than 12.5 ft. Width of root pits delivering soil to the stream were also larger on average but its inclusion to the model did not increase fitness. The authors speculate from their observations that the higher tree-fall rates in the 50-foot buffer during the first 3 years after harvest was due to an increase in wind-throw. However, in the second time period the reference patches showed an increase in windthrow following stronger storms during the 2006-2008 period. One of the two reference streams did show string evidence of mass wasting.

Ehinger et al. (2021; Soft Rock Study) in their investigation of sediment export following harvest along Type Np streams in western Washington (same prescriptions as described above for Schuett-Hames, 2011) also quantified bank erosion events to assess sediment source. To assess erosion events, the researchers placed two eye screws outside of the bank full width to attach a reel tape for measuring length and depth across the bank. No evidence of bank erosion events were found during the pre-harvest periods (1-2 years depending on site) for any stream reach. No erosion events were found at any of the treatment sites during the post-harvest period (3-4 years depending on site). However, there were observations of sediment being sourced from root-pits developed in 2 treatment sites during the post-harvest period, but these effects were not statistically analyzed. Because of the large mass wasting event in the reference the data collected does not support any strong conclusion about the effect of riparian timber harvest on bank stability.

McIntyre et al. (2018; Hard Rock Study) also investigated post-harvest surface erosion following harvest along Type Np streams (same prescriptions as Schuett-Hames, 2011) on competent lithologies in western Washington. They conducted visual surveys to identify recently eroded areas (source of erosion not discerned) in the treated riparian areas that were 10 m^2 or larger. Post-harvest stream-delivering surface erosion was documented at 11 of 17 sites observed. The total erosion area exceeded 110 m^2 at 5 of the 17 sites: 2 reference sites, 2 50-foot buffer sites, and 1 clearcut sites. At these five sites, post-harvest surface erosion was evident adjacent to only 1.5 to 4.6% (average = 2.2%) of the total stream channel length (including both mainstem and tributaries). At the remaining study sites where stream-delivering erosion events occurred, the total eroded area was 60 m2 or less and occurred adjacent to 0.3% to 0.8% (average = 0.6%) of the stream channel length. There were no statistically significant differences in stream-delivering surface erosion among treatments ($\alpha = 0.05$), and on average, reference and buffer treatments visually exhibited a similar amount of exposed bank.

The researchers also investigated the frequency of uprooted trees that developed root pits during the post-harvest period. The average rate of root pits developed in the 50-foot buffers was approximately 3 times higher (3.6 pits/ha/yr) than in the reference sites (1.2 pits/ha/yr) for 3 years following harvest. However, year to year values were highly variable with reference sites showing higher numbers of root pits per acre than either buffer treatment in the first year following treatment (27.4 vs. 18.5 vs. 6.4 for reference, 50-foot, and clearcuts respectively).

The results of the above studies on bank and riparian surface erosion after harvest show some evidence that bank erosion and soil disturbance is generally higher in treated areas than in untreated areas. Further, that bank erosion is likely higher in clearcut treatments without buffers than in treatments with no-cut buffers. However, development of root-pits (with and without sediment delivery pathways to streams) are more likely in treatments with no-cut buffers which is likely because no trees were left in the clearcuts to be toppled. When compared to a reference, the trends of surface erosion and soil disturbance shows there is generally an increase in the treated buffers within the first few years. However, these differences appear to stabilize within five years. Finally, soil disturbance and bank erosion (especially when caused by windthrow) are highly variable and in many instances (e.g., Ehinger et al. 2021; McIntyre et al. 2018) do not exceed the natural range of variability found in reference streams.

<u>Nutrients</u>

The function of riparian areas to regulate and filter the flow of sediments into streams is essential not only for water clarity and pool formation but also because of the ability of sediments to carry nutrients and pollutants (Cooper et al., 1987; Hoffman et al., 2009; Polyakov et al., 2005). . Sediment flux into streams can be affected by landscape factors, streamflow, vegetation composition, and disturbance including riparian and adjacent upland forest management (Crandall et al., 2021; Devotta et al., 2021; Vanderbilt et al., 2003). The movement of sediment into the active channel can, in turn, impact aquatic habitat and geomorphic processes, especially in small, forested streams (Benda et al. 2005; Gomi et al., 2005; Hassan et al., 2005).

The effects of riparian area timber harvest on sediment flux into streams has been documented, investigated, and incorporated into riparian forest management plans in western North America since the 1970s with the development of the Clean Water Act of 1972 (Bilby et al., 1989; Gregory 1990; Gresswell et al., 1989; Naiman et al., 1998; Salo & Cundy, 1986; Swanson et al., 1982: Swanson & Dyrness, 1975). Prior to the Forests and Fish Report (FFR 1999), several studies from western North America investigated the effects of riparian zone timber harvest practices on sediment flux into streams.

Specific to Washington, Rashin et al. (2006) evaluated the effectiveness of Washington State best management practices (BMPs) for controlling sediment related water quality impacts. Although this study was published in 2006, the data analyzed in this study were collected between 1992 and 1995. In their evaluation, Rashin et al. (2006) assessed site erosion, sediment delivery, channel disturbance, and aquatic habitat condition within the first two years of harvest along fish- and non-fish bearing streams across Washington state. From their results, the authors concluded that the site-specific factors influencing the effectiveness of BMPs in preventing chronic sediment delivery into streams were 1) the proximity of ground disturbance to the stream, 2) presence of a stream buffer, 3) falling and yarding practices that minimized disturbance to stream channel, and 4) timing of harvest activities for certain climate zones where frozen ground or snow cover may be exploited. The landscape factors that influenced BMP effectiveness were 1) the density (specific metric not reported) of unbuffered small streams at harvest sites, and 2) steepness of stream valley slopes. The authors conclude with a recommendation of excluding timber falling and yarding activities at least 10 m from streams and outside of steep inner gorges.

Similar results were reported by Lewis (1998) in their evaluation of logging activities' effect on erosion and suspended sediment transport in the Caspar Creek Watersheds of northwestern California. From their results the authors concluded that the dominant factors influencing the difference in suspended sediment loads between watersheds was the difference in road alignment, yarding methods, and presence of stream protection zones (i.e., buffers). Because of studies like these reviewed, contemporary riparian forest management practices in the western United States include rules that limit harvesting, use of equipment, and procedures that disturb soil in areas closest to the stream or on steep and unstable slopes (WAC 222-30-022; WAC 22-30-021; 2022 ODF; IDAPA 20.02.01)

Since 2000, many of the studies published that evaluate changes in sediment delivery or water turbidity following riparian timber harvest show similar results in that contemporary BMPs are effective in mitigating increases in sediment delivery to streams (Hatten et al., 2018; Reiter et al., 2009). For example, the studies reviewed that report a significant change in sediment delivery following harvest show evidence that these changes only persist for a short period of time (1-3 years) and that the magnitude of these changes are related to the intensity of the harvest prescriptions (Karwan et al., 2007; Macdonald et al., 2003a).

For example, Macdonald et al. (2003a) compared changes in stream discharge rates and in-stream suspended sediment concentrations during spring snowmelt between two harvest intensities and one unharvested control, for pre- and post-harvest in first order streams of interior British Columbia. Both treated riparian areas received a harvest of 55% of the watershed; one (low-retention) removed all merchantable timber >15 cm DBH for pine and > 20 cm DBH for spruce within 20 m of the stream; the other (high-retention) removed all merchantable timber > 30 cm within 20 m of the stream. The results showed an increase in spring snowmelt discharge for both treatments above predicted values for the study (5 years). However, increased in-stream total suspended sediments (TSS) only persisted for two-years post-harvest in the high-retention treatment, and for 3-years in the low-retention.

Karwan et al. (2007) investigated the effects of riparian timber harvest and road construction on TSS concentrations in the Mica Creek Experimental Watershed in northern Idaho. Treatments in the paired-watershed experiment consisted of 1) commercial clearcut of the watershed area by 50%, and was broadcast burned and replanted, 2) partial cut in which half the canopy was removed in 50% of the watershed area 3) a no-harvest control. All harvests were done according to best management practices and the Idaho Forest Practices Act. This included equipment exclusion zones of 50- and 30-feet for fish- and non-fish-bearing streams, respectively. On all skid trails, drainage features, such as water bars, were installed for erosion control at the end of the harvest period. Results showed that road construction in both watersheds did not result in significant impacts on monthly sediment loads in either treated watershed during the immediate (1-year post-harvest) or recovery (2-4 years post-harvest) time intervals. A significant and immediate impact of harvest on monthly sediment loads in the clear-cut watershed ($p = 0.00011$), and a marginally significant impact of harvest on monthly sediment loads in the partial cut ($p = 0.081$) were observed. However, after one year, the TSS loads in both treatments became statistically indistinguishable from the control.

Specific to Washington, McIntyre et al. (2021) evaluated the effectiveness of riparian buffers on non-fish-bearing streams underlain by competent lithologies (“Hard Rock”) in western Washington. Buffers were treated with one of three prescriptions 1) unharvested reference, 2) a two-sided 50-ft riparian buffer along the entire riparian management zone (RMZ), 3) a two-sided 50-ft riparian buffer along at least 50% of the RMZ, and 4) clearcut to stream edge (no-buffer). Results for suspended sediment export (SSE) following treatment showed episodic increases with storm events that rapidly declined. However, changes in SSE were poorly correlated with discharge and exhibited high variation between treatment sites. The authors suggest that these results show evidence that changes in SSE magnitudes were not related to harvest. Further, they conclude that the sites were likely sediment-limited considering the underlying lithology.

Site factors such as underlying lithology and physiography can interact with the effect of timber harvest operations on sediment delivery into streams. Bywater-Reyes et al. (2017) assessed the influence of natural controls (basin lithology and physiography) and forest management on suspended sediment yields in temperate headwater catchments in northeastern Oregon. Results from this study indicate that site lithology was the first order control over suspended sediment yield (SSY) with SSY varying by an order of magnitude across lithologies observed. Specifically, SSY was greater in catchments underlain by Siletz Volcanics ($r = 0.6$), the Trask River Formation ($r = 0.4$), and landslide deposits ($r = 0.9$) and displayed an exponential relationship when plotted against the percentage of watershed area underlain by these lithologies. In contrast, lithology had a strong negative correlation with percent area underlain by diabase ($r = 0.7$), with the lowest SSY associated with 100% diabase. Following timber harvest, increases in SSY occurred in all harvested catchments but returned to pre-harvest levels within 1 year except for sites that were underlain by sedimentary formations and were clearcut without protective buffers. The authors conclude that sites underlain with a friable lithology (e.g., sedimentary formations) had, on average, SSYs an order of magnitude higher following harvest than those on more resistant lithologies (intrusive rocks).

Mueller & Pitlick, (2013) found similar results in their assessment of the relative effect of lithology, basin relief, mean basin slope, and drainage density on in stream sediment supply for 83 drainage basins in Idaho and Wyoming. The strongest correlation of in stream sediment supply was with lithology relative softness (based on grouping of rock types – granitic, metasedimentary, volcanic, and sedimentary). Sediment concentrations at bankfull width increased by as much as 100-fold as basin lithology became dominated by softer sedimentary and volcanic rock compared to lithologies dominated by harder granitic and metasedimentary rock. Finally, Wissmar et al. (2004), developed and field-tested erosion risk indices for watersheds in western Washington based on land cover. These erosion risk indices used the presence of unstable soils (determined by geological formation and underlying lithology), rain-on-snow events, immature forest cover (stands <35 years old where open canopies and undeveloped root systems could contribute to hillslope instability), presence and coverage of roads, and critical slope (hillslope gradients >36%, for terrain with surficial deposits of coarse-textured colluvial materials). Results of this study showed these variables could explain ~65% of the variation associated with sediment input into channels. The lowest risk areas contained the fewest of these variables (most commonly critical slope with either rain-on snow events or immature forests), while higher risk areas contained a combination of 4 or more of these factors indicating a compounding effect.

Changes in sediment yield may also interact with increases in discharge rates caused by timber harvest as well as physiographic site factors. For example, Bywater-Reyes et al. (2018) quantified how sediment yields vary with catchment lithology and physiography, discharge, and disturbance history over 60 years in the H.J. Andrews experimental watershed in the western Cascade Range of Oregon. Methods for determining suspended sediment concentration involved using either vertically integrated storm-based grab samples, or discharge-proportional composite samples where composite samples were collected every three weeks at the outlet of each catchment. Data sets were taken from 10 watersheds, 7 with a history of management (mixture of selective canopy removal, patch-cut, 25-100% clearcut, broadcast burning, road building, and thinning), and 3 with no history of management that were used as a reference. A linear mixed effects model (log transformed to meet the normality assumption) was used to predict annual sediment yield. In this model, site was treated as a random effect while discharge and physiographic variables were treated as fixed variables. This allowed for the evaluation of the relationships between sediment yield and physiographic features (slope, elevation, roughness, and index of sediment connectivity) while accounting for site. To account for the effect of disturbance history a variable was added to the model when the watershed had a history of management or natural disturbances. If the models for the disturbed watersheds significantly underpredicted the sediment discharge, the timing of the sudden increases were further examined to assess whether it correlated with a disturbance event (e.g., harvesting, road building, and slash-burning.) The results of this study show that watershed physiography combined with cumulative annual discharge explains 67% of the variation in annual sediment yield across the 60-year data set regardless of lithology. Relative to other physiographic variables, watershed slope was the greatest predictor of annual suspended sediment yield. However, the results showed that annual sediment yields also moderately correlated with many other physiographic variables and caution that the strong relationship with watershed slope is likely a proxy for many processes, encompassing multiple catchment characteristics.

In contrast, Safeeq et al. (2020) compared instream and bedload sediment supply under multiple harvesting treatments in watersheds of western Oregon that were paired with control watersheds by size, aspect, and topography. The treatment watershed was 100% clearcut during the period from 1962-1966, broadcast burned in 1966, and re-seeded in 1968. For this study 15-minute streamflow data was recorded for both watersheds, and after large storm events. Sediment data was collected from 1952 (pre-harvest) through 1988 for suspended sediment data, and 2016 for sediment bedload. The control watershed was forested, and had no treatments (e.g., harvest) during the study period. Their results estimate that following streamside harvest, increased streamflow alone is estimated to be responsible for <10% of sediment transport into streams while the increased sediment supply caused by harvest operations is responsible for >90% of the sediment transported into streams.

Puntenney-Desmond et al. (2020) found similar results in their assessment of differences in instream sediment contributions from the buffer area, harvest area, and buffer-harvest interface. Sediment concentration in the runoff was 15.8 times higher for the harvested area than in the riparian buffer, and 4.2 times greater than in the harvest-buffer interface. Total sediment yields (mg m^{-2} min^{-1}) from the harvested area (sediment concentration x flow rate) were approximately 2 times greater than in the buffer areas, and 1.2 times greater in the harvest-buffer interface than in the buffer area.

Summary of Factors Impacting Sediment Delivery into Streams

From the studies reviewed there is evidence that sediment delivery into streams following timber harvest is influenced by not only the intensity of the harvest operation (e.g., presence of retention buffers, yarding and equipment use immediately adjacent to the stream, upland clearcut vs. thinning), but also by physiography (e.g., hillslope gradient), lithology relative softness, and climate (e.g., precipitation, frequency of large storm events). Thus, the change in magnitude of sediment delivery following harvest is context dependent and these landscape factors can interact with one another to compound these changes. However, from the studies reviewed above there is evidence that the implementation of BMPs since the 1970s in the northwestern United States lessen the impact and duration of these changes.

Table 4. List of treatments, variables, metrics, and results from publications reviewed for information on sediment inputs and source.

Reference	Treatment	Variables	Metrics	Notes	Results
Bywater-Reyes et al., 2017	Harvest had a mixture of intensities including clearcut to stream and clearcut with 15 m buffers.	Sediment concentration, basin lithology, geomorphology	Channel, stream, and riparian area characteristics sourced from a mixture of LiDAR and management data.	This study analyzed 6 years of data from the Trask River Watershed in Northeastern Oregon and included data from harvested and unharvested sub-catchments underlain by heterogenous lithologies.	Results from this study indicate that site lithology was a first order control over suspended sediment yield (SSY) with SSY varying by an order of magnitude across lithologies observed. Specifically, SSY was greater in catchments underlain by Siletz Volcanics (r = 0.6), the Trask River Formation (r = 0.4), and landslide deposits. In contrast, the site effect had a strong negative correlation with percent area underlain by diabase (r = 0.7), with the lowest SSY associated with 100% diabase independent of whether earthflow terrain was present. Sites with low SSY and underlain by more resistant lithologies were also resistant to harvest-related increases in SSY. The authors conclude that sites underlain with a friable lithology (e.g., sedimentary formations) had SSYs an order of magnitude higher, on average, following harvest than those on more resistant lithologies (intrusive rocks).
Bywater-Reyes et al., 2018	long-term data (60 years) of sediment, discharge, weather, and disturbance.	Sediment yield, discharge history, physiography.	suspended sediment concentration involved using either vertically integrated storm-based grab samples, or discharge-proportional composite samples.	The authors caution that the high variability of sediment yield over space and time (~0.2 - ~953 t/km2) indicates that the factors tested in this study should be tested more broadly to investigate their utility to forest managers.	The results of this study show that watershed slope variability combined with cumulative annual discharge explained 67% of the variation in annual sediment yield across the approximately 60-year data set. The results, however, show that annual sediment yields also moderately correlated with many other physiographic variables and the authors caution that the strong relationship with watershed slope variability is likely a proxy for many processes, encompassing multiple catchment For the relationships between disturbance and sediment yield the authors conclude that the few anomalous years of high sediment yield occurred in watersheds with high slope variability and within a decade of forest management and a large flood event.
Hatten et al., 2018	Data from pre restriction and post Oregon BMPs prescriptions for non-fish bearing streams.	suspended sediment concentrations (SSC)	suspended sediment, stream discharge, and daily precipitation	Phase I harvest: 2009 harvest of upper half of watershed. Phase II harvest: 2015 harvest of lower half of watershed.	Methods used in 1966 to harvest the same watershed (no buffer, road construction, broadcast burning) resulted in an approximate 2.8-fold increase in SSC from pre- to post-Harvest. In the contemporary study both the mean and maximum SSC were greater in the reference catchments (FCG and DCG) compared to the harvested catchment (NBLG) across all water years. In NBLG the mean SSC was 32 mg L−1 (~63%) lower after the Phase I harvest and

	BMPs: no buffer in non-fish-bearing streams with equipment exclusion zones, and a 15 m no-cut-buffer in fish-bearing streams				28.3 mg L−1 (~55%) lower after the Phase II harvest when compared to the pre-harvest concentrations. Compared to the reference watersheds, the mean SSC was 1.5-times greater in FCG (reference) compared to NBLG during the pre-harvest period. After Phase I harvest the mean SSC in FCG was 3.1-times greater and after Phase II harvest was 2.9-times greater when compared to the SSC in the harvested watershed. The authors conclude that contemporary harvesting practices (i.e., stream buffers, smaller harvest units, no broadcast burning, leaving material in channels) were shown to sufficiently mitigate sediment delivery to streams, especially when compared to historic practices.
Karwan et al., 2007	clearcut of the watershed area of by 50%, partial cut of 50% canopy removal, timber road construction Riparian zone harvest followed Idaho FPA rules.	Total suspended solid (TSS) yields	Monthly total suspended solid readings from multiple flume locations for pre-, and post-harvest, and pre- and post-road construction.		A significant and immediate impact of harvest on monthly sediment loads in the clear-cut watershed (p = 0.00011), and a marginally significant impact of harvest on monthly sediment loads in the partial-cut (p = 0.081) were observed. Total sediment load from the clearcut over the immediate harvest interval (1-year post-harvest) exceeded predicted load by 152%; however, individual monthly loads varied around this amount. The largest increases in percentage and magnitude occurred during snowmelt months, namely April 2002 (560%) and May 2002 (171%). Neither treatment showed a statistical difference in TSS during the recovery time, 2-4 years post-harvest (clearcut: p = 0.2336; partial-cut: p = 0,1739) compared to the control watersheds. Road construction in both watersheds did not result in statistically significant impacts on monthly sediment loads in either treated watershed during the immediate or recovery time intervals.
Litschert & MacDonald, 2009	Data collected from 4 NF of Nort CA. ~200 harvest sites near riparian zones with 90 m and 45 m buffer widths.	Sediment delivery pathway frequency and characteristics.	Pathway length, width, origins, and connectivity of sediment delivery pathways to streams.	Authors mention a caveat to the results of the study in that there is a potential of underestimating the frequency of rills and sediment plumes as sites recover.	Only 19 of the 200 harvest units had sediment development pathways and only 6 of those were connected to streams and five of those originated from skid trails. Pathway length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient.

Macdonald et al., 2003a	low-retention = removed all timber >15 cm DBH for pine and > 20 cm DBH for spruce within 20 m of the stream; high-retention = removed all timber > 30 cm within 20 m of the stream.	suspended sediment yields, stream discharge	Discharge rate and total suspended sediments (TSS) collected using Parshall flumes	Only 1-year pre-harvest data was collected to generated predicted TSS and discharge values post-harvest.	Immediately following harvest, TSS concentrations and discharge rates increased above predicted values for both treatment streams. Increased TSS persisted for two-years post-harvest in the high-retention treatment, and for 3-years in the low-retention. This study shows evidence that harvest intensity (low vs. high retention) is proportional to the increase in stream discharge, TSS concentrations, and recovery time to pre-harvest levels. The authors speculate that the treatment areas may have accumulated more snow (e.g., more exposed area below canopy) than in the control reaches leading to the increase in discharge.
McIntyre et al., 2021	1) unharvested reference, 2) 100% treatment, a two-sided 50-ft riparian buffer along the entire RMZ, 3) FP treatment a two-sided 50-ft riparian buffer along at least 50% of the RMZ, (4) 0% treatment, clearcut to stream edge (no-buffer).	stream discharge, turbidity, and suspended sediment export.		Type N (non-fish-bearing streams). Hard-Rock study.	Discharge increased by 5-7% on average in the 100% treatments while increasing between 26-66% in the FP and 0% treatments. Results for water turbidity and suspended sediment export (SSE) were stochastic in nature and the relationships between SSE export and treatment effects were not strong enough to confidently draw conclusions. The authors conclude that timber harvest did not change the magnitude of sediment export for any buffer treatment.
Mueller & Pitlick, 2013	The study used sediment concentration data from 83 drainage basins in Idaho and Wyoming.	Sediment concentration, basin lithology, geomorphology	Sediment concentration distribution, geomorphology, and weather data from multiple sources.		The strongest correlation of in stream sediment supply was with lithology relative softness. Bankfull sediment concentrations increased by as much as 100-fold as basin lithology became dominated by softer sedimentary and volcanic rock. Relief (elevation), basin sideslope, and drainage density showed little correlation strength with bankfull sediment supply.

Puntenney-Desmond et al., 2020	Variable retention buffers with clearcut.	surface and subsurface runoff rates, sediment.	Simulation metrics calibrated with runoff and sediment samples from sample area. Precipitation calibrated for 100-year-rain events.	Differences in sediment yield not statistically significant.	Surface and shallow subsurface runoff rates were greatest in the buffer areas than in the harvested areas or in the harvest-buffer interfaces especially during dry conditions. The authors speculate this was likely due to the greater soil porosity in the disturbed, harvested areas. Sediment concentration in the runoff, however, was approximately 15.8 times higher for the harvested area than in the riparian buffer, and 4.2 times greater than in the harvest-buffer interface. Total sediment yields from the harvested area (runoff + sediment concentration) were approximately 2 times greater than in the buffer areas, and 1.2 times greater in the harvest-buffer interface, however this difference was not significant.
Rachels et al., 2020	harvested following the current Oregon Forest Practices Act policies and BMPs	proportion of sediment from sources	Sediment collected in traps; sourced using chemical analysis	limited sample size (1 treatment, 1 paired reference watershed) and does not incorporate the effects of different watershed physiography on sediment erosion.	The proportion of suspended sediment sources were similar in the harvested (90.3 + 3.4% from stream bank; 7.1 + 3.1% from hillslope) and unharvest (93.1 + 1.8% from streambank; 6.9 + 1.8% from hillslope) watersheds. In the harvested watersheds the sediment mass eroded from the general harvest areas (96.5 + 57.0 g) was approximately 10 times greater than the amount trapped in the riparian buffer (9.1 + 1.9 g), and 4.6 times greater than the amount of sediment collected from the unharvested hillslope (21.0 + 3.3 g).
Safeeq et al., 2020	Long term (51 years) effects of clearcut to stream followed by broadcast burn.	streamflow, sediment transport	Historical streamflow data, precipitation data, sediment grab samples for bedload and suspended sediment.	Data compared one treatment watershed and one control watershed across 51+ years.	The results for post-treatment sediment yields showed suspended load declined to pre-treatment levels in the first two decades following treatment, bedload remained elevated, causing the bedload proportion of the total load to increase through time. Changes in streamflow alone account for 477 Mg/km2 (10%) of the suspended load and 113 Mg/km2 (5%) of the bedload over the post-treatment period. Increase in suspended sediment yield due to increase in sediment supply is 84% of the measured post-treatment total suspended sediment yield. In terms of bedload, 93% of the total measured bedload yield during the posttreatment period can be attributed to an increase in sediment supply. The authors conclude that Following harvest, changes on streamflow alone was estimated in being responsible for < 10% of the resulting suspended sediment transported into streams, while the increase in sediment supply due to harvest disturbance was responsible for >90%.

Wise, 2010	Streamflow patterns derived from instrumental data and from reconstructed tree-ring chronologies were compared with other previously reconstructed rivers in similar climates.	Streamflow	Dendrochronology, historical data records, seasonal patterns	The reconstruction model developed for the analysis explained 62% of the variance in the instrumental record after adjustment for degrees of freedom.	Results showed evidence that droughts of the recent past are not yet as severe, in terms of overall magnitude, as a 30-year extended period of drought discovered in the mid-1600s. However, in terms of number of individual years of < 60% mean-flow (i.e., low-flow years), the period from 1977-2001 were the most severe. Considering the frequency of consecutive drought years, the longest (7-year-droughts), occurred in the early 17th and 18th centuries. However, the 5-year drought period from 2000-2004 was the second driest period over the 415-year period examined.
Wissmar et al., 2004	Data sourced from management records and geospatial data to identify high erosion-risk areas.	Sediment, weather, stand characteristics, landscape factors	unstable soils, immature forests, roads, critical slopes for land failure, and rain-on-snow events		The highest-risk areas contained a combination of all landscape cover factor combinations (rain-on-snow zone, critical failure slope, unstable soil, immature forests, and roaded areas). The lowest risk categories contained only rain-on-snow zones, and critical failure slopes. Roaded areas and unstable soils were only present in risk categories 3-6.

Shade and stream temperature

Canopy cover provides shade for streams that decreases the amount of incoming solar radiation and thus influences stream temperatures, although that influence can be highly variable depending on shade structure and density surrounding stream courses. Temperature regulation is vital for sensitive salmonid fish species that require cooler waters, and shade is often the primary function assessed when developing state regulations (Groom et al., 2011; Groom et al., 2018; Teply et al., 2014). The importance of shade and cooler in-stream temperatures for fish habitat has been thoroughly investigated (Bjornn & Reiser, 1991; Chapman & Bjornn, 1969; Ebersole et al., 2001; Sullivan et al., 2000). The streamside shade will likely become even more critical with the predicted increases in air temperature over the next century (Manuta et al., 2009. While stream temperature is initially reflective of moisture source (e.g., snowmelt, liquid precipitation, groundwater inputs) and watershed subsurface soil characteristics. As water flows downstream and into higher-order streams, the net rate of temperature gain or loss is the sum of incident radiation, evaporation, conduction, and advection (Brown, 1983; Bescheta et al., 1987).

Bescheta et al. (1987) presented evidence that direct beam solar radiation inputs are of the highest importance to the stream's net heat exchange rate per unit area compared to other factors. Within the net heat exchange calculation, the heat released from evaporation generally cancels out the heat gained from warm air temperatures (convective and advective heat transfer). Thus, temperature fluctuations are expected to be more severe in less-shaded/more-exposed streams. This has been supported by many experimental field and simulation studies showing evidence that the reduction of effective shade can lead to considerable increases in peak summer stream temperatures primarily due to the increase of incoming solar radiation. However, while increases in solar radiation are accepted as the most important factor in stream temperature changes and fluctuations following harvest, other factors are also important and may compound these effects. For example,

Guenther et al. (2014) investigated the relationship between changes in stream temperature and changes in wind speed, vapor pressure, and evaporation following riparian thinning treatments along headwater streams in southwestern British Columbia. Treatment involved reduction of basal area by 50% (resulting in 14% reduction in canopy closure) in the upland and riparian forests. Results showed a post –harvest increase in wind speed, vapor pressure deficit, air temperature and evaporation above the stream, which coincided with increased stream temperatures and lower stability. The authors report that prior to harvest, vapor pressure gradients often favored condensation over evaporation. Further, they concluded that the relationships between the riparian and microclimate variables after harvesting became more strongly coupled to ambient climatic conditions due to increased ventilation. Contemporary riparian management practices in western North America vary by state. However, all require retention of protective buffers that preserve some percentage of shade or canopy cover to maintain or mitigate changes in stream temperatures, especially along fish-bearing streams. Many studies published in the last two decades report evidence that these practices have been effective in mitigating stream temperature changes after harvest.

For example, Bladon et al. (2016), assessed the effectiveness of riparian management prescriptions developed for the Oregon Forest Practices Act (FPA). Oregon State requires a 15 m buffer on either side of small fish-bearing streams with a 6 m no-cut buffer, and a minimum retention for conifer basal area of ~3.7 m^2 for every 300 m (~1000 ft) length of stream. This resulted in a reduction of mean canopy closure from ~96% in the pre-harvest period to ~89% in the post-harvest period in the treatment reaches. In contrast, mean canopy closure in the reference reaches changed from ~92% to ~91% from pre- to post-treatment periods. Results showed there was a significant increase in the 7-day moving maximum temperature from pre- to post-harvest values when data was constrained to the period of July 15 – August 15 by 0.6 +/- 0.2 °C. However, when analyzed by individually paired sites, and when interannual and site variability was accounted for, no significant changes in stream temperature were observed for 3 years post-harvest (length of study).

However, Groom et al., (2011a, b) showed evidence that the more stringent rules of the Northwest Oregon State Forest Management Plan (FMP; applied to riparian management zones on state owned land) was even more effective at maintaining stream temperatures post-harvest. The FMP requires a 52 m wide buffer for all fish-bearing streams, with an 8 m no cut buffer immediately adjacent to the stream. The results from Groom et al. (2011b) showed that FPA (Oregon Forest Practices) post-harvest shade values differed from pre-harvest values (mean change in Shade from 85% to 78%), while no difference was found for FMP shade values pre-harvest to post-harvest (mean change in Shade from 90% to 89%). Following harvest, maximum temperatures at FPA increased relative to FMP on average by 0.71 °C. Similarly, mean temperatures increased by 0.37 °C (range: 0.24 - 0.50), minimum temperatures by 0.13 °C (range: 0.03 - 0.23), and diel fluctuation increased by 0.58 °C (range: 0.41 - 0.75) relative to FMP sites.

Groom et al (2011a) developed prediction models from this data to estimate the probability of riparian harvest under each regulation causing an increase in stream temperatures >0.3 °C (the Protecting Cold Water criterion developed by the Department of Environmental Quality). Results indicate that sites harvested according to FPA standards exhibited a 40.1% probability of a temperature change of > 0.3°C from pre- to post harvest. Conversely, harvest to FMP standards resulted in an 8.6% probability of exceedance that did not significantly differ from all other comparisons.

In Montana, Sugden et al. (2019) investigated the effectiveness of state regulation which requires timber be retained within a minimum of 15.2 m (50 feet) of the stream. Within the riparian management zone, no more than half the trees greater than 204 mm (8 in) diameter at breast height (DBH) can be removed. In no case, however, can stocking levels of leave trees be reduced to less than 217 trees per hectare. Data for canopy cover, stream temperature, and fish population were collected for 30 harvest reaches in western Montana (northern Rocky Mountain Region), for a minimum of one-year pre- and one-year post-harvest. Shade over the stream surface was not directly measured in this study. Instead, canopy cover was used as proxy, using two independent estimates of canopy cover (1) used cruise data to populate a canopy cover model within Forest Vegetation Simulator, and (2) measured canopy cover in the harvested reach every

30 m, before and after harvest. Within harvest units, mean basal area was reduced by 13% (range: 0 – 36%), and again further by a mean of 2% due to windthrow. Mean canopy cover within the riparian management area reduced from 77% (pre-treatment) to 74% (post-treatment), and mean canopy cover over the stream changed from 66% (pre-treatment) to 67% (post-treatment) based on densiometer measurements. Neither of these changes were significant. Results for stream temperature also showed no significant changes in stream temperatures or fish populations in one-year post treatment compared to pre-treatment values.

Specific to Washington, Cupp & Lofgren (2014) conducted a study to test the effectiveness of riparian timber harvest rules for eastern Washington in preserving shade and stream temperatures. Regulations for fish-bearing streams in eastern Washington (in the mixed conifer/mid elevation zone) includes an "All Available Shade Rule" (ASR) for streams in the bull trout habitat zones, and a "Standard Shade Rule" (SR). Under the ASR it is required to retain all available shade within 75 feet of the stream. Under SR some harvest of shade providing trees is allowed within the 75-foot buffer depending on elevation and pre-harvest canopy cover. Unharvested reference reaches were located upstream from treatment reaches. Prior to harvest treatments, canopy closure measurements ranged from 89% to 97%, with a mean of 93%. Results showed post-harvest shade values decreased in SR sites (mean effect of -2.8%, $p = 0.002$), as did the canopy closure values (mean effect of -4.5%, $p < 0.001$). Shade and canopy closure values did not significantly change after treatment in the ASR sites. Post-harvest mean daily maximum stream temperature increased 0.16 °C in the SR harvest reaches, whereas stream temperatures in both the ASR sites and in the no-harvest reference reaches increased on average by 0.02 °C. Sample period means of daily maximum temperature responses varied from –1.1 °C to 0.7 °C in the first two years post-harvest for the ASR sites, from –0.5 to 0.8 °C, in the SR sites, and –0.5 to 0.9 °C in the reference sites. While these values show a slight increase in mean temperatures and temperature ranges with treatment, the authors interpret these results as evidence that temperature effects of the SR and ASR were similar to reference conditions along sampled reaches.

Riparian harvest rules along non-fish bearing streams tend to allow for narrower buffer widths (sometimes with no retention buffers) or more intense thinning within the buffer than for fish-bearing streams. For example, in western Washington the Forest Practices (FP) buffer prescription requires a two-sided 15 m (50 ft) wide buffer along a minimum of 50% of the length of a non-fish-bearing perennial stream (i.e., up to 50% of the stream may have no buffer) with a 9.1 m (30 ft) equipment exclusion zone. Two recent studies (Ehinger et al., 2021; McIntyre et al., 2021) have compared these FP buffers to two experimental buffer treatments, a 50 ft buffer along 100% of the stream length (100%), and no buffer (0%) treatment, and an unharvest reference (REF) on sites underlain by competent lithologies (McIntyre et al., 2021; "Hard Rock") or incompetent (friable) lithologies (Ehinger et al. 2021; "Soft Rock).

Results from the Hard Rock study showed that riparian canopy cover declined after harvest in all buffer treatments reaching a minimum around 4 years post-harvest (after mortality stabilized). The treatments, ranked from least to most change, were REF, 100%, FP, and 0% for all metrics and across all years. Effective shade results showed decreases of 11, 36, and 74 percent in the

100%, FP, and 0% treatments, respectively. These changes in shade were significant for all treatments. This led to changes in mean stream temperature from pre- to post-harvest in the 100% treatment by 2.4°C in the first year following treatment, but never exceeded 1.0°C in any year after (for up to 8 years). In contrast, the mean difference in pre- to post-harvest stream temperatures in the FP exceeded 1.0°C in the first year, declined in years 2-5 post-harvest, and then exceeded 1.0°C again in years 6-9. Results for the 0% treatment showed a mean difference of 5.3°C immediately following harvest and declined over time but never below 0.9°C by year 9. Comparatively, mean pre- to post-harvest differences in stream temperature never exceeded 1.0°C in the reference sites. Changes in mean difference from pre- to post-harvest stream temperatures were significant for all treatments at some point during the study. However, by year 11 mean stream temperatures had recovered to within 0.2°C of pre-harvest values for all treatments. A weak and nearly significant (P-value range: 0.008 - 0.108) negative relationship between canopy cover and stream temperature for the first 4 years after treatment was detected. These results provide evidence that the effectiveness of buffers in maintaining stream temperatures post-harvest is relative to the intensity of the treatment (e.g., presence of buffer, reduction in canopy cover). Further, post-treatment mortality within the buffer from events such as windthrow can cause fluctuations in stream temperature response during the first decade. Results from the Soft Rock Study showed similar trends in canopy cover reduction and stream temperature increases. Authors of the Soft Rock study note that stream temperature changes varied as a function of the proportion of the stream buffered and tree mortality, but limited and unbalanced sample sizes did not allow for statistical analysis.

Outside of Washington, several studies conducted in western North America since 2000 have shown results similar to the Hard Rock and Soft Rock studies. For example, Roon et al. (2021b) compared stream temperature changes following variable riparian thinning intensities in the redwood forests of northern California. Treatments to riparian stands included reduction of canopy cover that resulted in reduction of effective shade by either (19-30%) or by (4-5%). Their results showed that local changes in stream temperature were dependent on thinning intensity, with higher levels of canopy cover reduction leading to higher increases in local stream temperatures. In the reaches with higher reductions in shade (19-30%) there was accumulation of 45° to 115°C additional degree days from pre- to post treatment years, while the reaches with lower reductions in shade (4-5%) only accumulated 10° to 15°C additional degree days. Further, travel distance of increased stream temperatures also appeared to be dependent on thinning intensity. The lower shade reduction reaches had an increased temperature effect downstream with travel distance of 75-150 m, while the high shade reduction sites had a downstream travel distance of 300- ~1000 m.

Reiter et al. (2020) compared the changes in stream temperatures following different harvest treatments along headwater streams in the Trask River Watershed in the northwestern coast range of Oregon. Treatments included a clearcut to stream (no buffer but half of sites contained some leave trees along stream bank), upland clearcut with a 10 m no-cut buffer, upland thinning (basal area reduction to 30-50% of original stand) with a 10 m no-cut buffer, and an unharvested reference. Results showed that post-harvest stream temperature increases were only significant in the clear-cut treatments without buffers with a mean increase of 3.6°C (SE = 0.4°C) for four years after the study. They note that temperature changes were more severe in the unbuffered streams with no leave trees (4.2 and 4.4°C), however, this difference was not analyzed. No significant changes in stream temperature were detected in either treatment with a 10 m no-cut buffer. The authors speculate that 10 m wide buffers were sufficient in maintaining stream temperatures post-harvest in small, forested headwater streams.

In the sub-boreal forest ecosystems of British Columbia, Canada, Macdonald et al. (2003b) compared pre- to post-harvest stream temperature changes in first-order headwater streams under 3 different riparian forest treatments. These treatments included 1) low-retention – removal of all merchantable timber >15 or >20 cm DBH for pine or spruce respectively, within 20 m of the stream 2) high-retention – removal of merchantable timber >30 cm DBH within 20-30 m of the stream, and 3) patch-cut – high retention for the lower 60% of watershed approaching streams and removal of all vegetation in the upper 40% of the watershed. Results showed significant increase in stream temperatures ranging from 4 – 6 ºC in the low-retention and patch cut in the first three years following harvest. However, by year five, mortality in the high-retention buffer (due to windthrow) resulted in canopy cover reduction and increases in stream temperatures that became equivalent to the other treatments. The authors conclude that while the variation in harvest intensity initially appeared to dictate stream temperature responses, site effects (e.g., windthrow susceptibility) can impact the effectiveness of the buffer. While the studies above all show evidence that the impact of riparian forest harvest on stream temperatures are related to the severity of the harvest prescription (e.g., buffer width, thinning intensity, canopy reduction) the results are variable within treatments indicating other site factors are also important when evaluating buffer effectiveness. For example, in their review of experimental studies conducted in the Pacific Northwest of Canada and the United States, Martin et al. (2021) reported high variability in temperature response to streamside buffers. They report a substantial variability and overlap in the effect size of the mean 7-day maximum temperature metric with no-cut buffers, no-cut plus variable retention buffers, and no-cut patch buffers ≤ 20 m wide. The largest temperature response (> 3.4 ºC) occurred in the clearcut buffers while treatments with buffers (i.e., no cut buffers without variable retention) had the smallest response (< 0 ºC). The variable retention buffers < 20 m showed variable response (0.6 – 1.4 ºC). They conclude that the variation in temperature response following riparian harvest may be associated with multiple factors such as geology, hydrology, topography, latitude, and stream azimuth.

Bladon et al. (2018) investigated the changes in stream temperatures following treatments that varied from clearcuts to stream to buffers > 20 m in western Oregon. They performed a regression analysis to assess the relative relationship between catchment lithology and the percentage catchment harvested with stream temperature at all sites. Their results showed that at the upstream harvested sites there was a strong relationship between stream temperature increases and catchment lithologies, but no statistically significant relationship between stream temperature changes and percent of catchment harvested. Sites downstream from harvested areas showed a significant relationship with the interaction of percentage of catchment harvested and the underlying lithologies ($p = 0.01$). The greatest temperature increases at downstream sites were in areas with a higher percentage of catchment harvested and were underlain by more resistant lithologies. There was no evidence for increases in stream temperatures in catchments with a high percentage of harvest that were underlain by permeable geology. The authors suggest that this relationship may be due to the buffering effect of increases in summer low flows and greater groundwater or hyporheic exchange. They conclude that the variability of rock permeability and the relative contribution of groundwater during summer months, and their effect on stream temperatures following harvest should be investigated further.

There is evidence that geomorphology alone can impact stream temperature fluctuations throughout the year. Hunter & Quinn, (2009) compared seasonal fluctuations in stream temperatures between two watersheds in the Olympic Peninsula, Washington. Both watersheds were similar in all characteristics except for bed substrate. One was underlain by alluvial bed substrate while the other was underlain by bedrock. Results from this study show consistent differences in stream temperature response in alluvial versus bedrock channels. Seasonal maximum and minimum average daily temperatures varied less at the alluvial site compared to the bedrock site. This, the authors suggest, may be due to hyporheic exchange in alluvial channels helping to buffer surface water temperatures from gaining or losing heat. In addition, groundwater may also contribute to the increased stability at the alluvial site. Aside from shade reduction from timber harvest, there is evidence that light availability and canopy cover naturally changes over time as riparian stands develop. For example, Warren et al. (2013) compared canopy cover and stream light availability between old-growth-forests (>500 years old) and young harvest-aged stands (~40-60 years old) in the H.J. Andrews Experimental Forest in the Cascade mountains of Oregon. Streams were paired based on reach length and bankfull width, and north (n =2), and south (n=2) facing watersheds. Canopy cover was estimated using a convex spherical densiometer, and light reaching the stream bed was estimated using a fluorescent dye that degrades overtime from light exposure. Overall, three of the four paired old-growth reaches (2 south-facing, 1 north-facing) had significantly lower mean percent canopy cover ($p < 0.10$), and significantly higher mean decline in fluorescent dye concentrations ($p < 0.01$). The authors interpret these results as evidence that old-growth forest canopies were more complex and had more frequent gaps allowing for more light availability and lower mean canopy cover, on average, than in adjacent young, second growth forests.

Kaylor et al. (2017) presented similar results when they compared canopy cover and light availability between small mountain streams adjacent to late-successional forests (dominant canopy trees >300 years old) and second-growth forests that had been harvested to the stream 50-60 years prior to data collection. Like Warren et al. (2013), canopy cover was estimated with a convex spherical densiometer; and light availability to streams was estimated with a photodegrading fluorescent dye. However, for this study, fluorescent dye degradation was converted to photosynthetically active radiation (PAR) by building a linear relationship between the dye degradation and PAR sensors. Results showed that mean PAR reaching streams was 1.7 times greater, and canopy openness was 6.1% greater in >300-year-old forests than in 30–100-year-old forests. Of the 14 paired sites, differences in canopy openness and PAR were significant for 6 sites. The authors compared and combined their data with published data from 10 other similar studies. The combined datapoints for canopy openness (%) were plotted against stand age and fit it with a negative exponential curve. From the slope of the curve, the authors estimate that canopy openness reaches its minimum value in regenerating forests at ~30 years and maintains with little variability until ~100 years.

Summary of Factors Affecting Shade and Stream Temperature

From the studies reviewed above, the results show evidence that changes in canopy cover and effective shade are, not surprisingly, directly related to the intensity of harvest operation. Initial reduction in canopy cover and shade from pre- to post-harvest are influenced by the basal area removed and the width of the retention buffer. However, there is evidence that multiple site factors can interact with harvest operations (e.g., target basal areas).

Table 5. List of treatments, variables, metrics, and results from publications reviewed for information on shade and stream temperature.

Reference	Treatment	Variables	Metrics	Notes	Results
Bladon et al., 2016	15 m buffer with a minimum of ~3.7 m^2 conifer basal area retained for every 300 m length of stream). Historical data with no streamside vegetation maintenance (I.e., no buffer) .	Stream temperature	7-day moving mean stream temperature, daily mean stream temperature, and diel stream temperature fluctuation. Data was recorded with Tidbit data loggers.	The authors caution that the streams in this study have potential for a muted stream temperature response following harvest relative to other regions because of the (1) north-south stream orientation (2) steep catchment and channel slopes, (3) potential increases in groundwater contributions after harvesting.	Under the contemporary Oregon Forest Practices Act there was no significant changes in the 7-day moving mean of daily maximum stream temperature, mean daily stream temperature, and diel stream temperature for 3 years following harvest when analyzed across all sites for all summer months (July – September. There was a significant increase in the 7-day moving maximum temperature from pre- to post-harvest values when data was constrained to the period of July 15 – August 15 by 0.6 $\pm$ 0.2 °C. However, when analyzed by individually paired sites and when interannual and site variability was accounted for, no significant changes in stream temperature were observed. The authors caution that these results should not be generalized to areas outside the Oregon coast or to riparian areas of different contexts (see notes).
Bladon et al., 2018	Buffer widths at harvested sites varied but averaged 20 m on either side of streams.	Stream temperature, lithology	the 7-day moving average of daily maximum stream temperature adjacent to and downstream of harvest.	Conducted at 3 paired watershed studies on the coast and western Cascades of Oregon. The pre-harvest relationship in stream temperatures for paired sites were used to create predicted changes in stream temperatures post-harvest. Post-harvest stream temperatures exceeding the predictive temperature interval by more than 95% were reported as significant.	Results showed an increase in stream temperatures beyond the 95% predictive interval (PI) at 7 of the 8 sites within harvest areas. 4 of these 7 sites exceeded the PI between 22 and 100% of the time (all summer months for 3 years following harvest). In the reaming 3 sites, exceedance only occurred between 0 and 15% of the time. There was no evidence of elevated stream temperatures beyond the predicted intervals in any of the downstream sites following harvesting. At the harvested sites there was a strong relationship between stream temperature increases and catchment lithologies, but no statistically significant relationship between stream temperature changes and percent of catchment harvested. Downstream sites showed a strong relationship between stream temperatures and the interaction of harvest percentage and lithology. The greatest temperature increases at downstream sites were in areas with a higher percentage of catchment harvested and were underlain by more resistant lithologies. There was no evidence for increases in stream temperatures in catchments with a high percentage of harvest that were underlain by permeable geology

Cole & Newton, 2013	clearcut to stream, partial buffer (12 m width on predominant sun-side),), Oregon state BMP (15-30 m no-cut buffer both sides)	Stream temperature	Controlled for yearly fluctuations in temperatures by analyzing the difference in stream temperature entering and exiting the reach with digital temperature data loggers	Stream temperature data collected for 2 – years prior and 4 to 5 years following harvest. Unharvested control sites were located downstream of treatment sites. Treatment applied to four small fish-bearing streams.	Results showed the most significant increases in daily maximum, and mean, and diel fluctuations in temperatures post-harvest for all no tree buffers. Changes to daily maxima ranged from -0.11 to 3.84 ^{o}C, and changes to daily minimum ranged from -1.12 to 0.49 ^{o}C. The no tree buffers also showed small but significant changes below predicted summer minima between -1.12 and -0.49 ^{o}C. The partial buffer units varied in their response to treatment exhibiting increases, decreases, and no change from preharvest trends.
Cupp & Lofgren, 2014	the "all available shade" rule (ASR), and the standard rule (SR) in eastern WA. ASR: requires retention of all available shade within 75 feet of the stream. SR: some harvest is allowed within the 75-foot buffer depending on elevation and pre-harvest canopy cover.	Canopy closure, shade measurements, stream temperature	Hand-held densiometer (canopy closure), self-leveling fisheye lens digital camera (shade), temperature data loggers	Sites were between 65-100 years old and were situated along second to fourth order streams with harvest-regenerated or fire-regenerated forests. Reference reaches were located upstream from treatment reaches where harvest was applied.	Results showed post-harvest shade values decreased in SR sites (mean effect of -2.8%, $p = 0.002$), as did the canopy closure values (mean effect of -4.5%, $p < 0.001$). Shade and canopy closure values did not significantly change in the ASR sites. Mean shade reduction in the SR treatment sites exceeded the mean shade reduction in the ASR sites by 3%. Canopy closure reduction was also greater in the SR sites than in the ASR sites by a mean of 4%. Site seasonal means of daily maximum stream temperature treatment responses in the first two years following harvest ranged from - 0.7 °C to 0.5 °C in the ASR reaches and from -0.3 to 0.6 in the SR reaches. Site seasonal mean post-harvest background responses in reference reaches ranged from - 0.5 °C to 0.6 °C in the first two years following harvest. Mean daily maximum stream temperature increased 0.16 °C in the SR harvest reaches, whereas stream temperatures in both the ASR sites and in the no-harvest reference reaches increased on average by 0.02 °C.
Ehinger et al., 2021	1) Buffers encompassing the full width (50 feet), 2) <50ft buffers, 3) Unbuffered, harvested to the edge of the channel, and 4) Reference sites in unharvested forests.			Soft Rock study. Only descriptive statistics. Small sample sizes.	Mean canopy closure decreased in the treatment sites from 97% in the pre-harvest period to 75%, 68%, and 69% in the first, second, and third post-harvest years, respectively, and was related to the proportion of stream buffered and to post-harvest windthrow within the buffer. The seven-day average temperature response increased by 0.6°C, 0.6°C, and 0.3°C in the first, second, and third post-harvest years, respectively. During and after harvest, mean monthly water temperatures were higher, but equaled or exceeded 15.0°C only in 2 treatment sites by up to 1.8°C at one site and by 0.1°C at

					another. None of the three REF sites exceeded 15°C during the study.
Gravelle & Link, 2007	50% of the drainage area clearcut to stream edge, thinned to a 50% target shade removal in Fall 2001, and an unimpacted control. Riparian buffer zones were implemented according to Idaho Forest Practices.	stream temperatures at the headwater streams immediately adjacent to treatments, and downstream in larger fish-bearing streams.	Stream temperature data collected from digital sensors.	for the non-fish-bearing, headwater sites pre-treatment data was only collected one season prior to treatment.	In general, the downstream sites showed a cooling effect between –0.2 and –0.3°C. The estimated cooling effect could not be attributed to any cause (e.g., increase in water yield), but the authors conclude that there was no post-harvest increase in peak summer temperatures at the downstream sites. For streams immediately adjacent to the clearcut treatment (headwater streams) a significant increase in temperature was detected at 2 sites ranging between 0.4 and 1.9°C, while a marginally significant decrease in temperature was detected at the third site (-0.1°C, $p = 0.06$). At the sites located immediately adjacent to partial cuts, results showed mixed results with decreases in temperature (-0.1°C; non-significant) at one site and significant but minimal changes at another site (0.0-3.0°C) across the individual post-harvest years. Overall, there were minimal to no changes in stream peak temperatures following treatment in the partial-cut riparian areas. Despite slight increases in temperature in 2 of the headwater streams, no increase in stream temperature was detected in the larger downstream fish-bearing streams.
Groom et al., 2011a	Private site FPA rules are 15 and 21 m wide on small and medium fish-bearing streams of limited entry. State sites followed a 52 m wide buffer of limited entry. FPA = 6 m no entry buffer, State = 8 m no entry buffer. Thinning intensity not specified.	Stream temperature	Stream temperature collected with digital temperature sensors within harvested areas before and after treatment.	Eighteen of the 33 sites were on privately owned lands, and the other 15 were on state-managed forest land. Treatment reaches were harvested according to the FPA or FMP and included 26 clear-cuts and 7 partial cuts. All private sites were clear-cut. Seventeen sites were	Pre harvest to post harvest comparison of 2 years of data will detect a temperature change of > 0.3°C. Conversely, harvest to state FMP standards resulted in an 8.6% probability of exceedance that did not significantly differ from all other comparisons. The a-priori and secondary post hoc multi-model comparisons did not indicate that timber harvest increased the probability of PCW exceedance at state sites. The authors point out that the 0.3°C change threshold still lies 1 or 2 orders of magnitude lower than previous findings from studies which took place prior to the enactment of the riparian protection standards. Note: PCW criterion is that anthropogenic activities are not permitted to increase

				harvested along one stream bank, of which 13 were state forest sites. The remaining 16 sites were harvested along both banks.	stream temperature by more than 0.3 °C above its ambient temperature
Groom et al., 2011b	Private site FPA rules are 15 and 21 m wide on small and medium fish-bearing streams with a 6 m no-cut zone immediately adjacent to the stream. Harvesting is allowed in the remaining RMA to a minimum basal area of 10.0 (small streams) and 22.9 (medium streams) m2/ha. State sites followed a 52 m wide buffer with an 8 m no cut buffer. Limited harvest is allowed within 30 m of the stream only to create mature forest conditions.	Stream temperature, Shade, canopy cover	Stream temperature collected with digital temperature sensors. Stream temperature data was summarized to provide daily minimum, maximum, mean, and fluctuation for analysis. The temperature data was modeled using mixed-effects linear regression Shade analysis included trees per hectare, basal area per hectare, vegetation plot blowdown, and tree height. a linear regression analysis of shade data (n = 33) was performed.	A comparison of within site changes in maximum temperatures pre-harvest to post-harvest showed an overall increase at private sites, but not all sites behaved the same and some had decreases in maximum temperatures.	Following harvest, maximum temperatures at private sites increased relative to state sites on average by 0.71 °C. Similarly, mean temperatures increased by 0.37 °C (0.24 - 0.50), minimum temperatures by 0.13 °C (0.03 - 0.23), and diel fluctuation increased by 0.58 °C (0.41 - 0.75) relative to state sites. The average of maximum state site temperature changes = 0.0 ^{o}C (range = -0.89 to 2.27 ^{o}C). Observed maximum temperature changes at private sites averaged 0.73 ^{o}C (range = -0.87 to 2.50 ^{o}C) and exhibit a greater frequency of post-harvest increases from 0.5 to 2.5 ^{o}C compared to state sites. Private site shade values also appeared to decrease pre-harvest to post-harvest. Private post-harvest shade values differed from pre-harvest values (mean change in Shade from 85% to 78%); however, no difference was found for state site shade values pre-harvest to post-harvest (mean change in Shade from 90% to 89%). Results from this study show that between 68% and 75% of variability in post-harvest shade may be accounted for by basal area within 30 m of the stream, tree height, and potentially blow down. The authors speculate that their results suggest sites with shorter trees have higher post-harvest shade and this may be due to the negative correlation between crown ratios and tree heights.
Guenther et al., 2014	Partial retention (50% removal of basal area including riparian zone) methods resulting in approximately 14% reduction in canopy cover on average	Stream temperature, canopy cover, bed temperature	Bed temperatures, stream temperatures, and near stream shallow groundwater temperatures were collected with thermocouples.		Treated watersheds showed an increase of 1.6 - 3.0 °C in daily maximum stream temperatures during the summer months following harvest. Bed temperatures showed an overall increase in temperature but at lower magnitude averaging around 1 °C for up to 30 cm in depth. Bed temperature increases were higher in areas on downwelling flow than in areas of neutral and upwelling flows.

Hunter & Quinn, 2009	an alluvial study site and a bedrock study site whose overall characteristics were otherwise comparable apart from geomorphology.	Stream temperature, Alluvial depth	Water temperature was recorded at 75-m intervals along each channel during the summers of 2003 and 2004	Small sample sizes, results only from two sites for two summers. Actual numeric values not reported but shown in graphs.	Results from this study show consistent differences in stream temperature response in alluvial versus bedrock channels. Seasonal maximum and minimum average daily temperatures varied less at the alluvial site compared to the bedrock site. Two same-day measurements at each site showed the alluvial site gaining 8% of its flow, as compared to the bedrock site whose flow decreased by approximately 15%. Bedrock sites were shown to have the highest variation in reach-scale water temperatures during low flow.
Janisch et al., 2012	clearcut logging with two riparian buffer designs: a continuous buffer and a patched buffered stream. Buffers were 10-15 m wide.	Stream temperature	Channel and catchment attributes (e.g., BFW, Confinement, slope, FPA, etc.), Stream temperatures were recorded with a Tidbit datalogger in areas persistently submerged.	Separation of treatment streams into "clusters" based on year of treatment and an unbalanced experimental design resulted in small sample sizes. Thus, significant differences between treatments were not analyzed. Instead results presented as "significant" represent a significant increase in temperature different from zero.	In general, timber harvest with fixed-width continuous buffers, or patch buffers resulted in increased mean maximum daily summer stream temperatures in the first year following treatment by an average of 1.5 °C (range 0.2 – 3.6 °C). Mean maximum daily summer temperature increases were higher in the streams adjacent to continuous buffer (1.1 °C; range 0.0 to 2.8°C) than the patch buffered catchments (0.6 °C; range – 0.1 to 1.2°C). However, results were highly variable. Post-treatment temperature changes suggested that treatments ($p=0.0019$), the number of years after treatment ($p=0.0090$), and the day of the year ($p=0.0007$) were all significant effects explaining observed changes in temperature. Wetland area (0.96, $p<0.01$) and length of surface flow (0.67, $p=0.05$) were strongly correlated with post-logging temperature changes.
Johnson & Jones, 2000	clearcut to stream, patch cutting followed by debris flows (resulted in the removal of all streamside vegetation) , 450+ yo Doug-fir forest reference.	Stream temperature	long term monitoring of weekly stream temperature max, min, and average. Solar radiation data collected from digital sensors. Air and precipitation temperatures collected from local weather stations.	The experimental design used historic stream temperature data to examine changes in stream temperatures. This required conflating data from 2 different devices.	Removal of streamside vegetation whether by clearcut and burn (CCB), or patch-cut and debris (PCD) flow led to significant increases in mean weekly summer maximum and minimum stream temperatures relative to reference streams in the summer immediately following and for 3-4 years post treatment. The CCB's summer mean weekly maximum stream temperatures ranged from 5.4-6.4°C higher than the reference stream for 4 years following treatment. The PCD's summer mean weekly stream temperatures ranged from 3.5-5.2°C higher than the reference stream for 3 years following treatment. The diurnal fluctuations were significantly higher in both treatment streams (6-8 ^{o}C in CCB, and 5-6 ^{o}C in PCD) relative to reference stream (1-2°C). Pre-harvest temperatures recovered after 15 years of growth.

					Differences in treatment streams and reference stream temperatures were less than 1.1°C pre-treatment and 30-years post-treatment.
Kaylor et al., 2017	50 years post clearcut to streams, control stands were >300 years old	stream light availability, forest age	Stream bank-full width, wetted width, canopy openness, % red alder, and estimated photosynthetically active radiation (PAR) were quantified at 25-m intervals		PAR reaching streams was on average 1.7 times greater in >300-year-old forests than in 30–100-year-old forests. The greatest differences were in streams with both sides harvested. Mean canopy openness was higher in >300-year-old forests (18%) than in 30–100-year-old forests (8.7%). Space-for-time analysis with reviewed literature estimates that canopy closure and minimum light availability occurs at approximately 30 years and maintains until 100 years.
Kibler et al., 2013	Clearcut to stream	Stream temperature, discharge rate,	Stream temperature and discharge rate were recorded with thermistor gauging stations. Canopy cover was recorded with a densiometer as portion of sky covered with vegetation	Post-harvest data was collected only during the summer and autumn immediately following harvest (i.e., 1 season of post-harvest data). Pre-harvest data was collected for 3 years.	Harvest in treatment watersheds resulted in a significant decrease in stream temperatures ranging from –1.9 to -2.8 °C relative to pre-treatment temperatures. The authors attribute the lack of increased temperatures to the shade provided by woody debris.
Macdonald et al., 2003b	Low-retention – remove all timber >15 or >20 cm DBH for pine or spruce, 20 m of the stream 2) high-retention – remove timber >30 cm DBH 20-30m of stream, and 3) Patch-cut removal of all vegetation in the upper 40% of the watershed.	Stream temperature	Temperature data were recorded with Vemco dataloggers. Canopy cover was estimated with densiometers.		Significant increase in stream temperatures ranging from 4 – 6 °C at five years post-harvest, and increased ranges of diurnal temperature fluctuations for all treatment streams relative to the reference streams. Streams that had summer maximum mean weekly temperatures of 8°C before harvesting had maximum temperatures near 12°C or more following harvesting. Daily ranges of 1.0–1.3°C before harvesting became 2.0–3.0°C following harvesting, high-retention buffer treatment mitigated temperature increases for the first three years. Still, increased mortality (attributed to windthrow) caused a reduction in the canopy that, thus, led to increased stream temperatures equivalent to other treatment streams by year five.

McIntyre et al., 2021	(1) unharvested reference, (2) 100% treatment, a two-sided 50-ft riparian buffer along the entire Riparian Management Zone (RMZ), (2) FP treatment a two-sided 50-ft riparian buffer along at least 50% of the RMZ, (3) 0% treatment, clearcut to stream edge (no-buffer).			Hard Rock Study.	Results for canopy cover showed that riparian cover declined after harvest in all buffer treatments reaching a minimum around 4 years post-harvest (after mortality stabilized). The treatments, ranked from least to most change, were REF, 100%, FP, and 0% for all metrics and across all years. Effective shade results showed decreases of 11, 36, and 74 percent in the 100%, FP, and 0% treatments, respectively. Significant post-harvest decreases in shade were noted for all treatments and all years. Results for stream temperature showed that within treatment mean post–pre-harvest difference in the REF treatment never exceeded 1.0°C. In contrast, mean within treatment difference in the 100% treatment was 2.4°C in 2009 (Post-harvest year 1) but never exceeded 1.0°C in later years. The mean difference in the FP treatment exceeded 1.0°C immediately after harvest then again in 2014–2016 (post-harvest years 6–9) while in the 0% treatment the mean difference was 5.3°C initially, then decreased over time to near, but never below, 0.9°C. Stream temperature increased post-harvest at most locations within all 12 harvested sites and remained elevated in the FP and 0% treatments over much of the nine years post-harvest.
Pollock et al., 2009	A range of harvest from 0 – 100%, < 20 years old regrowth, ~ 40 years old regrowth . Unharvested sites were estimated as being >150-years old	Stream temperature, time since harvest, percent of watershed and stream network harvested.	average daily maximum (ADM), average daily range, seasonal range, average, maximum, and minimum Stream temperatures collected with Tidbit data loggers. Stand age grouped by time since harvest.	tested 3 hypotheses: (1) the condition of the riparian forest immediately upstream of a site primarily controls stream temperature, (2) the condition of the entire riparian forest network affects stream temperature, and (3) the forest condition of the entire basin affects stream temperature.	Results of general temperature patterns showed that average daily maximum (ADM) were strongly correlated with average diurnal fluctuations ($r2 = 0.87$, $p < 0.001$, $n = 40$), indicating that cool streams also had more stable temperatures. For basin-level harvest effects on stream temperatures. The percentage of the basin harvested explained 39% of the variation in the ADM among subbasins ($r2 = 0.39$, $p < 0.001$, $n = 40$) and 32% of variation in the average daily range (ADR) ($r2 = 0.32$, $p < 0.001$, $n = 40$). The median ADM for the unharvested subbasins was 12.8 ^{o}C (mean = 12.1 ^{o}C), which was significantly lower than 14.5 ^{o}C, the median (and average) ADM for the harvested subbasins ($p < 0.001$). Likewise, the median (and average) ADR for the unharvested subbasins was 0.9 ^{o}C, which was significantly lower than 1.6 ^{o}C, the median ADR (average = 1.7 ^{o}C) for the harvested subbasins ($p < 0.001$). Results for the correlations between the riparian network scale forest harvest and stream temperature showed that the total

					percentage of the riparian forest network upstream of temperature loggers harvested explained 33% of the variation in the ADM among subbasins ($r2 = 0.33$, $p < 0.001$, $n = 40$) and 20% of variation in the ADR ($r2 = 0.20$, $p = 0.003$, $n = 40$). However, the total percentage of upstream riparian forest harvested within the last 20 years was not significantly correlated to ADM or ADR. Results for near upstream riparian harvest and stream temperature showed either non-significant, or very weakly significant correlations. For example, there were no significant correlations between the percentage of near upstream riparian forest recently clear-cut and ADM temperature ($r2 = 0.03$, $p = 0.79$, $n = 40$), the ADR of stream temperatures ($r2 = 0.02$, $p = 0.61$, $n = 40$) or any other stream temperature parameters. The proportion of total harvested near upstream riparian forest (avg = 0.66, SD ± 0.34, range = 0.0-1.0) was weakly correlated with ADM ($r2 = 0.12$, $p = 0.02$, $n = 40$) and not significantly correlated with ADR ($r2 = 0.07$, $p = 0.06$, $n = 40$). Even when the upstream riparian corridor length was shortened to 400 m and then to 200 m, and the definition of recently harvested was narrowed to <10 year, no significant relationships between temperature and the condition of the near upstream riparian forest was found. for these models, the percentage of basin area harvested was the best predictor of variation in mean maximum stream temperatures. The probability of stream temperatures increasing beyond DOE standards (16 ^oC for seven-day average of maximum temperatures) increased with percent harvest. Nine of the 18 sites with 50-75% harvest and seven of the nine sites with >75% harvest failed to meet these standards. The authors interpret these results as evidence that the total amount of forest harvested within a basin, and within a riparian stream network are the most important predictors of changes in summer stream temperatures. They conclude that watersheds with 25-100% of their total area harvested had higher stream temperatures than watersheds with little or no harvest.

Reiter et al., 2020	Clearcut, no buffer (CC_NB), clearcut with 10-m no cut buffer (CC_B), thinning with 10 m no-cut buffer (TH_B), and unharvested reference (REF) streams.	Stream temperature	Temperature data was separated into 5th, 25th, 50th, 75th, and 95th percentiles. the researchers also quantified the percentage of summer where temperatures where above 16 and 15 ^{o}C.	Sample sizes are relatively low for some treatments. (CC_NB; n = 4); (CC_B; n = 3); (TH_B; n =1); (REF; n = 7).	A 10 m buffer was sufficient in maintaining summer temperature changes compared to reference streams regardless of upland treatment (clear-cut, thinning). Unbuffered streams (Clear-cut to streams) showed significant increases in stream temperatures with an average of 3.6 ^{o}C (SE = 0.4) increase relative to reference streams. Unbuffered streams spent 1.3% and 4.7% of the recorded time above 16 ^{o}C and 15 ^{o}C respectively (habitat temperature thresholds for two local amphibian larvae, coastal tailed frog, coastal giant salamander). The authors conclude that while significant changes in mean and percentile changes in temperature were observed, the amount of time spent above critical temperature thresholds for important amphibian species was minimal.
Reiter et al., 2015	. Various buffer prescriptions as regulations changed over time. (mid1970s – 1980s = “nominal”; mid 1980s – mid 1990s = 23 m; 2001 – 2009 = 30 m buffers)	Stream temperature data from four permanent sampling stations in the Deschutes River Watershed from 1975- 2009. Results for this analysis are for 3 watersheds (1-large, 1-medium, 1-small)	Long term stream and air temperature collected from sampling stations. To detect correlations of stream and air temperature change with land management activity separately from climate changes the data was fit to a model that included the effects of climate.	Methods for stream temperature data collection varied at different periods resulting in a margin of error for monthly temperatures of 0.14°C for 1975 - 1983, 0.09°C for 1984 – 1999, and 0.02°C. for 2000 – 2009.	Results for trends in stream temperature over the 35-year study period without adjustment for climate change showed no statistically significant trend in water temperature changes for the large watershed, while the medium watershed (Thurston Creek) showed decreasing trends in TMAX_WAT for June, July, and August, ranging in magnitude from 0.05°C (August) to 0.08°C (July) per year. For the smaller watershed, Hard Creek (Ware Creek was not included in this analysis), had significant decreasing trends in TMAX_WAT for July, August, and September. The magnitude of these trends was yearly decreases of TMAX_WAT by 0.05, 0.08, and 0.05°C, for July, August, and September, respectively. Significant changes in trends for TMIN_WAT were only found for the large basin site with yearly increases of 0.04, 0.03, and 0.04°C for July, August, and September, respectively. Results for stream temperature trends after adjusting for changes in air temperature (climate) showed significant decreasing trends in TMAX_WAT for the large basin by 0.04, 0.03, and 0.04°C yearly, for July, August, and September, respectively. For the medium basin, trends showed yearly decreases in TMAX_WAT of 0.07, 0.08, 0.06, and 0.03 for June, July, August, and September, respectively. For the small basin, climate adjusted trends in TMAX_WAT showed significant decreases in yearly trends by 0.05, 0.08, and 0.05 for July, August, and September, respectively. When stream temperature was examined with its correlation with estimated annual

					shade recovery from initial harvest (indexed by ACD). Significant correlations were found for monthly temperature metrics that were adjusted for climate, for all basins. The authors conclude that the results of this study show evidence that implementation of protection buffers in this area were sufficient in maintaining stream temperatures. Conversely, this study also shows evidence that despite these protections from land management induced stream temperature changes, these protections have been somewhat offset by the warming climate conditions.
Roon et al., 2021a	Thinning treatments resulting in a mean shade reduction of <5% (-8.0 - -0.5) at one watershed and 23.0% at two watersheds (-25.8, -20.1)	Stream temperature, solar radiation, Shade	Stream temperature was collected using digital sensors; solar radiation was measured using silicon pyranometers; riparian shade was measured using hemispherical photography.	Only 1-year pre- and post-treatment data. Site selection and replication was not random and thus may not be applicable outside of the northern California redwood forests.	No significant changes in stream temperatures were detected in the low-intensity thinning treatment watersheds. For the higher intensity thinning treatments. Maximum weekly average of the maximum temperatures increased during spring by a mean of 1.7 ˚C (95% CI: 0.9, 2.5), summer by a mean of 2.8 ˚C (1.8, 3.8), and fall by a mean of 1.0 ˚C (0.5, 1.5) and increased in downstream reaches during spring by a mean of 1.0˚ C (0.0, 2.0) and summer by a mean of 1.4˚ C (0.3, 2.6). Thermal variability of streams were most pronounced during summer increasing the daily range by a mean of 2.5˚ C (95% CI: 1.6, 3.4) and variance by a mean of 1.6˚C (0.7, 2.5), but also increased during spring (daily range: 0.5 ˚C; variance: 0.3˚ C) and fall (daily range: 0.4˚ C; variance: 0.1 ˚C). Increases in thermal variability in downstream reaches were limited to summer (daily range: 0.7˚ C; variance: 0.5 ˚C). The authors interpret their results as evidence that that changes in shade of 5% or less caused minimal changes in temperature while reductions in shade of 20–30% resulted in much larger increases in temperature.
Roon et al., 2021b	Effective shade reductions ranging between 19-30% along 200 m reach, or 4-5% along 100 m reach.	local and downstream temperature	Stream temperature collected with digital temperature sensors within harvest area and every 200 m downstream of stream network.	Stream temperature data was only collected for one-year pre- and one-year post-harvest.	In the reaches with higher reductions in shade (19-30%) there was accumulation of 45° to 115°C additional degree days from pre- to post treatment years, while the reaches with lower reductions in shade (4-5%) only accumulated 10° to 15°C additional degree days. Travel distance of increased stream temperatures also appeared to be dependent on thinning intensity. The lower shade reduction reaches had an increased temperature effect downstream with travel distance of 75-150 m, while the high shade reduction sites had a downstream travel

					distance of 300- ~1000 m. In the high shade reduction sites, treatment reaches that were further apart (> 400 m) showed dissipation in increased stream temperatures downstream, while in parts of the stream where treatments were <400 m apart, temperature increases did not always dissipate before entering another the next treatment reach.
Sugden et al., 2019	Montana state law : 15.2 m wide buffers no more than half the trees greater than 204 mm (8 in) diameter at breast height (DBH). In no case, however, can stocking levels of leave trees be reduced to less than 217 trees per hectare. .	Stream temperature, fish population, Canopy cover	Daily max, min, and average stream temperatures collected with data loggers during summer months. The fish community was inventoried 100 m reaches using an electro-fishing pass of capture method. Canopy cover was estimated using a combination of simulation modeling and using a concave spherical densiometer.	Data only collected for one year pre-harvest and one year post-harvest.	The mean basal area (BA) declined from 30.2 m2/ha pre-harvest to 26.4 m2/ha post-harvest (mean = –13%, range from -32% to 0%). Windthrow further reduced the mean BA to 25.9 m2/ha (mean = -2%, range = -32% -0%). Change in mean canopy cover were not significant based on the simulation modeling (-3%), or densiometer readings (+1%). Results of the model for the effect of harvest on stream temperature showed no detectable increase in treatment streams relative to control streams. The estimated mean site level response in maximum weekly maximum temperatures (MWMT) varied from –2.1 °C to +3.3 °C. Overall, 20 of 30 sites had estimated site level response within ±0.5 °C. There were five sites that had an estimated site-level response greater than 0.5 °C (i.e. warming) and five sites that had an estimated site level response less than –0.5 °C (i.e. cooling). Results for the fish population showed approximately 7% increase in trout population from pre-harvest to post-harvest, but this difference was not significant.
Swartz et al., 2020	In the experimental reaches 30 m gaps were created, centered on a tree next to the stream and at least 30 m in from the beginning of the reach. Actual gap sizes varied across sites from approximately 514 m2 to 1,374 m2 with a mean of 962 m2.	Stream temperature, Light reaching stream, canopy cover	Riparian shade-hemispherical photos. Light reaching the stream-photodegradation of fluorescent dyes. Stream temperature - HOBO sensors for seven-day moving average of mean and maximum temperatures.	Data was collected for one year pre-harvest, during harvest year (harvest took place in late fall 2017), and one-year post-harvest.	Results showed that after gaps were cut, the BACI analysis showed strong evidence for significant increase in mean reach light ($p < 0.01$) to a mean of 3.91 (SD ± 1.63) moles of photons m−2 day−1 , overall resulting in a mean change in light of 2.93 (SD ± 1.50) moles of photons m−2 day−1. Through the entirety of the treatment reach mean shading declined by only 4% (SD ± 0.02%). Overall, the gap treatments did not change summer T 7DayMax or T 7DayMean significantly across the 6 study sites. However, reaches showed a statistically significant effect of the gap for average daily maximums ($p < 0.01$) and for average daily means ($p = 0.02$). The regression comparison reveals there will be on average an additional 0.12 °C/°C increase in daily maximum temperature in the reach with a gap.

					Likewise, for the daily mean, for every degree increase in the shaded reference reach, an average additional increase of 0.05 °C in a reach with a small gap is expected. The regression comparison reveals there will be on average an additional 0.12 °C/°C increase in daily maximum temperature in the reach with a gap. Likewise, for the daily mean, for every degree increase in the shaded reference reach, an average additional increase of 0.05 °C in a reach with a small gap is expected.
Warren et al., 2013	Old-growth forests were estimated to be over 500 years old, and mature second growth forests were estimated to be between 31 and 59 years old.	Light reaching bottom of stream, canopy cover	The percent of canopy cover was estimated using a densiometer, the amount of light reaching the bottom of the stream was estimated using a fluorescent dye that degrades overtime from light exposure	Relatively small sample sizes (n = 4). Significant differences were only found in 3 of the four paired reaches.	Results showed that the differences in stream light availability and percent forest cover between old-growth and second-growth reaches were significant in both south-facing watersheds in mid-summer at an alpha of 0.01 for the dye results and 0.10 for the cover results. For the north-facing watersheds differences in canopy cover and light availability (alpha = 0.01, and 0.10 respectively) were only significant at 1 of the two reaches. Overall, three of the four paired old-growth reaches had significantly lower mean percent canopy cover, and significantly higher mean decline in fluorescent dye concentrations The authors interpret these results as evidence that old-growth forest canopies were more complex and had more frequent gaps allowing for more light availability and lower mean canopy cover, on average, than in adjacent mature second- growth forests.

Results/discussion by focal question

Focal Question 1

1. *What are the effects of timber harvest intensities and extent on the riparian functions, with an emphasis on the five key functions listed above, in comparison to conditions* *before* *harvest?*

From the perspective of an experimental design, this question inquires how the values of the metrics used to describe the five key functions (large woody debris recruitment, sediment filtration, stream bank stability, shade, litterfall and nutrients) differ from pre- to post-harvest within particular riparian areas of interest. An attempt to answer this question would require data collection before and after treatment with or without a control site. Thus, only studies that used a BACI or BAI approach are appropriate for discussing this question. From our review, 22 papers report pre- to post-harvest changes in the magnitude of one or more of the key functions with the majority of these papers focusing on changes in shade. No studies published since 2000 that apply an experimental design in western North America to quantify changes in bank stability could be found in the literature.

Function	Count
Shade	12
Litter	3
LW	2
Sediment	4
Nutrients	3
Bank Stability	0

Shade

Specific to fish-bearing streams of eastern Washington, Cupp & Lofgren (2014) reported changes in canopy closure (quantified with handheld densiometer) and shade (quantified with fisheye lens digital camera) within reaches adjacent to riparian forests harvested under the All Available Shade Rule (ASR) and the Standard Shade Rule (SR). Both shade rules have a 30-ft no-cut buffer (core zone) immediately adjacent to the stream. The SR prescription allows thinning in the buffer zone 30-75 feet (inner zone) from the stream while the AAS prescription requires retention of all shade providing trees in this area. Results showed post-harvest shade values decreased in SR sites (mean effect of -2.8%, $p = 0.002$), as did the canopy closure values (mean effect of -4.5%, $p < 0.001$). Shade and canopy closure values did not significantly change in the treatment reaches of the ASR sites. Mean shade reduction in the SR treatment sites exceeded the mean shade reduction in the ASR sites by 3%. Canopy closure reduction was also greater in the SR sites than in the ASR sites by a mean of 4%.

For non-fish bearing streams of western Washington, McIntyre et al. (2021) report changes in canopy closure following 3 different harvest prescriptions. Prescriptions included a two-sided 50-ft wide riparian buffer along the entire stream (100%), a two-sided 50-ft riparian buffer along at least 50% of the stream consistent with the current Forest Practices buffer prescription (FP), and a clearcut to stream edge without a buffer (0%). The canopy cover was estimated at mid-stream with a handheld densiometer and was converted to effective shade values. Results for canopy cover showed that riparian cover declined after harvest in all buffer treatments reaching a minimum around 4 years post-harvest. The treatments, ranked from least to most change, were 100%, FP, and 0% for all metrics and across all years. Effective shade results showed decreases of 11, 36, and 74 percent in the 100%, FP, and 0% treatments, respectively. Significant post-harvest decreases were noted for all treatments and all years (9 years post-harvest). Another study, Janisch et al. (2012) also compared the effects of similar treatments (clearcut to stream, a full continuous buffer (10-15 m wide), and a patched buffer (~50-110 m long were retained in distinct patches along some portion of the channel) to canopy cover. Canopy cover in all streams averaged 95% (SE = 0.4) prior to harvest. Following treatment, canopy cover in the clearcut catchments averaged 53%, (SE = 7.4) canopy cover in the patch buffer treatment averaged 76%, (SE = 5.1) and canopy cover in the continuous buffer treatment averaged 86% (SE = 1.7). The changes were significant in the clearcut and patch buffers.

Outside of Washington, Bladon et al. (2016) assessed the effects of harvest treatments under the Oregon Forest Practices Act (FPA) on shade reduction and stream temperature. This study took place in the Siuslaw National Forest in the Oregon Coast Range in the Alsea Watershed. Treatment under the FPA includes a 15 m riparian management area with a minimum of ~3.7 m^2 conifer basal area retained for every 300 m length of stream and an additional 4-5 wildlife leave trees per hectare. This resulted in a mean canopy closure reduction from ~96% (pre-harvest) to ~89% (post-harvest) based on measurements from a densiometer along the stream channel for 3 years pre- and 3 years post-harvest. Unfortunately, the authors did not compare these changes with statistical analysis. Groom et al. (2011b) compared changes in shade from pre- to post-harvest under the FPA and under the Northwest Oregon State Forest Management Plan (FMP). The FMP requires a 52 m wide buffer for all fish-bearing streams, with an 8 m no cut buffer immediately adjacent to the stream.

Results from Groom et al. (2011b) showed that FPA site post-harvest shade values differed from pre-harvest values (mean change in Shade from 85% to 78%); While no difference was found for FMP site shade values pre-harvest to post-harvest (mean change in Shade from 90% to 89%). In the Trask Watershed of the northwestern Oregon Coast range, Reiter et al. (2020) compared three riparian zone treatments: 1) clearcut, no buffer (CC_NB; n = 4), 2) clearcut with 10-m no cut buffer (CC_B; n = 3), 3) thinning with 10 m no-cut buffer (TH_B; n =1) in small non-fish bearing streams. Pre- to post-harvest values in shade were quantified with hemispherical analysis over the stream one-year prior and one-year post-treatment. However, post-harvest overstory buffer width varied within each treatment depending on landscape factors. For this reason, we will present the change in percent shade with residual buffer width (Table 6). Again, changes in shade were not statistically analyzed.

In fish-bearing streams within the McKenzie River basin in the western Cascade Mountains of Oregon Swartz et al. (2020) assessed the effects of experimental canopy gap treatments on shade and light availability to the stream. In each treatment reach, 20 m gaps were prescribed to mimic gap openings that naturally occur after individual large tree mortality or small-scale disturbance events in late successional forests. Shade was recorded in the year before and the year after treatment with hemispherical photos. Changes in effective shade were estimated in HemiView 2.1 software. Mean stream shading could not be evaluated in the full BACI analysis because post-treatment hemispherical photographs could not be taken at all sites due to fire impeding access in 2018. For the remaining sites, the areas beneath each gap had notable localized declines in shade, through the entirety of the treatment reach mean shading declined by only 4% (SD ± 0.02%).

Table 6. Results for changes in shade following treatment for the Trask River Watershed Study headwaters. Reproduced from Reiter et al (2020).

Treatment	Mean residual buffer width (2-sided)	Pre-harvest shade (%)	Post-harvest shade (%)
CC_B	33.2	85.9	82.7
CC_B	22.6	91.3	89.1
CC_B	23.9	84.7	82.9
CC_NB	0.0	83.6	7.0
CC_NB	0.0	85.5	10.9
CC_NB	16.0	84.3	65.7
CC_NB	14.1	80.6	76.6
TH_B	*	81.2	84.0

CC_B = clearcut with 10 m buffer, CC_NB = clearcut no buffer, TH_B upland thinning with buffer. *Unable to determine exact buffer width because adjacent to thinning

Gravelle & Link (2007) compared changes in shade following treatment for non-fish bearing streams in northern Idaho. For non-fish-bearing streams there is a 30 ft (9.1 m) equipment exclusion zone on each side of the ordinary high-water mark (definable bank). There are no shade requirements and no leave tree requirements, but skidding logs in or through streams is prohibited. Harvesting treatments included (1) clearcut and (2) thinning to a 50% shade removal. Canopy cover measurements were made using a concave spherical densiometer. Preharvest canopy measurements ranged from 56% to 88%, with an average of 63% in the clearcut reaches, and 74% in the partial cut reaches. In the clearcut reaches, canopy was reduced to 52% in 2002 and 41% in 2003, immediately following broadcast burning and replanting. In 2004 and 2005, overall canopy was measured at 56% and 54%, respectively. Streamside shade recovery can be attributed entirely to low-lying understory species, as evidenced by the increase in understory/deciduous cover of 26% in 2003 to 39% and 37% in 2004 and 2005, respectively. In the partial cut reaches, canopy shade remained near 75%.

In fish-bearing streams of Montana, Sugden et al. (2019) assessed the effectiveness of state riparian management harvest prescriptions in maintaining canopy cover. Montana state law requires timber be retained within a minimum of 15.2 m of fish-bearing streams, with equipment exclusion zones extended on steep slopes for up to 30.5 m. Within the riparian management zone, no more than half the trees greater than 204 mm (8 in) diameter at breast height (DBH) can be removed. In no case, however, can stocking levels of leave trees be reduced to less than 217 trees per hectare. Shade over the stream surface was not directly measured in this study. Rather, canopy cover was used as a general proxy, with two independent estimates of canopy cover employed. One method used the riparian cruise data to populate a canopy cover model within the Forest Vegetation Simulator (FVS), which estimated canopy cover for each study site, pre- and post-harvest. The second method measured canopy cover in the harvest reach every 30 m, both before and after timber harvest, using a concave spherical forest densiometer. Mean canopy cover in the SMZ, as modelled in FVS, decreased from 77% to 74% following timber harvest and 73% when subtracting windthrow (Table 3). The mean canopy cover over the stream channel based on densiometer measurements was 66% pre-harvest and 67% post-harvest. Neither of these changes was statistically significant.

Roon et al. (2021a) compared the effects of two experimental thinning treatments on shade in second growth redwood stands (40-60 years old) of northern California. This study took place between 2016 and 2018 with thinning treatments applied during 2017 giving 1-year pre-treatment and 1-year of post-treatment data. Two study sites prescribed treatment on one side of the stream of a 45 m buffer width with a 22.5 m inner zone with 85% canopy retention and a 22.5 m outer zone that retained 70% canopy cover (Tectah watershed). At the third treatment site, thinning prescriptions included removal of up to 40% of the basal area within the riparian zone on slopes less than 20% on both sides of the channel along a ~100–150 m reach (Lost Man watershed, Redwood national park). Shade over streams was measured with hemispherical photos and effective shade was calculated in HemiView Canopy Analysis Software version 2.1. Results for the Tectah watershed showed a significant reduction in canopy closure by a mean of 18.7%, (95% CI: -21.0, -16.3) and a significant reduction of effective shade by a mean of 23.0% (-25.8, -20.1) one-year post treatment. In the Lost man watershed, a non-significant reduction of mean shade by 4.1% (-8.0, -0.5), and mean canopy closure by 1.9% was observed in 2018. Results for below canopy light availability showed significant increases by a mean of 33% (27.3, 38.5) in the Tectah watershed, and non-significant increases in Lost man watershed of 2.5% (-1.6, 5.6) by 2018.

In general, the results from the studies reviewed above suggest changes in shade or canopy cover from pre- to post-harvest are directly impacted by the intensity of the treatment prescription. Buffer treatments vary between states and within states by stream type (e.g., fish-bearing or non-fish-bearing), For the studies that quantified pre- to post-changes in shade along fish-bearing streams (Cupp & Lofgren, 2014; Sugden et al. 2019), results show evidence that the application of best management practices (BMPs) cause minimal or non-significant changes in shade following harvest. For non-fish-bearing streams harvest prescriptions are much more variable. Further, there are many more examples of application and comparison of different experimental buffer treatments which vary by width or thinning targets.

Litter

Specific to western Washington, McIntyre et al. (2018) compared the change in litterfall inputs from pre- to post-harvest under three different riparian harvest treatments. Treatments included a two-sided 50-ft riparian buffer along at least 50% of the stream (FP; with clearcut to stream's edge outside of the buffer), a two sided 50-ft buffer along the entire stream (100%), and a clearcut to stream without a buffer (0%). Litterfall was collected with litter traps placed along the mainstem channel of each site. Litter was dried and sorted by type (e.g., deciduous, conifer, small wood) and ashed to compare weight. Results for litterfall input showed a decrease in total litterfall input in the FP (P = 0.0034) and 0% (P = 0.0001) treatments between pre- and post-treatment periods. Leaf litterfall (deciduous and conifer leaves combined) input decreased in the FP (P = 0.0114) and 0% (P <0.0001) treatments in the post-treatment period. In addition, conifer (conifer needles and scales) litterfall input decreased in the FP (P = 0.0437) and 0% (P <0.0001) treatments, deciduous leaves in the 0% (P <0.0001) treatment, wood (twigs and cones) in the FP (P = 0.0044) and 0% (P = 0.0153) treatments, and misc. (e.g., moss and flowers) in the 0% (P = 0.0422) treatment.

In the Malcom Knapp Research Forests of British Columbia, Canada, Kiffney & Richardson (2010) compared changes in litter input between riparian harvest prescriptions that included clear-cut to stream edge, 10 m wide buffer reserve, and 30 m buffer reserves over the course of 8 years. No thinning was applied within the reserves. Upland treatment at all sites used clearcutting methods. Vertical litter inputs were collected monthly and at approximately 6–8-week intervals during each season for years 1,2,6,7, and 8 years after harvest. Litter was separated into broadleaf deciduous, twig, needles, and other (seeds, cones, and moss) categories following collection and subsequently dried and weighed using a microbalance. Results for post-harvest changes in litterfall input by treatment per year are summarized in Table 7. Actual values of pre- to post-harvest changes in litterfall input by type, treatment, and year were not directly reported, however, the authors report that post-harvest inputs of needles, twigs, and total particulate matter were significantly lower for clearcuts compared to all other treatments.

Table 7. Percent change in total litterfall percentage post-harvest by treatment per year from Kiffney & Richardson (2010). Table reproduced and modified from Yeung et al. (2019) supplementary materials Appendix C, Table C3.

Harvest type (% of watershed area harvested)	Change in litterfall (%)	Time after harvest (year)
Clearcut (33%) no buffer	~ -91	1
	~ -78	2
	~ -79	6
	~ -47	7
	~ -11	8
Clearcut (23%); with 10-m riparian buffers	~ -2	1
	~ 6	2
	~ -14	6
	~ 6	7

	~ 37	8
Clearcut (18%); with 30-m riparian buffers	~ 11	1
	~ 44	2
	~ 14	6
	~ -6	7
	~ 74	8

Large Wood (LW) recruitment

Specific to western Washington, McIntyre et al. (2021) compared the change in mean in-stream large wood from pre- to post-harvest under three different riparian harvest treatments in non-fish-bearing streams. Treatments included a two-sided 50-ft riparian buffer along at least 50% of the stream (FP; with clearcut to stream's edge outside of the buffer), a two sided 50-ft buffer along the entire stream (100%), and a clearcut to stream without a buffer (0%). Results showed a 66% (P <0.001), 44% (P = 0.05) and 47% (P = 0.01) increase in mean large wood density in the 100%, FP and 0% treatments, respectively, in the first 2 years post-harvest compared with the pre-harvest period and after controlling for temporal changes in the references. Five years post-treatment the mean LW density in the FP continued to increase 42% (P = 0.08), and again 8 years post-treatment (41%; P = 0.09).

Ehinger et al. (2021) also quantified changes in in-stream LW following similar riparian harvest prescription. Because of unstable slopes, total buffer area was 18 to 163% greater than the prescribed 50-foot-buffer. This resulted in 2 different buffer types 1) buffers encompassing the full width (50 feet), 2) <50ft buffers, and 3) unbuffered, harvested to the edge of the channel. Because of the separation into multiple treatments, sample sizes became small and unbalanced. Thus, no statistical analyses were conducted, and only descriptive statistics were applied for changes in stand structure and wood loading. However, given the lack of studies presenting changes in LW recruitment from pre- to post-harvest, it is presented here for comparison. Results showed the full buffer sites and <50 ft buffer sites received an average of 23 and 10 pieces/100 m and 2.3 and 0.7 m3/100 m of large wood, respectively, post-harvest. The majority of recruited large wood pieces had stems with roots attached (SWRW); 70, and 100% in the full buffer, and <50 ft buffer types, respectively. Pre-harvest channel large wood loading ranged from 55.8 to 111 pieces/100 m and from 9.8 to 25.2 m3/100 m among buffer types. Piece counts increased in the full buffer and unbuffered sites (8 and 13%, respectively), and decreased in the <50 ft buffers (15%).

Sediment

No studies from Washington published since 2000 provide changes in sediment concentration or transport from pre- to post-harvest. The Hard Rock study (McIntyre et al., 2021) reported their results for water turbidity and suspended sediment export (SSE) were stochastic in nature and the relationships between SSE export and treatment effects were not strong enough to confidently draw conclusions. The lack of SSE in some high discharge events suggests that the basins are likely to be supply limited. The Soft Rock study (Ehinger et al., 2021) similarly reported that their results for changes in sediment post-harvest were highly variable. Harvest treatment effects on suspended sediment export could not be calculated.

Hatten et al. (2018) compared pre- to post-harvest suspended sediment concentrations (SSC) in a western Oregon Alsea watershed. Treatments followed contemporary harvesting practices (no buffer in non-fish-bearing streams with equipment exclusion zones, and a 15 m no-cut-buffer in fish-bearing streams) resulted in non-significant changes in SSC at all treatment sites. Surprisingly, in the fish-bearing streams there was a decrease in SSC (~63% and ~55%, after first and second harvest, respectively) compared to pre-harvest values. Bywater-Reyes et al. (2017) compared pre- to post-harvest changes in suspended sediment yield (SSY) following harvest in the Trask River Watershed of western Oregon. Harvest treatments of study sub-watersheds consisted of clearcuts (UM2 and GC3) and a clearcut with buffers (50 ft; ~15 m; PH4). Following timber harvest, (water year 2013), increases in SSY occurred in all harvested catchments. The SSY in both PH4 (clearcut with buffers) and GC3 (clearcut without buffers) declined to pre-harvest levels by water year 2014. Interestingly, the SSY in UM2 (clearcut without buffers) increased annually throughout the post-harvest period, ultimately resulting in the highest SSY of all catchments during the final two years (2015-2016) of the study after producing the lowest SSY in the pre-harvest period. Actual values for SSY and significance were not reported.

Karwan et al. (2007) compared changes in total suspended solids (TSS) in streams from pre- to post-harvest in northern Idaho. Treatments in the paired-watershed experiment consisted of 1) commercial clearcut of the watershed area of 50%, and was broadcast burned and replanted by the end of May 2003, and 2) partial cut in which a target of 50% the canopy was removed in 50% of the watershed in 2001, with final 10% of log processing and hauling in early summer of 2002. All harvests were carried out according to best management practices and in accordance with the Idaho Forest Practices Act. Results showed a significant and immediate impact of harvest on monthly sediment loads in the clear-cut watershed (p = 0.00011), and a marginally significant impact of harvest on monthly sediment loads in the partial cut (p = 0.081). Total sediment load from the clearcut over the immediate harvest interval exceeded predicted load by 152% (6,791 kg km -2); however, individual monthly loads varied around this amount. The largest increases in percentage and magnitude occurred during snowmelt months, namely April 2002 (560%, 2,958 kg km -2) and May 2002 (171%, 3,394 kg km -2). Neither treatment showed a statistical difference in TSS during the recovery time 2-4 years after harvest (clearcut: p = 0.2336; partial cut: p = 0,1739) compared to the calibration loads (pre-harvest).

Nutrients

The “Hard Rock” study (McIntyre et al., 2021) results showed an increase in total-N export of 5.73 (P = 0.121), 10.85 (P = 0.006), and 15.94 (P = 0.000) kg/ha/yr post-harvest in the 100%, FP, and 0% treatments, respectively, in the first 2 years; and of 6.20 (P = 0.095), 5.34 (P = 0.147), and 8.49 (P = 0.026) kg/ha/yr in the extended period (7-8 years post-harvest). Results for nitrate-

N export showed changes similar to but slightly less than those seen in the total-N analysis with a relative increase in nitrate-N export of 4.79 ($P = 0.123$), 9.63 ($P = 0.004$), and 14.41 ($P <0.001$) kg/ha/yr post-harvest in the 100%, FP, and 0% treatments, respectively in the first 2 years. None of the changes in the extended period were significant. However, the authors note that there was high variability in the data for the extended period and nitrate-N export only returned to pre-harvest levels in one watershed. Total phosphorus export increased post-harvest by a similar magnitude in all treatments: 0.10 ($P = 0.006$), 0.13 ($P = 0.001$), and 0.09 ($P = 0.010$) kg/ha/yr in the 100%, FP, and 0% treatments, respectively in the first 2 years post-harvest. Changes in phosphorus were not reported in the extended period.

Gravelle et al. (2009) compared pre- to post changes in NO^3 and NO^2 concentrations in headwater streams following a clearcut and a partial cut (50% removal of canopy cover) in northern Idaho. Riparian buffers and leave trees are not required for non-fish bearing headwater streams in Idaho. Results showed statistically significant increases in NO^3 and NO^2 concentrations following clearcut and partial harvest cuts in headwater streams ($p < 0.001$). Increases at the clearcut treatment site were greatest, where mean monthly concentrations increased from 0.06 mg-N L -1 during the calibration period to 0.35 mg-N L –1 in the post-harvest period. Mean monthly concentrations in the partial cut increased from 0.04 mg-N L –1 in the pre-harvest period to 0.05 mg-N L –1 in the post-harvest period. No significant changes of in-stream concentration of any other nutrient recorded (total Kjeldahl nitrogen (TKN), TP, total ammonia nitrogen (TAN) consisting of unionized (NH3) and ionized (NH4+) ammonia, and unfiltered orthophosphate (OP)) were found between time periods and treatments.

Deval et al. (2021) compared changes in the same nutrient concentrations in the same area of northern Idaho but with an additional harvest prescription several years later. For this analysis, time periods were broken into four distinct phases: 1) pre-disturbance (1992–1997), 2) post-road (1997–2001), 3) experimental-harvest Phase I (PH-I) (2001–2007), and 4) operational sequential harvest Phase II (PH-II) when the extent and frequency of harvests increased (2007–2016). PH-I represents an experimental treatment phase during which harvest activities were experimentally controlled (only upstream headwater watersheds were harvested and mature vegetation (size or age threshold for “mature” not reported) removal ranged between 24% and 47%) followed by site management operations including broadcast burning and replanting. PH-II represents the post-experimental phase where the study area transitioned to operational treatments that consisted of additional road construction and timber harvest, with site management operations including pile burning and competition release herbicide application. During this operational phase, the mature vegetation (size or age threshold for “mature” not reported) removal in the upstream watersheds ranged between 36% and 50%. The response in $NO^3 + NO^2$ concentrations was negligible at all treatment sites following the road construction activities. However, $NO^3 + NO^2$ concentrations during the PH-I period increased significantly ($p < 0.001$) at all treatment sites. Similar to the PH-I period, all watersheds experienced significant increases in $NO^3 + NO^2$ concentration during the PH-II treatment period ($p < 0.001$). Similar to Gravelle et al. (2009), significant increases in all other nutrients recorded were not detected.

Focal Question 1a

1a. What are the effects of thinning (intensity, extent) on the riparian functions, over the short and long-term compared to untreated stands?

Based on the wording of this question, papers deemed appropriate are those that compare changes in measurable data indicative of the riparian functions between harvested and unharvested stands. Further, studies chosen for this question should compare the response of these functions based on different thinning intensities. Thus, the design of the studies reviewed for this review should be a BACI or ACI design with results reported for differences between treatment and reference reaches. Also included are a few simulation modeling experiments that follow these designs.

Considering these criteria, 22 papers published since 2000 were deemed useful in providing information relevant to focal question 1a. Of these 22 papers, seven used a BACI design, 10 used an ACI design, and 4 used simulation modeling that followed either an ACI or BACI design. Because the BACI design is also acceptable for this focal question, there is some overlap with the papers reviewed for focal question 1. However, only the information relevant to this question was extracted and discussed below.

Function	**Count**
Shade	2
Litter	0
LW	2
Sediment	1
Nutrients	1
Bank Stability	0

Shade

Anderson et. al. (2007) compared changes in canopy cover at stream centers between sites adjacent to different riparian zone treatments and an untreated control. This study was conducted in young headwater forests of western Oregon. Treatments included three buffer widths: 1) one site-potential tree averaging 69 m (B1), 2) variable width buffer averaging 22 m (VB), or 3) streamside retention buffer averaging 9 m (SR-T). Adjacent upland to each buffer treatment was thinned to ~198 trees per hectare. Results showed that visible sky at stream center only differed significantly between SR-T (9.6%) and the untreated (4.2%) sites post-harvest. These results were reported for the period 2-5 years post-harvest.

Roon et. al. (2021a) used a BACI analysis to evaluate significant changes in canopy cover relative to untreated reaches following 2 different thinning intensities in second growth redwood forests of northern California. One study site prescribed treatment on one side of the stream of a 45 m buffer width with a 22.5 m inner zone with a target 85% canopy retention and a 22.5 m outer zone that retained 70% canopy cover (Green Diamond Resource Company, Tectah watershed). The treatment site, thinning prescriptions included removal of up to 40% of the basal area within the riparian zone on slopes less than 20% on both sides of the channel along a ~100–150 m reach (Lost Man watershed, Redwood national park). Control reaches were located upstream from treatment reaches. Data analysis was conducted separately for each experimental watershed (i.e., 1 Lost man site, 2 Tectah sites). Results for the Tectah watershed showed a significant reduction in canopy closure by a mean of 18.7%, (95% CI: -21.0, -16.3) and a significant reduction of effective shade by a mean of 23.0% (-25.8, -20.1) one-year post treatment. In the Lost Man watershed, a non-significant reduction of mean shade by 4.1% (-8.0, -0.5), and mean canopy closure by 1.9% was observed. Results for below canopy light availability showed significant increases by a mean of 33% (27.3, 38.5) in the Tectah watershed, and non-significant increases in Lost Man watershed of 2.5% (-1.6, 5.6). Data for canopy closure and effective shade were recorded for 1-year pre- and 1-year post-harvest.

LW

Benda et al. (2016) used simulation modeling to estimate the changes in in-stream LW volume over time between sites with thinning treatments and unharvested reference sites. They used ORGANON growth models to simulate forest growth and LW recruitment over a 100-year period. The model simulated treatments of single entry thinning from below (thinning from below removes the smallest trees to simulate suppression mortality) with and without a 10 m width no-cut buffers; and a double entry thinning from below with the second thinning occurring 25 years after the first with and without 10 m no-cut buffers (results with 10 m buffer presented in question 1b). Each thinning treatment was also combined with some mechanical introduction of thinned trees into the stream encompassing a range between 5 and 20 % of the thinned trees. The single-entry thin reduces stand density to 225 tph in 2015 (-67 %) and declines further to 160 tph by 2110 (-77 %). The double entry thinning resulted in 123 tph after the second thinning in 2040 (-82%) and maintained that density until 2110. Both thinning treatments resulted in a substantial reduction of dead trees that could contribute to in-stream wood loads. The model output for single entry thinning treatments predicts a 33% or 66% reduction of in-stream wood over a century relative to the unharvested reference for harvest on one side or both sides of the stream, respectively. Including mechanical tipping of 5,10,15, and 20% of cut stems without a buffer in the single-entry thinning treatment changes the relative in-stream percentages of wood relative to the reference stream to –15, -6, +1, and +6%, respectively. Double entry thinning treatments without a buffer predicted further reduction in wood recruitment over a century of simulation with 42 and 84% reduction of in stream wood relative to the reference stream when one side and both sides of the channel were harvested. To offset the predicted changes of in stream wood volume following double entry harvest would require tipping of 10% of cut stems. The authors conclude that thinning without some mitigation efforts resulted in large losses of in stream wood over a century.

Schuett Hames and Stewart (2019a) compared recruitment rates of LW and volume of in-stream LW between different riparian buffer thinning treatments and unharvested reference sites. Treatments evaluated included prescriptions for standard shade rule (a 30-ft no-cut buffer width, and thinning 30-75 ft from the stream), and all available shade rule (requires retention of all shade providing trees in this area) for eastern Washington. Results showed cumulative wood recruitment from tree fall over the five-year post-harvest interval was highest in the standard shade rule (SR) group, lower in the all-available-shade rule (AAS) group and lowest in the reference (REF) group. The SR and AAS rates by volume were nearly 300% and 50% higher than the REF rates, respectively. Wood recruitment in the SR sites was significantly greater than in the AAS and reference sites ($P < 0.05$). Conversely, differences in wood recruitment did not differ significantly between the AAS and reference sites.

Sediment

Karwan et al. (2007) used BACI analysis to compare changes in total suspended solid (TSS) yields between thinned sites and unharvested reference sites. This study was conducted in the Mica Creek Experimental watershed of northern Idaho and focused on non-fish bearing headwater streams. The thinning treatment included a target 50% canopy removal without no-cut buffers. Results showed a marginally significant ($P = 0.081$) increase in TSS relative to the reference streams in the first year following treatment. However, differences in TSS between the treatment streams and refence streams were not significant ($p = 0.174$) in the period 2-4 years post-harvest.

Nutrients

Yang et al. (2021) compared changes in stream chemistry between streams along thinned stands and unharvested reference stands in young mixed conifer headwater basins of the Sierra National Forest. Thinning treatment included mastication of shrub cover to < 10% and harvesting of trees to a target basal area of 27–55 m^2 ha^{-1}. Data for dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) were recorded for 2 years prior to and 3 years after treatment. For stream water, volume-weighted concentrations of DOC were 66- 94% higher in thinned watersheds than in control watersheds for all three consecutive drought years following thinning ($p = 0.06$, 0.01, and 0.05 for years 1,2, and 3 post-harvest, respectively). No differences in DOC concentrations were found between thinned and control watersheds before thinning ($p = 0.50$, and 0.74 for pre-harvest years 1 and 2, respectively). Volume-weighted concentrations of DIN were 24% higher in thinned than in control watersheds only in the third year following thinning ($p = 0.04$). No differences in DIN were detected between treatment and reference streams in the 2 pre-harvest years ($P \geq 0.44$). Note: Drought occurred at both sites during the three post-harvest years which may have compounded these effects. This is discussed in more detail in question 3.

Focal Question 1b

1b. How do buffer widths and adjacent upland timber harvest prescriptions influence impacts of riparian thinning treatments?

An experimental design that could provide information useful in answering this question would involve a comparison of sites with different buffer widths, all with upland harvest, and data would need to be recorded before and after thinning, with or without a control site (BAI, BACI), or differences after thinning between treatment and control sites (ACI). Three papers include an experimental design that investigate different buffer widths or different upland treatments along with riparian thinning treatments.

Shade

Anderson et al. (2007) compared changes in canopy cover at stream centers between sites adjacent to different riparian zone treatments and an untreated control. This study was conducted in young headwater forests of western Oregon. Treatments included three buffer widths (1) one site-potential tree averaging 69 m (B1), (2) variable width buffer averaging 22 m (VB), or (3) streamside retention buffer averaging 9 m (SR-T); the adjacent upland to each buffer was thinned to ~198 trees per hectare. Results showed that visible sky at stream center only differed significantly between SR-T (9.6%) and the untreated (4.2%) sites post-harvest. These results were reported for the period 2-5 years post-harvest.

LW

Burton et al. (2016) examined the relationship between annual in-stream wood loading and riparian buffer widths adjacent to upland thinning operations. Buffer widths were 6, 15, or 70 meters and upland thinning was to 200 trees per ha (tph), with a second thinning (~10 years later) to ~85 tph, alongside an unthinned reference stand of ~400 tph. Their results showed that slightly higher volumes of wood were found in sites with a narrow 6-m buffer (not significant), as compared with the 15-m and 70-m buffer sites in the first 5 years after the first harvest and maintained through year 1 of the second harvest (end of study). The authors attributed this difference to a higher likelihood of logging debris and/or windthrow, but these factors were not analyzed.

Benda et al. (2016) used simulation modeling to estimate the changes in in-stream LW volume over time between sites with thinning treatments and unharvested reference sites. They used ORGANON growth models to simulate forest growth and LW recruitment over a 100-year period. The model simulated treatments of single entry thinning from below (thinning from below removes the smallest trees to simulate suppression mortality) with and without a 10 m width no-cut buffers; and a double entry thinning from below with the second thinning occurring 25 years after the first with and without 10 m no-cut buffers. Each thinning treatment was also combined with some mechanical introduction of thinned trees into the stream encompassing a range between 5 and 20 % of the thinned trees. The single-entry thin reduces stand density to 225 tph in 2015 (-67 %) and declines further to 160 tph by 2110 (-77 %). The double entry thinning resulted in 123 tph after the second thinning in 2040 (-82%) and maintained that density until 2110. Both thinning treatments resulted in a substantial reduction of dead trees that could contribute to in-stream. The model output for single entry thinning treatments predicts a 33% or 66% reduction of in-stream wood over a century relative to the unharvested reference for harvest on one side or both sides of the stream, respectively. Adding the 10-m no cut buffer reduced total loss to 7 and 14%. Including mechanical tipping of 5,10,15, and 20% of cut stems without a buffer in the single-entry, thinning treatment changed the relative in-stream percentages of wood relative to the reference stream to –15, -6, +1, and +6%, respectively. To completely offset the loss of in stream wood due to single entry thinning, mechanical tipping of 14 and 12% were required without and with buffers. Double entry thinning treatments without a buffer predicted further reduction in wood recruitment over a century of simulation with 42 and 84% reduction of in stream wood relative to the reference stream when one side and both sides of the channel were harvested. Adding a 10 m buffer reduced total reduction of in stream wood to 11 and 22% for thinning on one and both sides of the channel. To offset the predicted changes of in stream wood volume following double entry harvest would require tipping of 10 and 7% of cut stems without and with the 10-m buffer. The authors conclude that thinning without some mitigation efforts resulted in large losses of in stream wood over a century.

Focal Question 1c

1c. What are the effects of clearcut gaps in riparian stands (intensity, extent) on the riparian functions, over the short and long-term, compared to untreated stands?

This question uses the general term "clearcut gaps" as a treatment within the riparian area but does not define a minimum or maximum threshold for gap size. Thus, studies reviewed that used a "patch" treatment were included as having information useful in answering this question. The question also identifies a comparison with untreated stands. Therefore, any design with a control site (BACI, ACI) is appropriate.

There appears to be a paucity of studies in the literature that investigate the effects of gaps or patch harvesting treatments on riparian function within riparian stands. Only 4 papers discussed the effects of prescribed gaps or patches in the riparian area on riparian function.

The "Hard Rock" study from McIntyre et al. (2021) and the "Soft Rock" study from Ehinger et al. (2021) present the most relevant results useful for answering this question. Riparian buffer prescriptions for non-fish bearing streams in western Washington use a gap design. In this design, a 50-foot buffer is required along at least 50% of the treated stream length. The remaining 50% or less of the treated riparian management zone can be clear cut to the stream edge. The Hard Rock study compared differences in shade, in-stream sediment and nutrient concentrations, and large wood recruitment between treated and unharvested reaches for 8-9 years post-harvest. The first iteration of the Hard Rock study (McIntyre et al. 2021) also compared differences in litter inputs following treatment for 2 years post-harvest between treatment and reference reaches.

The Soft Rock study compared differences in the same functions between treated and unharvested reaches, but only for 3 years post-harvest. However, because of unstable slopes in some of the sites in the Soft Rock study, many of the buffers were required to be wider than 50-feet (ranging from 18 –160% wider than 50-feet). Conversely, some of the sites treated ended up with buffers narrower than 50 feet. Further, there was limited availability of sites that fit the criteria (marine sediment lithology, timing of treatment). Because of these limitations, statistical analysis, and comparison of response between treatments and references for many functions, could not be performed. Thus, the results are only descriptive, but they provide useful information for comparison to the Hard Rock study.

Shade

The Hard Rock study reported that decreases in canopy cover (measured at 1 meter above the stream surface with a spherical densiometer) were significant across all years for the treated sites compared to the reference sites ($p < 0.05$). The mean canopy cover decreased from 96% (pre-harvest) to 72% in the first-year post-harvest and continued to decline for four years reaching a minimum of 54%. After year four, mean canopy cover began to recover increasing annually until year 9 to 74%. In contrast, mean canopy cover in the reference sites was 95% before harvest and never fell below 85% for 9 years. In the Soft Rock study, mean canopy closure decreased in the treatment sites from 97% in the pre-harvest period to 75%, 68%, and 69% in the first, second, and third post-harvest years, respectively; and was further related to the proportion of stream buffered and to post-harvest windthrow within the buffer. Canopy closure remained stable in the reference sites throughout the course of the study, ranging from 95 to 99%.

Janisch et al. (2012) compared canopy cover before and after application of a “patched buffer” treatment with unharvested control reaches in headwater streams of western Washington. The “patched buffer” treatment included retention of portions of the riparian forests ~50-110 m long in distinct patches along the channel with the remaining riparian area clearcut. There was no standard width for patched buffers, with buffers spanning the full width of the floodplain area and/or extending some undefined distance away from the stream. Canopy density was measured once in the summer prior to logging and once in the summer following logging. The percentage of visible sky was determined from digital photos taken with a fish-eye lens using Hemiview Canopy Analysis software. Canopy cover in all streams averaged 95% prior to harvest and did not differ between treatment and reference streams. Following treatment, canopy cover in the patch buffer treatment averaged 76% and differed significantly from reference reaches.

Swartz et al. (2020) tested the effects of adding canopy gaps within young, regenerating forests of western Oregon on stream light availability and stream temperatures. While light availability and stream temperature are not functions described in the FPHCP, they are directly related to shade. Further, considering the paucity of studies available that investigate the effects of clearcut gaps, the results are presented here. The addition of gaps in the young regenerating forests were used to theoretically mimic the natural disturbance regimes and the higher canopy complexity of late-successional forests. The researchers used a BACI design on six replicated streams within the Mckenzie River Basin. In each treatment reach, gaps were designed to create openings in the canopy that were approximately 20 m in diameter. Gaps were centered on a tree next to the stream and spaced approximately 30 meters apart along each reach. The BACI analysis showed strong evidence for significant increase in mean reach light ($p < 0.01$) up to 3.91 (SD ± 1.63) moles of photons m^{-2} day^{-1} and an overall mean change in light of 2.93 (SD ± 1.50) moles of photons m^{-2} day^{-1}. Mean stream shading could not be evaluated in the full BACI analysis because post-treatment hemispherical photographs could not be taken at all sites due to fire impeding access. For the remaining sites, the areas beneath each gap had notable localized declines in shade, though the entirety of the treatment reach mean shading declined by only 4% (SD ± 0.02%).

Litter

The Hard Rock study only quantified changes in litter input for 2 years after treatment (McIntyre et al., 2018). While significant decreases in litter input were observed from pre- to post-harvest in the treatment sites (described in focal question 1) these values were not significant when compared to the changes in the reference sites. Litter input was not quantified in the Soft Rock study.

LW

For the Hard Rock study, large wood recruitment and loading were only compared between the reference reaches and the buffered portion of the treatment reaches. The authors report large wood recruitment into the channel was 3 times greater on average in the treatment buffer than in the reference over the 8-year post-treatment period. However, while considerable, these differences were not significant for any analyzed post-harvest interval (e.g., 1-2 years post, 1-5 years post, or 1-8 years post). The lack of significance was attributed to the large variability in recruitment values among treatment sites. The greatest increase in LW recruitment in the treatment sites relative to the reference sites occurred in the first 2 years post-harvest. Large wood loading (pieces/m of channel length) increased significantly ($\alpha = 0.10$) in the treatment reaches, relative to the reference sites in the first 2 years (47%; $p = 0.05$), 5 years (42%; $p = 0.08$), and 8 years (41%; $p = 0.09$) post-harvest. For the Soft Rock study there was little post-harvest large wood input in reference sites: an average of 4.3 pieces and 0.34 m3 of combined in- and over-channel volume per 100 m of channel. In contrast, the full buffer sites and <50 ft buffer sites received an average of 23 and 10 pieces/100 m and 2.3 and 0.7 m3/100 m of large wood, respectively.

Sediment

For the Hard Rock study, results for water turbidity and suspended sediment export (SSE) were stochastic in nature and the relationships between SSE and treatment effects were not strong enough to confidently draw conclusions. Water turbidity and SSE increased with stream discharge during large storm events but rapidly declined. The Soft Rock study reported similar issues with the data for SSE in that it appeared to be driven by site and event specific factors and strong conclusions could not be drawn. The authors report that the softer lithologies sampled as part of this study were more erodible than the competent lithologies sampled in the companion Hard Rock Study.

Nutrients

The Hard Rock study analyzed changes in total nitrogen and nitrate export in the gap buffers relative to untreated reference streams. Results showed an increase in total nitrogen export in the treatment sites of 10.85 kg/ha/yr ($p = 0.006$) in the first two years post-harvest relative to the reference sites. In the extended periods, total nitrogen export increased by 5.34 ($p = 0.147$) kg/ha/yr relative to the reference streams. Results for NO^3 export showed similar but slightly lower increases than total nitrogen with a relative increase in NO^3 export of 9.63 ($p = 0.004$) kg/ha/yr for the first two years post-harvest relative to the reference. None of the changes in nitrate exports in the extended period were significant. The Soft Rock study reported significant increases in concentrations of total nitrogen ($p < 0.05$) and NO^3 ($p < 0.05$) post-harvest in the treatment sites relative to the reference sites. The change in export appeared related to the proportion of stream buffered.

Focal Question 1d

1d. How do buffer widths and upland timber harvest influence impacts of clearcut gaps treatments?

The wording of this question implies that the effects of clearcut gaps (discussed in focal question 1c) on riparian function could be impacted when paired with different buffer widths and upland harvest prescriptions. Similar to the results of the search in literature for focal question 1c, there was a paucity of riparian function studies that implemented a clearcut gap or patch cutting method within the riparian area. The added layer of complexity in this question specifying differences in buffer widths and upland harvests only further refined the selection of appropriate papers. Of the studies reviewed above, none included the evaluation of different buffer widths or different upland harvests in their experimental design. The Hard Rock study compared the clearcut gap buffers to full retention buffer and unbuffered sites (discussed in the literature review section), but different widths were not compared in the gap buffer treatments.

Focal Question 1e

1e. What are the effects of any combinations of the above treatments?

No studies found in our search compared the effects of combined treatments on one or more of the five functions, likely because combining multiple treatments into one design has the potential to confound results and are difficult to implement with sufficient sample sizes. The majority of the studies listed in our review investigate the effects of buffer width, thinning treatments, and upland treatments separately.

The only papers with some extractable evidence of the compounding/ameliorating effects of combined treatments were focused on shade. One study, Reiter et al. (2020), compared the effects of thinned and unthinned buffers, and clearcut on changes in percent shade over adjacent streams (discussed in focal question 1). However, changes in shade were not statistically analyzed and the implementation of the upland thinning treatment only occurred at one site (Table 6).

Focal Question 2

2. How and to what degree do specific site conditions (e.g., topography, channel width and orientation, riparian stand age and composition) influence the response of the riparian functions?

Multiple studies have investigated the influences of site conditions on riparian function. Few studies reviewed (4) investigated the interaction between specific site conditions (e.g., slope, lithology, elevation) and harvest on the response of riparian function. However, if these specific site conditions influence the magnitude of riparian function in the absence of harvest, it is possible they can compound the effects of harvest on their response. Thus, studies that assess the relationship between site factors and riparian function may provide some useful insight for management and are presented below. Further, we also included studies that investigated the relationships between road development and sediment transport because road development is directly related to changes in local topography.

Litter

Hart et al. (2013) compared litter delivery into streams between riparian zones dominated by deciduous (red alder) and coniferous (Douglas-fir) tree species in western Oregon. Results from this study show that deciduous forests dominated by red alder delivered significantly greater vertical and lateral inputs (g m^{-2} y^{-1}) to adjacent streams than did coniferous forests dominated by Douglas-fir. Deciduous-site vertical litter input (mean = 504 g m-2 y-1) exceeded that from coniferous sites (394 g m-2 y-1) by 110 g/m2 over the full year. Annual lateral inputs at deciduous sites (109 g m-2 y-1) were 46 g m-2 y-1 more than at coniferous sites (63 g m-2 y-1). The timing of the inputs also differed, with the greatest differences occurring in November during autumn peak inputs for the deciduous forests. Further, annual lateral litter input increased with slope at deciduous sites (R2 = 0.4073, p = 0.0771), but showed no strong relationship at coniferous sites (R2 = 0.1863, p = 0.2855). These results were partially consistent with Bilby & Heffner (2016) in that they suggest litter type, and topography (slope) can affect the litter input rates.

Bilby & Heffner (2016) used a combination of field experiments, literature review, and modeling to estimate the relative importance of factors affecting litter delivery from riparian areas into streams of western Washington in the Cascade mountains at high and low elevations. Their results for conifer needles released at mature sites had a higher proportion of cumulative input from greater distances than needles or leaves released at younger sites. The authors suggest from their interpretation of the model that the width of the litter contributing area was ~35% greater at mature sites than at young sites. The mean age of “mature” and “young” sites was not specified but the mean tree heights were 47.0 m and 32.4 m for the mature and young sites, respectively. Thus, tree height is related to the width of the litter contributing area for conifer needles. Litter travel distance was also linearly related to wind speed ($p < 0.0001$). Doubling wind speed at one site led to a 67-87% expansion of the riparian litter contribution zone in the study area. Interpretation of the regression curves revealed a trend that suggests hillslope gradient affects the width of the litter contributing area as well. However, the authors did not apply statistical analysis to these values and only speculated that increasing the slope from 0-45% would increase the width of the litter contributing area by up to 70%.

LW

Wing & Skaugset (2002) investigated the relationships between channel and habitat characteristics with LW piece count and volume in stream reaches in western Oregon. This study analyzed an extensive spatial database of aquatic habitat conditions created for western Oregon using stream habitat classification techniques and a geographic information system (GIS). Regression tree analysis (an exploratory regression analysis that allows for the inclusion of multiple explanatory variables) was used to compare the relative strength of each variable in predicting LW volume. Explanatory variables used in this analysis included morphology of active channel (hillslope, terrace, terrace hillslope, unconstrained), and lithology (e.g., alluvium, basalt, etc.). Results for channel characteristics showed that stream gradient was the most important explanatory variable for LW volume. The split for stream gradient occurred for reaches with < 2.3% gradient (mean LW volume: 5.8 m^3 per reach) while higher gradient streams showed a mean LW volume of 17.9 m^3 per reach.

For LW pieces in forested stream reaches bankfull channel width was the most important explanatory variable with the split occurring for streams channels less than 12.2 m wide. LW pieces for streams <12.2 m wide averaged 11.1 LW pieces per reach while larger channels averaged 4.9 pieces per reach; in this model the BFW split explained 7% of the variation in LW pieces found in forested streams. For key LW pieces (logs at least 0.60 m in diameter and 10 m long) in forested reaches, stream gradient was again the most important explanatory variable with the split occurring at a slope of 4.9%. The streams with a gradient < 4.9% averaged 0.5 key LW pieces per reach while streams with higher gradients averaged 0.9 key LW pieces per reach; in this model stream gradient explained 8% of the variation in key LW pieces found in streams.

Lithology caused second, third or fourth level splits after stream gradient or BFW. Specifically, Mesozoic sedimentary and metamorphic geologies, located in southern Oregon stream reaches, were grouped and split from basalt, Cascade, and marine sedimentary geologies. In stream reaches with Mesozoic sedimentary and metamorphic geologies, the quantity of LWD was roughly half the amount found in other geologies. The only exception to this grouping was for LW volume in larger stream reaches, where basalt and marine sedimentary geologies contained more LW volume when grouped separately from all other geologies in a fourth-level split. The authors conclude that the geomorphic characteristic of stream reaches, in particular stream gradient and bankfull width, correlated best with LW presence.

Sobota et al. (2006), evaluated patterns of riparian tree fall directions in diverse environmental conditions and evaluate correlations with tree characteristics, forest structural variables, and topographic features. Specifically, the authors were interested in correlations between fall directionality and tree species type, tree size, riparian forest structure, and valley topography (side slope). Data was collected from 21 field sites located west of the Cascade Mountains crest (11 sites: Coast Range and west slopes of the Cascades), and in the interior Columbia Basin (10 sites: east slopes of the Cascades, Blue Mountains, and Northern Rockies) of Oregon, Washington, Idaho, and Montana, USA. Streams were second- to fourth-order channels and had riparian forests that were approximately 40 to >200 years old. Model projections of LW recruitment estimated that sites with uniform steep side slopes (>40%) produced between 1.5 to 2.4 times more in stream LW by number of tree boles than sites with uniform moderate side slopes (< 40%). The authors warn that while side slope categories (>40%, <40%) was the strongest predictor of tree fall direction in this study, they believe the differences in tree fall direction between these categories mainly characterized differences between fluvial (88% of moderate slope sites) and hillslope landforms (71% of steep slope sites). They suggest that the implications from this study are most applicable to small- to medium-size streams (second to fourth order) in mountainous regions where sustained large wood recruitment from riparian forest mortality is the significant management concern.

Sediment

Bywater-Reyes et al. (2017) assessed the influence of natural controls (basin lithology and physiography) and forest management on suspended sediment yields in temperate headwater catchments. This study analyzed 6 years of data from the Trask River Watershed in northeastern Oregon and included data from harvested and unharvested sub-catchments underlain by heterogenous lithologies. Results from this study indicate that site lithology was the first order control over suspended sediment yield (SSY) with SSY varying by an order of magnitude across lithologies observed. Specifically, SSY was greater in catchments underlain by Siletz Volcanics ($r = 0.6$), the Trask River Formation ($r = 0.4$), and landslide deposits ($r = 0.9$) and displayed an exponential relationship when plotted against the percentage of watershed area underlain by these lithologies. In contrast, site lithology had a strong negative correlation with percent area underlain by diabase ($r = 0.7$), with the lowest SSY associated with 100% diabase. Following timber harvest, increases in SSY occurred in all harvested catchments but returned to pre-harvest levels within 1 year except for sites that were underlain by sedimentary formations and were clearcut without protective buffers. The authors conclude that sites underlain with a friable lithology (e.g., sedimentary formations) had, on average, SSYs an order of magnitude higher following harvest than those on more resistant lithologies (intrusive rocks).

Bywater-Reyes et al. (2018) quantified how sediment yields vary with catchment lithography and physiography, discharge, and disturbance history (management or natural disturbances) over 60 years in the H.J. Andrews experimental watershed in the western Cascade Range of Oregon. A linear mixed effects model (log transformed to meet the normality assumption) was used to predict annual sediment yield. In this model, site was treated as a random effect while discharge and physiographic variables were treated as fixed variables. This allowed for the evaluation of the relationships between sediment yield and physiographic features (slope, elevation, roughness, and index of sediment connectivity) while accounting for site. To account for the effect of disturbance history a variable was added to the model when the watershed had a history of management or natural disturbances. If the models for the disturbed watersheds significantly underpredicted the sediment discharge, the timing of the sudden increases were further examined to assess whether it correlated with a disturbance event. The results showed that watershed physiography combined with cumulative annual discharge explained 67% of the variation in annual sediment yield across the 60-year data set. Relative to other physiographic variables, watershed slope was the greatest predictor of annual suspended sediment yield. However, the results showed that annual sediment yields also moderately correlated with many other physiographic variables and caution that the strong relationship with watershed slope is likely a proxy for many processes, encompassing multiple catchment characteristics.

Mueller & Pitlick used correlation analysis to assess the relative impact of lithology, basin relief, mean basin slope, and drainage density on in stream sediment supply defined by the bankfull sediment concentration (bedload and suspended load). The study used sediment concentration data from 83 drainage basins in Idaho and Wyoming. Lithologies of the study area were divided into four categories ranging from hardest to softest- granitic, metasedimentary, volcanic, and sedimentary. The results showed the strongest correlation of bankfull sediment concentration was with basin lithology, and showed little correlation strength with slope, relief and drainage density. As lithologies become dominated by softer parent materials (volcanic and sedimentary rocks), bankfull sediment concentrations increased by as much as 100-fold. The authors interpret these results as evidence that lithology can be more important in estimating sediment supply than topography.

Rachels et al. (2020) used sediment source fingerprinting techniques to quantify the proportional relationship of sediment sources (hillslope, roads, streambanks) in harvested and un-harvested watersheds of the Oregon Coast Range. The study included one catchment (Enos Creek) that was partially clearcut harvested in the summer of 2016 and an unharvested reference catchment (Scheele Creek) located ~3.5 km northwest of Enos Creek. The paired watersheds had similar road networks, drainage areas, lithologies and topographies. The treatment watershed was harvested with a skyline buffer technique in the summer of 2016 under the Oregon Forest practices Act policy that requires a minimum 15 m no-cut buffer. The proportion of suspended sediment sources were similar in the harvested (90.3 $\pm$ 3.4% from stream bank; 7.1 $\pm$ 3.1% from hillslope) and unharvest (93.1 $\pm$ 1.8% from streambank; 6.9 $\pm$ 1.8% from hillslope) watersheds. However, the harvested watershed contained a small portion of sediment from roads (3.6 $\pm$ 3.6%), while the unharvested reference watershed suspended sediment contained no sediment sourced from roads. In the harvested watersheds the sediment mass eroded from the general harvest areas (96.5 $\pm$ 57.0 g) was approximately 10 times greater than the amount trapped in the riparian buffer (9.1 $\pm$ 1.9 g), and 4.6 times greater than the amount of sediment collected from the unharvested hillslope (21.0 $\pm$ 3.3 g). These results suggest that the riparian buffer was efficient in reducing sediment erosion relative to the harvested area. The caveat of this study was the limited sample size (1 treatment, 1 paired reference watershed) and does not incorporate the effects of different watershed physiography on sediment erosion. However, it is presented here as evidence that the formation of roads within a riparian area may interact with timber harvest to increase the potential flow of sediments from roads.

Litschert & MacDonald, (2009) investigated the frequency of sediment delivery pathways in riparian management areas and their physical characteristics and connectivity following harvest. In this study the authors describe sediment delivery pathways (“features”) as rills, gullies, and sediment plumes that form when excess sediment relative to overland flows transports sediment from the hillslope to the stream. The authors surveyed 200 riparian management areas (RMA) in four different National Forests of the Sierra Nevada and Cascade Mountains of California. USFS policy requires 90-m wide RMA along each side of perennial streams and 45-m wide RMA along each side of all ephemeral and intermittent streams. When features were found within an RMA, data for years since harvest, soil depth, soil erodibility (K), feature length, feature gradient, aspect, elevation, hillslope gradient, hillslope curvature, surface roughness, and connectivity were recorded for analysis. Association between these variables were analyzed with a Spearman’s rank correlation. The variables most strongly associated with feature length were used to develop a multiple linear regression model to predict feature length. Only 19 of the 200 harvest units had sediment development pathways. Feature pathways ranged in age (time since harvest) from 2 to 18 years, and in length from 10 m to 220 m. Of the 19 feature pathways, only six were connected to streams, and five of those originated from skid trails. Feature pathway length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient ($R^2 = 64\%$, $p = 0.004$). These results suggest that within treated riparian areas topographic characteristics such as aspect, elevation and hillslope gradient can affect delivery of sediment into streams.

Rashin et al. (2006) evaluated the effectiveness of Washington State best management practices (BMPs) for controlling sediment related water quality impacts. Although this study was published in 2006, the data analyzed in this study were collected between 1992 and 1995. In their evaluation, Rashin et al. (2006) assessed site erosion, sediment delivery, channel disturbance, and aquatic habitat condition within the first two years of harvest along fish- and non-fish bearing streams across Washington state. From their results, the authors concluded that the site-specific factors influencing the effectiveness of BMPs in preventing chronic sediment delivery into streams were 1) the proximity of ground disturbance to the stream, 2) presence of a stream buffer, 3) falling and yarding practices that minimized disturbance to stream channel, and 4) timing of harvest activities for certain climate zones where frozen ground or snow cover may be exploited. The landscape factors that influenced BMP effectiveness were 1) the density (specific metric not reported) of unbuffered small streams at harvest sites, and 2) steepness of stream valley slopes. The authors conclude with a recommendation of excluding timber falling and yarding activities at least 10 m from streams and outside of steep inner gorges.

From the studies reviewed there is evidence that sediment delivery into streams following timber harvest is influenced by not only the intensity of the harvest operation (e.g., presence of retention buffers, yarding and equipment use immediately adjacent to the stream, upland clearcut vs. thinning), but also by physiography (especially hillslope gradient), lithology relative softness, and the presence of roads. Thus, the change in magnitude of sediment delivery following harvest is context dependent and these landscape factors can interact with one another to compound these changes. However, from the studies reviewed in the sediment section of the literature review, there is evidence that the implementation of BMPs since the 1970s in the northwestern United States has lessened the impact and duration of these changes.

Nutrient

None of the studies published since 2000 and conducted in western North America provide experimental evidence of the effects of site factors on nutrient flux into streams. However, Zhang et al. (2010) conducted a global review and meta-analysis of the effectiveness of buffers in reducing nonpoint source pollution. They reported slope (hillslope gradient) as having a linear relationship with buffer pollutant removal efficacy that switched from positive to negative when slope increased beyond 10% (i.e., hillslope gradients of ~10% were optimal for buffer efficacy in removing pollutants).

Focal Question 3

3. What is the frequency of weather-related effects (e.g., windthrow, ice storms, excessive heat, flood and drought events) on riparian areas? What are the weather-related effects (positive and negative) on the riparian functions, and how are they distinguished from harvest effects? How do these effects differ between treated and untreated riparian forests?

The first part of this question "What is the frequency of weather-related effects (e.g., windthrow, ice storms, excessive heat, flood and drought events) on riparian areas?" is a generally worded question asking how often weather events in riparian areas occur. The second part of this question "What are the weather-related effects (positive and negative) on the riparian functions, and how are they distinguished from harvest effects?" contains within it 2 parts 1) what the effects on the riparian functions are, and 2) how they are distinguished from timber harvest effect. Any study reviewed that answers one or more parts of this question have been included.

Shade

McIntyre et al. (2021), the "Hard Rock" study, compared changes in shade from pre- to post-harvest between three riparian harvest treatments and a reference. Treatments included a two-sided 50-ft riparian buffer along at least 50% of the stream (FP; with clearcut to stream's edge outside of the buffer), a two sided 50-ft buffer along the entire stream (100%), and a clearcut to stream without a buffer (0%). The canopy cover was measured 1 meter above the stream surface with a spherical densiometer. The changes in canopy cover were distinguished from harvest effects and compared to unharvested reference sites by using a BACI design. For the FP treatment, mean canopy cover declined from 96% to 72% in the first-year post-harvest but continued to decline for 4 years to a minimum of 54%. In the 100% treatment mean canopy cover was more stable, decreasing from 94% to 88% in the first year and reaching a minimum of 82% also by year 4. Canopy cover began to increase after year 4 through year 9 in both treatments. In contrast, the reference sites experienced much smaller reductions in canopy cover from 95% to 89% in the first four years. The cause of mortality in the treatment sites was primarily attributed to windthrow. However, while post-harvest mortality in the treatment sites were higher on average than in the reference sites there was a high amount of variability between sites in both the treated and reference sites. For example, in the first 2 years following harvest mortality ranged from 1.8 to 34.6% (loss of basal area) between sites in the FP treatment. In contrast, mortality in the reference sites ranged from 1.1 to 20.4% (loss of basal area) during the same period.

Litter

Bilby & Heffner (2016) showed evidence that wind speed has a strong effect on the width of litter delivery areas within riparian areas. They used a combination of field experiments and simulation modeling to estimate the influence of different site factors (physiography, stand age, species composition, wind speed) on litter delivery into streams. Their results showed that litter travel distance was also linearly related to wind speed ($p < 0.0001$). Doubling wind speed at one site led to a 67-87% expansion of the riparian litter contribution zone in the study area. However, this study does not compare the differences in the influence of wind speed on the width of the litter contributing area between harvested and unharvested sites.

LW

Chapter 3 of the Hard Rock study compared changes in stand mortality and LW input from pre- to post-harvest and between treated and untreated reference sites. Results showed that by year 8, post-harvest mortality as a percentage of pre-harvest basal area was lower in the reference (16.1%) than in the 100% (24.3%) and FP (50.8%) treatments. The FP–Reference contrast in mortality was not significant 2 years post-harvest, but it was at 5- and 8-years post-harvest as mortality in FP increased relative to the Reference over time. The contrast in mortality between the 100% and Reference were not significant for any time interval 8 years post-harvest. Wind/physical damage was the primary cause of mortality for all treatments, including the Reference. In the 100% treatment it accounted for 78% and 90% of the loss of basal area and density (stem/ha), respectively; in FP it accounted for 78% and 65% of the loss. Wind accounted for a smaller proportion of mortality in the reference (52% and 43%, respectively).

LW recruitment to the channel was greater in the 100% and FP treatment than in the reference for each pre- to post-harvest time interval. Eight years post-harvest mean recruitment of large wood volume was two to nearly three times greater in 100% and FPB RMZs than in the references. Annual LW recruitment rates were greatest during the first two years, then decreased. However, there was a great deal of variability in recruitment rates within treatment sites and the differences between treatments were not significant. Mean LW loading into the channel (pieces/m of channel length) differed significantly between treatments in the magnitude of change over time. There was a 66%, 44% and 47% increase in mean large wood density in the 100%, FP and 0% treatments, respectively, in the first 2 years post-harvest compared with the pre-harvest period and after controlling for temporal changes in the references. By year 8, only the FP treatment showed a significantly higher proportional increase (41%) in wood loading when compared to the reference. In the time interval 2-8 years post-harvest wood loading in the 100% treatment stabilized.

Liquori (2006) investigated treefall characteristics within riparian buffer sites in a managed tree farm in the Cascade Mountains of western Washington. Buffer widths ranged between 25-100 feet along non-fish bearing and fish bearing streams. Results showed that within no-cut buffers, windthrow caused mortality was up to 3 times greater than competition induced mortality for 3 years following treatment with tree fall probability highest in the outer areas (closest to upland clearcuts) of the buffers. Their results showed that treefall was generally highest at the outside edges of buffers (50+ feet), representing about 60% of the total observed treefall, while the 0–25-foot zone represented ~18%, and the 25–50-foot zone represented ~22%. The researchers interpret these results as evidence that windthrow susceptibility within riparian buffers increases with increasing distance from the stream.

Martin & Grotenfendt (2007) compared riparian stand mortality and in-stream LW recruitment characteristics between riparian buffer strips with upland timber harvest and riparian stands of unharvested watersheds using aerial photography in the northern and southern portions of Southeast Alaska. All buffer strips in this study were a minimum of 20 m wide and included selective harvest within the 20 m zone (thinning intensity not specified or included in the analyses as an effect). The results from this study showed significantly higher mortality (based on cumulative stand mortality: downed tree counts divided by standing tree counts + downed tree counts by number/ha), significantly lower stand density (269 trees/ha in buffer units and 328 trees/ha in reference units), and a significantly higher proportion of LW recruitment from the buffer zones of the treatment sites than in the reference sites. Also, results showed that mortality varied with distance to the stream. Differences in mortality for the treatment sites were similar to the reference sites for the first 0-10 m from the stream (only a 22% increase in the treated sites). However, mortality in the outer half of the stream buffers (10-20 m) across treatment sites was more than double (120% increase) that observed within the reference sites. The authors estimate that windthrow mortality was twofold and fivefold greater in the inner and outer halves of the treatment buffers than in the reference buffers, respectively.

Bahuguna et al. (2010) evaluated the difference in windthrow caused mortality between 10 m, 30 m buffer widths (neither had thinning within the buffer and both had upland clear-cuts) and unharvested controls in the Coast Mountains, British Columbia. Following harvest, 11% of initially standing timber was blown down in the first and second years in the 10 m buffer, compared to 4% in the 30 m buffer, and 1% in the unharvested controls. However, after 8 years post-harvest, a significant amount of annual mortality occurred when winter storms brought down multiple trees in the unharvested control at 30%, compared to 15% in both 30 m and 10 m buffers. These results show evidence that timber harvest can increase windthrow caused mortality within protective buffers in the short term but can stabilize within a decade. Further, this study shows evidence that windthrow caused mortality is stochastic and large storm events can cause significant mortality within untreated riparian forests.

Schuett-Hames and Stewart (2019a) compared changes in stand mortality and LW recruitment between treated and untreated riparian areas along fish-bearing streams in eastern Washington. Treatments were prescribed under the Standard Shade Rule (SR), under the All-Available Shade rule (AAS), and unharvested reference sites. Both shade rules have a 30-ft no-cut buffer (core zone) immediately adjacent to the stream. The SR prescription allows thinning in the buffer zone 30-75 feet (inner zone) from the stream while the AAS prescription requires retention of all shade providing trees in this area. Thinning non-shade providing trees within the inner zone is allowed under the AAS rule. Results from a mixed model comparison showed that the frequency of wood input from fallen trees was significantly greater in SR group compared to both the reference and AAS groups ($p < 0.001$), while the difference between reference and AAS groups was not significant. Over 60% of pieces recruited from AAS and SR fallen trees consisted of stems with attached rootwads (SWAR), double the proportion in the reference sites. The reference-AAS and reference-SR differences in recruitment of SWAR pieces were significant ($p < 0.001$). The authors comment that the higher mortality and recruitment of LW in the SR sites was primarily due to windthrow.

Schuett-Hames et al, (2011) compared tree mortality and LW recruitment between treated and untreated riparian stands along non-fish bearing streams in western Washington. Treated sites were prescribed a 50-foot-wide no-cut buffer. Annual fall rates of live and dead standing stems combined were over 8 times (by % of standing trees) and 5 times (by trees/acre/yr) higher in the 50-foot buffers than in the reference buffers 3 years after treatment. These differences were significant for both metrics ($p < 0.001$). Over the entire five-year period, the percentages of standing trees that were uprooted and broken (as well as the combined total) were significantly greater in the 50-foot buffer. Wind was the dominant tree fall process, accounting for nearly 75% of combined fallen trees, 11% fell from other trees falling against them and 1.8% of fallen trees fell from bank erosion. Differences in mortality followed a similar pattern to tree fall rates. In the 50-foot buffer sites mortality rates were significantly higher (3.5 times higher) than in the reference sites for the first three years following harvest. However, in years 4-5 mortality rates increased in the reference buffers after high-intensity storms resulting in non-significant differences in mortality during this period. The cumulative percentage of live trees that died over the entire five-year period was 27.3% in the 50-ft buffers compared to 13.6% in the reference reaches, but the difference was not statistically significant. The authors suggest that the lack of significance was likely due to the high variability in mortality between sites in the 50-foot buffers.

In the follow-up study, Schuett-Hames & Stewart (2019b) reported that over a 10-year period, stand mortality in the 50-ft buffer treatment stabilized and showed a cumulative 14.1% reduction in live basal, while the reference stands showed a 2.7% increase in live basal area. The differences in these values were not significant. Cumulative LW recruited into stream channel over the 10-period was double in the 50-ft buffer treatment streams than in the reference streams.

In general, the studies reviewed above show evidence that upland timber harvest with riparian retention buffers initially increases stand mortality within the buffers and increases LW recruitment relative to unharvested reference stands in the short-term. Hence, treated riparian forests appear to have a higher susceptibility to windthrow caused mortality, at least in the short term, compared to untreated stands. Depending on the streams in question, an increase in LW could be considered a positive or negative impact This increase in mortality and LW recruitment is attributed to an increase in the susceptibility to windthrow within the riparian buffers relative to the unharvested controls. Further, multiple studies (Liquori, 2006; Martin & Grotefendt, 2007, Schuett-Hames & Stewart 2019a) showed evidence that the increase in windthrow caused mortality is highest in the outer area of the riparian buffers (area closest to upland treatments). There is some evidence that thinning within the buffer can also affect mortality rates, but these studies are few. In the three studies that collected post-harvest data for 8 or more years (Bahuguna et al., 2010; McIntyre et al., 2021; Schuett-Hames & Stewart 2019b), there is indication that mortality in the riparian buffers and annual LW recruitment into adjacent streams stabilizes within 5-10 years. However, in the subsequent decades following treatments with upland clearcuts there is evidence that LW recruitment rates can continue to decrease and in stream wood loads may become depleted before recruitment rates can recover (Nowakowski & Wohl, 2008; Reid & Hassan, 2020) depending on applied management practices (e.g., buffer widths, road construction, etc.). For example, Teply et al. (2007) used simulation modeling to estimate the effectiveness of Idaho Forest Practices for riparian buffers and found no significant difference between predicted LW loads for harvested and unharvested sites 30-, 60-, or 100-years post-harvest.

Nutrient

Vanderbilt et al. (2003) analyzed long-term datasets (ranging 20-30 years for each watershed) from six watersheds in the H.J. Andrews Experimental Watershed in the west-central Cascade Mountains of Oregon to investigate patterns in dissolved organic nitrogen (DON) and dissolved inorganic nitrogen (DIN) export with watershed hydrology. The researchers used regression analysis of annual N inputs and outputs with annual precipitation and stream discharge to analyze patterns. Their results showed that total annual discharge was a positive predictor of annual DON export in all watersheds with R^2 values ranging between 0.42 to 0.79. In contrast, relationships between total annual discharge and annual export of nitrate (NO3-N), ammonium (NH4-N), and particulate organic nitrogen (PON) were variable and inconsistent across watersheds. The authors speculate that different factors may control organic vs. inorganic N export. The authors emphasize the importance of analyzing data from multiple watersheds in a single climactic zone to make inferences about stream chemistry.

Yang et al. (2021) investigated the effects of drought and forest thinning operations (independently and combined) on stream water chemistry in the Mediterranean climate headwater basins of the Sierra National Forest. The effects of drought alone were examined by comparing water samples collected from control watersheds for 2 years before and 3 years after drought. The effects of drought and thinning combined were examined by comparing water samples collected from treated sites to reference sites for three years post-harvest (all drought years). Drought alone altered the concentration of dissolved organic carbon (DOC) in stream water. Volume-weighted concentration of DOC was 62% lower ($p < 0.01$) and the ratio of dissolved organic carbon to dissolved inorganic nitrogen (DOC:DON) was 82% lower ($p = 0.004$) in stream water in years during drought (WY 2013–2015) than in years prior to drought (WY 2009 and 2010). Drought combined with thinning altered DOC and DIN concentrations in stream. For stream water, volume-weighted concentrations of DOC were 66- 94% higher in thinned watersheds than in control watersheds for all three consecutive drought years following thinning. No differences in DOC concentrations were found between thinned and control watersheds before thinning. The authors conclude that their results showed evidence that the influences of drought and thinning are more pronounced for DOC than for DIN in streams.

Drought Frequency

Wise (2010) used reconstructed newly collected tree-ring data augmented with existing chronologies from sites at three headwater streams in the Snake River Basin to estimate streamflow patterns for the 1600-2005 time-period. Streamflow patterns derived from instrumental data and from reconstructed chronologies were compared with other streamflow previously reconstructions of three other western rivers (the upper Colorado, the Sacramento, and the Verde Rivers) in similar climates to examine synchronicity among the rivers and gain insight into possible climatic controls on drought episodes. The reconstruction model developed for the analysis explained 62% of the variance in the instrumental record after adjustment for degrees of freedom. Results showed evidence that droughts of the recent past are not yet as severe, in terms of overall magnitude, as a 30-year extended period of drought discovered in the mid-1600s. However, in terms of number of individual years of < 60% mean-flow (i.e., low-flow years), the period from 1977-2001 were the most severe. Considering the frequency of consecutive drought years, the longest (7-year-droughts), occurred in the early 17th and 18th centuries. However, the 5-year drought period from 2000-2004 was the second driest period over the 415-year period examined. The correlative analysis of the chronologies developed for the upper Snake River with other rivers of the West showed mixed results with periods of positive and negative correlations. The author interprets these results as evidence that drought frequency, in general, in this area appears to be increasing in severity and that mean annual flow appears to be reducing in the latter half of the 20th and the beginning of the 21st century. The exceptions being the 1930's dustbowl, and an unusually long dry period in the early 1600s.

Fire Frequency

Dwire & Kauffman (2003) in their reviewed and summarized the available conducted on fire regimes in forested riparian areas relative to uplands in the western United States. They summarized the distinctive features of riparian areas that can influence the properties of fire as (1) higher fuel loads because of higher net primary productivity, (2) higher fuel moisture content due to proximity to water, shallow water tables, and dense shade, (3) active channels gravel bars and wet meadows may act as fuel breaks, (4) topographic position (canyon bottoms, low point on landscape) leads to higher relative humidity, fewer lightning strikes, but more human-caused ignitions, (5) microclimate may lead to cooler temperatures and higher humidity that can lessen fire intensity and spread. They highlight a need for more extensive research on the history and ecological role of fire in the riparian areas of the western United States.

There is a logical assumption that fire in riparian zones would be less frequent than in adjacent uplands because of its proximity to water. However, several studies have been conducted which reconstruct historical fire regimes in riparian areas relative to adjacent uplands and have provided varying results. Everett et al. (2003) used fire-scar and stand-cohort records to estimate the frequency and seasonality of fire in Douglas-fir dominated riparian areas and adjacent uplands. They sampled sites along 49 stream segments on 24 different streams in the Wenatchee (33 segments) and Okanogan (16 segments) National Forests. The data collected allowed for reconstruction of fire occurrence back to 1896. Their results showed that the mean count of fire scars was significantly fewer in riparian areas than in adjacent uplands regardless of valley type, aspect, or plant association group. However, the difference between riparian and upland fire scars was greatest for western aspects and least for northern aspects. Also, the differences were greatest for the 'warm mesic shrub/herb' plant association group (e.g., common snowberry), and least in the cool dry grass plant association group (e.g., pinegrass, or elk sedge).

Prichard et al. (2020) evaluated drivers of fire severity and fuel treatment effectiveness at the 2014 Carlton Complex in north-central Washington State. While this study's objective does not specifically evaluate differences in fire severity between riparian and upland forests, it did evaluate differences in fire severity based on variations in topographic and vegetation type variables. One vegetation variable was classified broadly as “riparian vegetation” from the publicly available data set LANDFIRE. The authors used a combination of simultaneous autoregression and random forests approaches to model drivers of fire severity. In the study area's southern section (1 of 2 designated study areas), the results showed cover type was a significant predictor with negative correlations with fire severity in non-forest types and riparian forests.

Conversely, Olson & Agee (2005) provide evidence that fire return intervals in the riparian areas of the Umpqua National Forests, Oregon, may not have differed significantly from adjacent upland forests. They reconstructed historical fire return intervals from fire scar cross sections taken from 15 stream reaches and 13 paired upland forests. Sites were primarily dominated by Douglas-fir, western red cedar, and western hemlock. The number of fires per plot, maximum and minimum fire return intervals, and the Weibull median fire return interval (WMPIs) were compared between riparian and upland stands using the Wilcoxon signed rank test, the Mann-Whitney U-test for unmatched samples, and the Kruskal-Wallis one-way analysis of variance. The results showed that between 1650 and 1900, 43 fire years occurred on 80 occasions. Of these 80 occasions, 33 were recorded in the riparian and adjacent upslope forest, 23 were recorded in only the riparian area, and 24 were recorded only in the upland forests. The riparian WMPIs were somewhat longer (ranging from 35-39 years, with fire return intervals ranging from 4-167 years) than upslope WMPIs (ranging from 27-36 years, with fire return intervals ranging from 2-110 years), but these differences were not significant. The authors, Olson & Agee (2005), interpret these results as evidence that fires in this area were likely patchy and smaller in scale with a high incidence of fires occurring only in the riparian area or only in the upland forests, and less commonly in both. The authors also suggest that fire is a natural occurrence in the riparian areas of this area and should be restored to protect riparian forest health.

Another study from the Klamath Mountains in northern California showed evidence that fires in riparian forests may have been more frequent than in adjacent upland forests (Skinner, 2003). Skinner (2003) used dendrochronological methods to construct fire return intervals for 5 riparian and adjacent upland forests sites, each between 1-2 hectares. Because of the small sample size, statistical analysis was not conducted, and their results are only descriptive. The ranges of fire return intervals (FRIs) were similar between riparian and upland forests. However, the median FRI for the riparian forests was nearly double that in adjacent uplands. The authors conclude that these limited data suggest fire in the riparian areas may be more variable than in the uplands in frequency and intensity.

Yet, another study from Harley et al. (2020) showed evidence that the differential fire occurrence riparian and adjacent uplands may have been dependent on weather (i.e. drought). Harley et al. (2020) reconstructed low-severity fire histories from tree rings in 38 1-ha plots. This data was supplemented with existing fire histories from 104 adjacent upland plots. 2633 fire scars were sampled from 454 (127 riparian; 329 upland) trees from two sites in the Blue Mountains in north-eastern Oregon: One in the Wallowa-Whitman (WWNF) and one in the Malheur (MNF) National Forests. Fire-scar dates were used to construct plot composite fire chronologies, excluding fire dates recorded from only one tree. These were used to compute median fire intervals for riparian and upland forests for each site and for both sites combined. A mixed linear model with fire interval as a response and plot type (riparian vs. Upland) as a predictor was used to check for statistical difference in fire frequency. The influence of climate on fire occurrence was inferred by assessing whether the summer Palmer Drought Severity Index (PDSI) differed significantly during the fire year or preceding or following years (-3 to +1 years) using superimposed epoch analysis. Results showed that Fires burned synchronously in riparian and upland plots during more than half of the fire years at both WWNF and MNF (55%and57%, respectively). At WWNF, fires burned during 65 years of the analysis period (1650–1900); 36 burned in both riparian and upland plots, 7 burned only in riparian plots and 22 burned only in upland plots. At MNF, fires burned during 74 years of the analysis period; 42 burned in both riparian and upland plots, 3 burned only in riparian plots and 29 burned only in upland plots. At both sites, average PDSI was significantly warm–dry during synchronous fire years. However, climate was not significantly cool–wet during non-synchronous fire years at either site. The authors interpret these results as evidence that historical synchronized fire occurrence was more likely during excessively dry or drought years.

There is also evidence that riparian forest fire regimes have been altered in many areas from pre-Euro-American settlement due to fire suppression. Messier et al. (2012), used dendro-ecological methods to reconstruct pre-Euro-American settlement riparian forest structure and fire frequency for comparison of changes post-settlement in the Rouge River of southwestern Oregon. Fire events were dated from increment cores and fire-scar cross-sections back to the year 1600, approximately. Changes in annual radial growth rates were used to infer changes in stand density over time. Results showed the age distribution prior to 1850 followed a pulse pattern of recruitment with recruitment peaks occurring around 1850, 1800, and between 1740-1770 (though this pulse was difficult to discern because the sample size of trees established prior to 1740 were relatively few). After 1900, many mixed conifer sites showed a dramatic increase in the recruitment of more more-shade tolerant white fir (*Abies concolor)* compared to Douglas-fir (*Pseudotsuga menziesii).* White fir comprised 51% of the live trees recruited after 1900, but only 18% of the live trees before 1900. Results from the 26 cross-dated fire scars spanned from 1748 – 1919 with the highest number of detected fires occurring in the early-settlement period (1850-1900). The authors interpret these results as evidence that fire suppression over the last century has changed the successional pathway and stand structure of riparian forests in this area.

Van de Water & North (2011) found similar results from their study in the northern Sierra Nevada. They compared current field data with reconstructed data to estimate changes in stand structure, fuel loads, and potential fire behavior over time. Additionally, they estimated how these conditions for riparian forests compared to adjacent upland forests during the reconstructed and current periods. Data for current forest structure, species composition, and fuel loads were collected from 36 adjacent riparian and upland sites (72 sites total). The reconstruction period was set at the year of the last fire (ranging from 1848 – 1990), determined from fire-scar records. Potential fire behavior, effects, and canopy bulk density were estimated for current and reconstructed stand conditions for riparian and upland sites using Forest vegetation Simulator (FVS). Stand structure (BA, stand density, snag volume, QMD, average canopy base height), species composition, fuel load, potential fire behavior, canopy bulk density, and mortality were compared between current and reconstructed periods for riparian and upland sites, and between sampling areas (riparian vs. Upland) with an analysis of variance (ANOVA). Results showed that under current conditions, riparian forests were significantly more fire prone than upland forests, with greater stand density (635 vs. 401 stems/ha), probability of torching (0.45 vs. 0.22), predicted mortality (31% vs. 16% BA), and lower quadratic mean diameter (46 vs. 55 cm), canopy base height (6.7 vs. 9.4 m), and frequency of fire tolerant species (13% vs. 36% BA). However, the reconstructed periods showed no significant difference between riparian and upland forests for fuels and structure. The authors suggest that these results provide evidence that the historic fire return intervals may not have differed significantly between riparian and upland forests in this area.

Fire Effects on Function

Litter and Nutrients

Musetta-Lambert et al. (2017) compared changes in leaf-litter inputs into streams following adjacent riparian forest harvesting or wildfire to reference sites. This study took place in the boreal forest of the White River Forest management Area in Ontario, Canada, ~75 km inland from the northern shore of Lake Superior. This study is outside of western North America (the focal area for this review), but it is the only study found that provides experimental evidence of wildfire's effects on litter inputs. The study sites consisted of ~50 m reaches in 25 catchments, 10 that were harvested, 7 that experienced wildfire, and 8 references. Of these reaches a subset was used to riparian forest structure, leaf litter inputs, and water chemistry (5 harvest, 7 fire, 6 reference). The harvested catchments were harvested 7-17 years prior to the study (minimum 30 m riparian buffers; specific harvest rules/methods not described). The wildfire catchments had burned 12 years prior to the study and had no dead material removed. The reference catchments had no fire or harvesting for a minimum of 40 years. Water grab samples were collected in September, October and November 2010, and May, June and September of 2011 from the study reaches.

Water samples were analyzed to obtain measurements for pH, conductivity, dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) concentrations, soluble reactive phosphorous (SRP), along with a suite of other major elements and nutrient measurements (total N, NH4, total P, Ca, K, Mg, etc.). Vertical leaf litter traps consisting of plastic bins were placed at 10 locations along the bankfull width of each site. Lateral leaf fall was not collected or analyzed. Leaf litter inputs were focused on leaves from deciduous trees and shrubs. Leaves were separated to the lowest possible taxonomic level, dried and weighed for analysis.

Univariate one-way ANOVA models were used to determine differences in water chemistry, riparian forest characteristics of juvenile tree and shrub communities (richness, Shannon's diversity index, relative occurrence of individual taxa), mature tree communities (total basal area, stem density), and litter subsidies (richness, mass input). Results for water chemistry showed that Conductivity, pH, and dissolved inorganic carbon were significantly higher at fire sites than at reference sites ($p = 0.02$, $p = 0.04$, $p = 0.03$, respectively) but did not differ between harvested and fire sites or harvested and reference sites.

Results for stand structure showed there was significantly higher taxa richness in fire sites than in reference sites or harvested sites ($p = 0.04$). Taxa richness did not differ significantly between reference and harvested sites. Reference sites had significantly higher total mean densities (# ha -1) of mature riparian trees (>10 cm DBH) than fire ($p < 0.001$) and harvested sites ($p = 0.036$). Total mature tree densities in reference sites were 1.7x and 4x higher than in harvested and fire sites, respectively. 3.3. Leaf litter subsidies Taxa richness in leaf litter subsidies did not significantly differ among disturbances ($p = 0.477$). Total leaf litter input (g m^{-1}) significantly higher at fire sites than at harvest ($p = 0.02$) or reference sites ($p = 0.02$). Fire sites had significantly greater leaf litter inputs of willow spp. ($p = 0.0002$, 0.006, respectively), Atlantic ninebark ($p = 0.002$, 0.003, respectively) and speckled alder ($p = 0.02$, 0.04, respectively) than in both reference and harvested sites. The authors interpret these results as evidence that natural fire disturbance in low-order boreal forest streams had higher leaf litter inputs, and different stand structures and composition than harvested or untreated riparian stands. They suggest that while harvested stands were more structurally similar to fire affected stands than reference stands, the future implementation of these treatments should intend to emulate the patchy nature of wildfire disturbance. This would enhance the diversity of riparian forest structure and increase litter subsidies into streams.

Nutrients

Rhoades et al. (2011) monitored stream chemistry and sediment 1-year before and for 5-years after the 2002 Hayman Fire in Colorado. Monthly water samples were collected from streams in three burned and three unburned watersheds. Pre-fire and post-fire water nitrate, cation concentration (Ca^{2+}, Mg^{2+}, K^{+}), acid neutralizing capacity (ANC) and turbidity were compared graphically and statistically between the three burned and unburned basins. Results for cation concentrations and ANC showed an immediate and significant increase that peaked during the 4-month period following the fire. The Ca^{2+} concentrations, ANC, and conductivity remained elevated in the burned streams for 2 years compared to pre-fire conditions, and unburned streams. Stream water nitrate and turbidity increased linearly with the proportion of a basin burned or burned at high severity. No other chemical analyte showed a significant response to fire severity or extent. Streams draining basins affected by extensive stand-replacement fires showed a 3.3-fold higher ($p =0.000$) nitrate concentration than basins that burned less. Also, turbidity was 2.4-fold ($p = 0.000$) higher average turbidity compared to streams in basins burned less severely or extensively. In the extensively burned basins, stream water nitrate concentrations did not decline over the five years of the study and the mean concentrations of nitrate in the fifth year did not differ from the fourth year. The authors conclude that wildfire can have immediate and mid-term (up to 5 years) impacts on water chemistry and turbidity. Further, the magnitude and temporal increases of nitrate and turbidity, specifically, have a positive relationship with burn severity and extent.

Son et al. (2015) compared stream water samples before and after an intense wildfire in the Cache la Poudre River basin in Colorado. Stream water samples for total phosphorus (TP) and total nitrogen (TN) were collected over 2 years (2010 – May 2012) before the fire in June 2012. Two post-fire water samples were taken: 1) immediately following containment of the fire (July

4, 2012) and 2) twelve days after the fire was contained (July 16, 2012). For each pre- and post-fire sampling date water samples were collected at three randomly selected points at two sites. Riverbed sediments were also collected at each site and sieved through a 2 mm sieve to capture the geochemically reactive portion of the riverbed. The pre- and post-fire sediment and stream water quality were compared with t-test. Correlations of sediment and stream water quality with other factors (e.g., stream temperature, precipitation, streamflow) were evaluated with a Pearson's correlation at 0.05 and 0.1 significance levels. Results for turbidity showed no significant differences between pre- and post-fire ranges immediately following fire. However, after the first post-fire rainfall (2.5 mm) nephelometric turbidity ranged from 113.6 - 2099.4 NTU (mean = 641.62 NTU), a considerable increase from pre-fire data (mean 11.3 NTU), and post-fire data before rainfall (47.3 NTU). Post-fire aqueous TP and TN loads ranged from 30.5 - 56,086 and 45.4 - 1203 kg/day, respectively, and were significantly higher than pre-fire values (390 and 6 times higher than pre-fire values for TP and TN, respectively). The authors note that this is likely due to the transport and input of ash into the stream. After the first rainfall, all forms of P were significantly higher than pre-fire concentrations, such as soluble reactive phosphorus (SRP; $p = 0.000$), dissolved organic phosphorus (DOP; $p = 0.009$), and particulate phosphorus (PP; $p = 0.02$). Riverbed sediment equilibrium P concentrations increased significantly ($p = 0.007$) from pre- to post-fire in all sites. The authors conclude that this study shows evidence that stream TP and TN, and riverbed sediment TP all increased significantly after the first rainfall, post-fire. They further suggest that the effects of wildfire on riverbed sorption mechanisms are very complex but further research would be valuable because fire impacted sediments highly concentrated P can become a long-term source of P.

LW

Bendix & Cowell (2010) investigated the effects of fire and flooding on LW input in two tributaries of Sespe Creek (Potrero John Creek and Piedra Blanca Creek) in the Los Padres national Forest in southern California. Both sites were located within the perimeter of the Wolf Fire that burned in June of 2002. Extensive flooding in the area occurred during January and February of 2005. The study area is characterized by chapparal dominated communities and a Mediterranean-type climate. While there is a scarcity of trees in the uplands, the riparian areas contained substantial growth of *Alnus rhombifolia* (white alder), *Populus fremontii* (Fremont cottonwood), *Quercus agrifolia* (coast live oak), *Quercus dumosa* (scrub oak) and *Salix* sp. (willows) on the valley floors. Thus, any change in in-stream or riparian area LW was sourced exclusively from the riparian area. Data for LW and standing live and dead stems in the riparian area were collected in July, of 2003 (1-year pre-fire) and again in July of 2005 (3-years post-fire, 5-6 months after flood events). This data was used to answer 4 questions: 1) How many of the burned snags fell during this time, and what was the species composition?, 2) Did snags differ by species or size in the rate at which they fell?, 3) How did flooding after the fire affect the rate at which snags fell?, 4) How did flooding affect the mobilization of fallen snags? Questions 1 was analyzed by comparing descriptive data (i.e., no statistical analysis). A t-test was used to compare mean diameter of standing and fallen stems (question 2). T-tests were also used to analyze differences in mean flow depth for standing vs. fallen snags and for fallen snags still present vs. snags that had been transported after flooding (questions 4 and 5). Results showed high post-fire mortality (94%) with 339 of 362 stems killed. By 2005, 57 of the 339 snags had fallen (16.8%). The majority of fallen stems were either *Alnus* or *Salix* species. Standing snags varied in size from 3 cm to 69.2 cm, whereas those that had fallen ranged from3 cm to 33 cm. Among the fallen snags, those <10 cm were not proportionate to the overall numbers, whereas snags between 10 cm and 30 cm were disproportionately likely to fall. While fewer snags in the larger size classes the mean diameter of fallen snags was larger than the mean diameter of standing snags (11.4±10.9 cm vs. 11.0±8.0 cm) and did not differ significantly. The mean flood depth for fallen snags (1.05±0.68 m) was significantly greater than those still standing (0.40±0.56 m; $p < 0.0001$, n=339). The three species experiencing no snagfall at all (*Abies glauca*, *Rhamnus californica* and *Quercus agrifolia*) occurred only in higher quadrats, which had experienced virtually no flooding. Of the 57 snags that had fallen by July 2005, 43 (75%) were gone from the quadrats in which they had been recorded in 2003. The snags that had been mobilized were from quadrats that had experienced deeper flood depths (1.14±0.69 m) than those that had remained. (0.80±0.62 m), but the difference is insignificant. The authors interpret these findings as an indication that short-term rates of snagfall following wildfire are influenced by the species composition of burned stems and by post-fire flood depth. Thus, although wildfire resulted in many burned snags across the valley floor, the rate at which these stems are recruited into the fluvial system as woody debris varies by the ecological characteristics and the geomorphic setting.

Focal Question 4

4. How do various treatments within riparian buffers relate to forest health and resilience to fire, disease, and other forest disturbances?

While there are several studies that discuss the frequency, dynamics, or potential for disturbances, especially fire, in riparian areas of the western United States (Dwire & Kauffman, 2003; Everett et al., 2003; Merschel et al., 2014) there is a dearth of studies that investigate how treatments within the riparian area or in riparian buffers relate to the riparian area's resilience to disturbance. No studies found in our literature search and review were suitable for providing direct experimental evidence of the effects of riparian buffer treatments on riparian health and resilience to disturbance except for several studies that provide evidence that riparian harvest treatments have the potential to increase susceptibility to windthrow caused mortality. Post-harvest changes in windthrow susceptibility are discussed in focal question 3.. One study used simulation modeling to estimate changes in health and susceptibility to disturbance with and without treatment.

Ceder et al. (2018) used Forest Vegetation Simulator (FVS) to predict how treatment along fish-bearing streams of eastern Washington affects riparian stand health and susceptibility to insects, disease, and crown fire. The projected changes in susceptibility were produced for the low- and mid-elevation regulatory zones for timber harvest. Models were run for 50 years with and without application of prescribed treatments. Prescriptions for these zones include a buffer width of 75-130 ft depending on stream width category. For all treatments, no harvest is allowed within the first 30 feet from the bankfull channel. Timber harvest is allowed in the remaining width of the buffer but must meet a minimum basal area based on the regulatory zone. The authors report high variability in the data and the outputs of each modeling scenario. However, they report that overall, as riparian zone growth was simulated with and without management, tree size and stand density increased, along with some increases in insect and disease susceptibility and potential fire severity without management and decreases with management.

Focal Question 5

5. How do the functions provided by riparian stands change over time (e.g., large woody debris recruitment from farther away from the stream)?

This question addresses the effect of time on riparian function. While harvest is not specified as a factor, studies that quantify changes to riparian function in harvested reaches have been included. Studies that compare differences in one or more functions between comparable sites in different successional stages (i.e., different mean age) are also included. Papers that investigate the changes in LW source distance following harvest have been included because of the given example (*large woody debris recruitment from farther away from the stream).*

Shade

Kaylor et al. (2017) compared canopy cover throughout stream networks adjacent to old-growth (> 300 years old) and mid-successional (50-60 years old) Douglas-fir dominated forests in the H.J. Andrews Experimental Forest in the Cascade Mountains of Oregon. Canopy openness was quantified with a handheld spherical densiometer. Data was supplemented with a review of literature studies conducted in the Pacific Northwest that reported stand age and canopy cover over the stream. The combined datapoints for canopy openness (%) were plotted against stand age and fit with a negative exponential curve. From the slope of the curve, the authors estimate that canopy openness reaches its minimum value in regenerating forests at ~30 years and maintains with little variability until ~100 years. Mean canopy openness in stands 30-100 years old was 8.7% with a range from 1.2 to 32.0% (standard deviation = 5.7). Canopy openness over streams in old-growth forests averaged 18.0% but was highly variable and ranged from 3.4 to 34.0% (standard deviation = 5 7.9).

Warren et al. (2013) compared canopy cover between old-growth-forests (>500 years old) and young second-growth stands (~40-60 years old) in the H.J. Andrews Experimental Forest in the Cascade Mountains of Oregon. Canopy cover was estimated using a convex spherical densiometer. Streams were paired based on reach length, bankfull width, and north (n =2), vs. south (n=2) facing watersheds. Results showed significant differences in percent forest cover between old-growth and second-growth reaches in both south-facing watersheds in mid-summer ($p < 0.10$). For the north-facing watersheds, differences in canopy cover and light availability ($p < 0.10$) were only significant at 1 of the two reaches. Overall, three of the four paired old-growth reaches had significantly lower mean percent canopy cover. The authors interpret these results as evidence that old-growth forest canopies were more complex and had more frequent gaps.

Litter

Kiffney & Richardson (2010) compared changes in litter input between riparian harvest prescriptions that included clear-cut to stream edge, 10 m wide buffer reserve, 30 m buffer reserves, and an uncut control over the course of 8 years. No thinning was applied within the reserves. Upland treatment at all sites applied clearcut. Results showed differences in litter flux relative to riparian treatment persisted through year 7, while a positive trend between reserve width and litter flux remained through year 8. Needle inputs remained 6x higher in the buffer and control sites through year 7, and 3-6x higher in year 8 than in the clearcut sites. Twig inputs into the control and buffered sites were ~25x higher than in the clearcut sites in the first year after treatment. The linear relationship between reserve width and litter inputs was strongest in the first year after treatment, explaining ~57% of the variation, but the relationship could only explain ~17% of the variation in litter input by buffer width by year 8 (i.e., the relationship degraded over time). The authors interpret these results as evidence that litter flux from riparian plants to streams, was affected by riparian reserve width and time since logging.

Bilby & Heffner (2016) used linear mixed effects models developed for young and old-growth forests of western Washington to estimate controls on litter delivery. Litter samples were released from canopy height at one old-growth forest site and one young forest site. The mean age of "mature" and "young" sites was not specified but the mean tree heights were 47.0 m and 32.4 m for the mature and young sites, respectively. Results showed that needles released at mature sites had a higher proportion of cumulative input from greater distances than needles or alder leaves released at younger sites. The model estimated that the width of the contributing area for needles was ~35% greater at older sites than at younger sites.

Source distance curves for LW

Schuett-Hames & Stewart (2019a) compared differences in LW recruitment between riparian management zones harvested under the current standard Shade Rules (SR), the All-Available Shade Rule (AAS), and unharvested references for fish-bearing streams in the mixed conifer habitat type (2500 - 5000 feet elevation) for eastern Washington. Both shade rules have a 30-ft no-cut buffer (core zone) immediately adjacent to the stream. The SR prescription allows thinning in the buffer zone 30-75 feet (inner zone) from the stream while the AAS prescription requires retention of all shade providing trees in this area. Results showed that cumulative wood recruitment from tree fall after the five-year post-harvest interval was highest in the SR group, lower in the AAS group and lowest in the REF group. The SR and AAS LW recruitment rates by volume were nearly 300% and 50% higher than the REF rates, respectively. Wood recruitment in the SR sites was significantly greater than in the AAS and reference sites. Conversely, differences in wood recruitment did not differ significantly between the AAS and reference sites. Considering the source distance of post-harvest recruited LW, most recruited fallen trees originated in the core zone (76%, 72%, and 64% for the REF, AAS and SR groups, respectively), while the proportion from the inner zone (30–75 feet from the stream) was ~10% greater for the SR group compared to the AAS and REF groups. These results provide evidence that the thinning treatments applied in the inner zone of the SR treatment changed the spatial pattern (source distance) of wood recruitment from fallen trees within 5 years post-harvest.

Burton et al. (2016) examined the relationship between annual in-stream wood loading and riparian buffer widths adjacent to upland thinning operations. Buffer widths were 6, 15, or 70 meters and upland thinning was to 200 trees per ha (tph), with a second thinning (~10 years later) to ~85 tph, alongside an unthinned reference stand ~400 tph. Data for LW in streams were collected for 6 years (5 years after the first harvest and 1 additional year after the second harvest). The results showed that between 82-85% of the wood with discernable sources (90% for wood in early stages of decay; 45% of wood in late stages of decay) came from within 15 m of the stream, and the relative contribution of wood to streams declined rapidly with increasing distance.

Martin & Grotenfendt (2007) compared riparian stand mortality and in-stream LW recruitment characteristics between riparian buffer strips with upland timber harvest and riparian stands of unharvested watersheds using aerial photography. All buffer strips in this study were a minimum of 20 m wide and included selective harvest within the 20 m zone (thinning intensity not specified or included in the analyses as an effect). The results showed significantly higher mortality (based on cumulative stand mortality: downed tree counts divided by standing tree counts + downed tree counts), significantly lower stand density (269 trees/ha in buffer units and 328 trees/ha in reference units), and a significantly higher proportion of LW recruitment from the buffer zones of the treatment sites than in the reference sites. LW recruitment based on the proportion of stand recruited (PSR) was significantly higher in the buffered units compared to the reference units. However, PSR from the inner 0-20 m was only 17% greater in the buffer units than in the reference units; while PSR of the outer unit (10 – 20 m) was more than double in the buffered units than in the reference units. From their analysis they also estimate that future potential supply of LW is diminished by ~10% in the buffered sites compared to the reference sites.

LW and stand age

Jackson and Wohl (2015) compared in-stream wood loads between old-growth (> 200 years) and young forests (age not reported). This study took place within the Arapaho and Roosevelt National Forests in Colorado. In-stream wood loads (m^3/ha) were recorded for reaches in 10 old-growth forests and 23 young forests. Paired t- test or Kruskall-Wallis tests were used to check for significant differences in wood load. Results indicated that channel wood load (OG = 304.4 + 161.1; Y = 197.8 + 245.5 m3 /ha), floodplain wood load (OG = 109.4 + 80; Y = 47.1 + 52.8 m3 /ha), and total wood load (OG = 154.7 + 64.1; Y = 87.8 + 100.6 m3 /ha) per 100 m length of stream and were significantly higher in streams of old-growth forests than in young forests. Streams in old-growth forests also had significantly more wood in jams, and more total wood jams per unit length of channel than in younger forests (jam wood volume: OG = 7.10 +/- 6.9 m3; Y = 1.71 +/- 2.81 m3)

Nutrient dynamics over time

Vanderbilt et al. (2003) investigated long-term datasets (ranging from 20-30 years) from six watersheds in the H.J. Andrews Experimental Watershed (HJA) in the west-central Cascade Mountains of Oregon. Their objective was to characterize long-term patterns of N dynamics in precipitation and stream water at the HJA. Patterns between nitrogen with precipitation and discharge were analyzed with logistic regression. Results showed that dissolved organic nitrogen (DON) concentrations increased in the fall in every watershed. The increase in concentration began in July or August with the earliest rain events, and peak DON concentrations occurred in October through December before the peak in the hydrograph. DON concentrations then declined during the winter months. However, other forms of N showed inconsistent patterns across all other watersheds. The authors conclude that total annual stream discharge was a positive predictor of DON output suggesting a relationship to precipitation. Also, DON had a consistent seasonal concentration pattern. All other forms of N observed showed variability and inconsistencies with annual and seasonal stream discharge. The authors speculate that different factors may control organic vs. inorganic N export. Specifically, DIN may be strongly influenced by terrestrial or in-stream biotic controls, while DON is more strongly influenced by climate. Last, the authors suggest that DON in streams may be recalcitrant, and largely unavailable to stream organisms.

Focal Question 6

6. Are there feedback mechanisms (e.g., microclimate changes within the riparian buffer) related to forest management that affect the recovery rates of riparian functions?

The studies considered appropriate for answering this question are those that quantify how forest management practices impact one or more factors that can in-turn impact the rate of recovery of riparian function. The regeneration, growth and development of vegetation within the riparian area following treatment can impact the rate of recovery of litter inputs, shade, sediment and nutrient filtration. Reduction in shade may affect the amount of light reaching the forest understory that then could impact productivity in the riparian area. Also, disturbance of soil and removal of vegetation during riparian management operations can impact streamflow and sediment supply, which in turn impacts sediment flux into streams. The studies summarized below provide experimental evidence in how these factors (e.g., vegetation productivity, streamflow discharge, sediment disturbance) are impacted by management.

However, considering the second part of this question on how these feedback mechanisms affect the recovery rates of riparian function can only be inferred. To properly answer the full question a study would require an experimental design which 1) tracks the changes in site conditions (e.g., microclimate, light availability to groundcover, exposed soil…) after treatment relative to untreated stands, 2) evaluates how these changes in site conditions lead to changes in stand development that can then impact function (e.g., vegetation), and finally 3) how these changes in development affect the recovery rates of function. This third step would require separating out the effect of these “feedback mechanism” so that the differences in recovery rates in treated stands with and without these effects (e.g., blocking newly available light to the understory) can be compared quantitatively. No studies that specifically, and entirely address these 3 objectives collectively could be found in the literature. Thus, the following reviewed studies provide evidence of how feedback mechanisms can affect function (e.g., increased light = increased primary productivity), but how these mechanisms affect the recovery rates of any particular function (e.g., timing of recovery with and without the feedback mechanism) can only be assumed.

Litter

Yeung et al. (2019) simulated post-harvest responses to leaf-litter derived coarse particulate organic matter (CPOM) quantity in a coastal rainforest stream in British Columbia. This study used a CPOM model that was calibrated using data from multiple published studies from, primarily the Pacific Northwest region, and several other North American regions. Calibration data included stream flow and temperature, and CPOM following different timber harvest intensities within 4 years of harvest. The model used estimated litterfall decreases of (-10%, -30%, -50%, -90%) for low, moderate, high, and very high basal area removal ; peak streamflow increases of +20%, +40%, +100%, +300%); and stream temperature increases of +1°C, +2°C, +4°C, and +6 °C. Treatment intensities in litterfall, peak flow, and stream temperature were modeled and analyzed individually and cumulatively to estimate their relative and combined effects on in-stream CPOM standing stocks. Results of the model showed that, in general, the standing stocks of CPOM decreased under the independent effects of reduced litterfall and elevated peak flows and increased with higher stream temperatures.

Along the gradient of increasing timber removal, litterfall reductions on depleting CPOM standing stocks were at least an order of magnitude greater than those of elevated peak flows. The magnitude of CPOM changes induced by litterfall reductions was consistently greater than stream temperature increases, but their differences in magnitude became smaller at higher levels of disturbance severity. Only the effects of litterfall-temperature interactions on CPOM standing stocks were significant ($p < 0.001$). The authors interpret these results as evidence that litterfall reduction from timber harvest was the strongest control on in-stream CPOM quantity for 4 years post-harvest. However, the authors propose that the decreased activity of CPOM consumers caused by increasing stream temperatures may be enough to offset the loss of litterfall inputs on standing CPOM stocks. The caveat of this study is that it did not include LW dynamics in preserving CPOM post-harvest. There is evidence that in-stream LW can act as a catchment for CPOM (May & Gresswell, 2003; Richardson et al. 2007).

Sediment

Safeeq et al. (2020) analyzed a long-term data set to changes in streamflow, and suspended sediment load and sediment bedload in streams between two watersheds; one with a history of timber management and one with no history of timber management. The two watersheds were located in the H.J. Andrews Experimental Forest and were paired by size, aspect, and topography. The treatment watershed was 100% clearcut during the period from 1962-1966, broadcast burned in 1966, and re-seeded in 1968. Streamflow and sediment data were taken intermittently; suspended sediment data after large storm events between 1952 (pre-harvest) and 1988; and sediment bedload in 2016. The researchers used a reverse regression technique to evaluate the relative and absolute importance of changes in streamflow versus changes in sediment supply from timber harvest on sediment transport. There were no significant changes in precipitation patterns before or after harvest. The results for post-treatment sediment yields showed suspended load declined to pre-treatment levels in the first two decades following treatment and bedload remained elevated, causing the bedload proportion of the total load to increase through time. Changes in streamflow alone account for 477 Mg/km2 (10%) of the suspended load and 113 Mg/km2 (5%) of the bedload over the post-treatment period. Increase in suspended sediment yield due to increase in sediment supply from timber harvest activities was 84% of the measured post-treatment total suspended sediment yield. The authors estimate that following harvest, changes on streamflow alone was estimated in being responsible for < 10% of the resulting suspended sediment transported into streams, while the increase in sediment supply due to harvest disturbance was responsible for >90%. Thus, while timber harvest-induced increases in streamflow does increase sediment transport, it is negligible compared to the increase in sediment source created from management practices.

Litschert & MacDonald (2009) investigated the frequency of sediment delivery pathways in riparian management areas and their physical characteristics and connectivity following harvest. In this study the authors describe sediment delivery pathways ("features") as rills, gullies, and sediment plumes that form when excess sediment relative to overland flows transports sediment from the hillslope to the stream. The authors surveyed 200 riparian management areas (RMA) in four different National Forests of the Sierra Nevada and Cascade Mountains of California. USFS policy requires 90-m wide RMA along each side of perennial streams and 45-m wide RMA along each side of all ephemeral and intermittent streams. When features were found within an RMA, data for years since harvest, soil depth, soil erodibility (K), feature length, feature gradient, aspect, elevation, hillslope gradient, hillslope curvature, surface roughness, and connectivity were recorded for analysis. Association between these variables were analyzed with a Spearman's rank correlation. The variables most strongly associated with feature length were used to develop a multiple linear regression model to predict feature length. Only 19 of the 200 harvest units had sediment development pathways. Feature pathways ranged in age (time since harvest) from 2 to 18 years, and in length from 10 m to 220 m. Of the 19 feature pathways, only six were connected to streams, and five of those originated from skid trails. Feature pathway length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient ($R^2 = 64\%$, $p = 0.004$). The authors conclude that in general, USFS riparian forest harvest practices are effective in reducing the development of sediment delivery pathways. They also interpret these results as evidence that skid trails should be directed away from streams, maintain surface roughness, and promptly decommissioned.

Impacts on Microclimate

Anderson et al. (2007) compared changes in understory microclimate above the stream, within the channel, and within the riparian area between thinned and unthinned riparian stands. The focus of this study was on second-growth (30- to 80-year-old) riparian Douglas-fir forests along headwater streams in the western Oregon Coast and Cascade Range. Stands were either thinned to approximately 198 trees per acre (TPA) or were left unthinned and ranged from 500-865 TPA. Streams within treated stands were surrounded by buffers of either 1) one site-potential tree averaging 69 m (B1, B1-T thinned and unthinned respectively), 2) variable width buffer averaging 22 m (VB, and VB-T), or 3) streamside retention buffer averaging 9 m (SR, and SR-T). Further, directly adjacent randomly selected B1-T and VB-T buffers patch openings (0.4 ha) were created (B1-P, VB-P). Microsite and microclimate responses were repeat sampled for each treatment and compared with untreated stands (UT). Within the riparian buffer zones, daily maximum temperatures were higher in all treated stands when compared to UT stands. The differences in daily maximum temperatures between treated and untreated stands ranged from 1.1°C (B1) to 4.0°C (SR-T), but the difference was only significant in one SR-T stand. Daily maximum air temperature within buffer zones adjacent to patch openings were 3.5°C higher than in UT stands. Within patch openings daily maximum temperatures were on average 6 to 9°C higher than in UT stands. Soil temperature changes were only evident within patch openings ranging from 3.6 - 8.8°C higher than in UT stands. VB-T buffers that were 15 m wide or wider exhibited changes in daily maximum air temperature above stream centers <1°C and daily minimum relative humidity <5% lower than in untreated stands. The authors conclude that in general, thinned stands are warmer and drier than unthinned stands. However, the results for differences in microclimate were only significant in narrow (9 m) thinned buffers and patch openings.

Anderson & Meleason (2009) conducted a companion study to Anderson et al. (2007) and compared changes in small (5-29 cm diameter) and large (≥30 cm diameter) downed wood abundance and understory vegetation between treated and untreated stands 5 years after harvest. Treatments compared were the same as those described in Anderson et al. (2007) discussed above. The results for small and large downed wood were highly variable between pre- and post-harvest periods and between treatments but the authors speculate from trends in the data that both wood and vegetation responses within buffers ≥15 m wide were insensitive to treatments. The strongest contrast in rate of change in herb cover was between the SR-T and VB-T buffers with higher herbaceous cover in the SR-T buffers and highest in SR-T buffers adjacent to patch openings. The authors conclude that in general these thinning treatments only led to subtle changes in understory vegetation cover and composition. Because of the high variability in responses among and between treatments significance could not be confirmed. The authors further conclude that a better functional understanding of the changes in ecological processes associated with changes in habitat characteristics following changes in understory wood and vegetation cover is needed to help discern ecological significance.

Focal Question 7

7. What major data gaps and uncertainties exist relative to effects of timber harvest (both riparian and adjacent upland) on the riparian functions?

Our search of the literature focused on how treatments within or adjacent to forested riparian areas impact one or more of the riparian functions. Most of the studies found in our search focus on the impacts of riparian treatment on LW and shade (commonly coupled with stream temperature). There is also a significant body of research that considers the impact of harvest on nutrient and sediment flux into streams. Fewer studies could be found that quantify changes in litter input following riparian management. No studies that provide experimental evidence that quantifies how specific treatments within the riparian area affect bank stability were found based on our search criteria (published after 2000, conducted in western North America). However, this may be because bank erosion relates directly to sediment transport and thus bank stability is inferred by the magnitude of change in sediment export. Furthermore, the importance of vegetation retention and equipment exclusion in areas closest to the stream for maintaining bank stability appears to be well understood considering its prevalence in riparian forest management plans (WAC 222-30-022; WAC 22-30-021; 2022 ODF; IDAPA 20.02.01).

While few studies could be found that provide direct experimental evidence of how bank stability is affected by timber harvest, two studies were found that compared the relative influence of different factors on bank stability. Both of which showed evidence that bank stability is influenced by the type of vegetation dominating the riparian area. Rood et al. (2015) compared the relative erosion resistance of riverbanks occupied by forests versus grassland along the Elk River in British Columbia, Canada. This study used a combination of field sampling and aerial photo analysis from 1995 to 2013 to estimate the differences in channel migration between forest and grass dominated riparian areas. Relative tree cover was binned into 5 categories ranging from (1) no trees to (5) completely treed. Relative channel change was binned into 2 categories as ‘moderate change’ for channels that migrated between 45 and 75 m, and as ‘major change’ for channels that migrated more than 75 m. Chi square analysis was used to assess the distributions of vegetation of channels with moderate and major changes. Results of the chi square analysis showed that the distribution of the observed vegetation types differed significantly ($p < 0.05$) by channel change categories. Of the 15 sites assessed with moderate or major erosion (changes), 7 were along banks dominated by grasslands without trees (‘1’), four were assessed as a ‘2’, with some trees, and three were in a ‘3’ with a mixed zone of similar proportions of trees and clearing. Only one site with a ‘4’ showed a moderate amount of change. The authors interpret these results as evidence that trees are better than grass at stabilizing banks, and that stability increases with tree cover.

Outside of the U.S., Krzeminska et al. (2019), investigated the effect of different types of riparian vegetation on stream bank stability in a small agricultural catchment in South-Eastern Norway. The dominating soil type within the catchment is coarse moraine in the forested areas and marine deposits with silt loam and silty clay loam texture in agriculture areas. The researchers used a combination of field collected data with stream bank stability modeling using Bank-Stability and Toe-Erosion Modeling (BSTEM). Three experimental plots were established, one for each dominant vegetation type, grass dominated, shrub dominated, and tree dominated. Investigations of in-situ undrained shear strength of the root-reinforced soil were done with a Field Inspection Vane Tester. Additionally, potential changes in the bank profile were monitored with a series of erosion pins, 6 pins per each plot. Changes in root cohesion and % cover over time for each vegetation type were estimated using the RipRoots sub-model in BSTEM. Their results showed a difference in bank stability based on vegetation type, that varied seasonally with groundwater level and stream water level. The grass dominated and tree dominated plots, specifically, showed the lowest estimated stability during spring (March to April) and early autumn (September to November), and the highest estimated stability during the summer months (May-June). This seasonal trend was also observed for the shrub plots but not as strongly. Steeper slopes in the grass and shrub dominated plots showed a trend of reduced stability for plots 54° slopes showing potential for failure. The tree dominated plots showed a trend of lower stability for steeper slopes, however, it wasn’t as strong of a trend and the model did not predict potential for failure or 'instability'. Regardless of season, groundwater levels, or slope steepness the tree plots showed the highest estimated bank stability overall.

These two studies that investigate bank stability use methods which could be applied to an experimental design that also considers differences in stability between treated (harvested) and untreated stands. The combination of field observation and simulation modeling used by Krzeminska et al. (2019), especially, could be used to estimate how timber harvest affects bank stability (or erosion) while also accounting for geomorphic and hydrological differences.

Considering the topics included in the focal questions, studies that investigate the effects of clearcut gaps, and studies that quantify how treatment within the riparian zone relates to resilience to fire had the fewest studies providing experimental evidence. Other than the Hard Rock and Soft Rock studies, only 2 other studies (Janisch et al., 2012, Swartz et al., 2020) were found that investigate the effects of similar buffer treatment designs (patched buffers and riparian canopy gaps). For how treatments within the riparian zone relate to resilience to fire, there were no studies that provide experimental evidence on this topic based on the search criteria. Some studies were found to quantify the probability of fire or fire severity within riparian zones in general (Reeves et al. 2006; Van de Water & North, 2011). However, none compares the resilience of riparian stands between treated and untreated stands after fire. One study, Ceder et al. (2018) used simulation modeling to compare fire susceptibility between managed and unmanaged stands and has been included in focal question 4.

Indeed, Stone et al. (2010) surveyed fire management officers from 55 national forests across 11 western states and found that fewer than half (43%) of them indicated that they were conducting fuel reduction treatments in riparian areas. The primary objective for most of these treatments involved some form of fuel reduction (83%), while others focused on multiple objectives such as ecological restoration and habitat improvement. Most of these treatments (93%) were of small extent (< 300 acres) and occurred in the wildland urban interface (73%). The authors conclude that these results are promising, but that well-designed monitoring programs are needed to estimate the consequences of these treatments on fire risk and other ecological effects.

The study from Prichard et al. (2020), discussed in question 3, used a combination of simultaneous autoregression (SAR) and random forest (RF) modeling approaches to model the drivers of fire severity and the effectiveness of fuel treatments in mitigating fire severity in the 2014 Carlton Complex. Results from this study provided evidence on how vegetation (based on broad LANDFIRE classifications), topography, and different fuel treatments (e.g., thinning only, thin and pile burn, thin and broadcast burn, etc.) related to fire severity and fire spread. This approach has potential to be used in riparian areas burned by wildfires. In terms of the topic of how various treatments relate to riparian forest resistance and resilience to fire would require using a dataset of riparian forest stand characteristics that includes information on fuel treatments, time since last fire, and basin characteristics. This information could be used along with spatial information of burn severity immediately following a fire.

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Appendix

Shade and LW

Anderson & Meleason, 2009

Anderson, P.D., Meleason, M.A., 2009. Discerning responses of down wood and understory vegetation abundance to riparian buffer width and thinning treatments: an equivalence-inequivalence approach. Can. J. For. Res. 39, 2470–2485 https://doi.org/10.1139/X09-151

The purpose of this study was to determine the effect of buffer width on understory vegetation and down woody responses both within the unthinned buffer and in the adjacent thinned stand. A secondary objective of this study was to explore the ability of equivalence-nonequivalence statistical tests at assessing the degree of similarity between stands. The focus of this study was on second-growth stands dominated by Douglas-fir at multiple sites along the coast and Cascade Range in western Oregon. Six combinations of buffer width and upslope density management prescription were evaluated: one site potential tree height buffer averaging 69 m adjacent to thinning and a 0.4 patch opening; variable width buffer averaging 22 m adjacent to thinning and a 0.4 patch opening; streamside retention width averaging 9 m adjacent to thinning; and an unthinned stand serving as a reference. Pearson correlation and multivariate analysis of variation were used to examine data on percent cover of small and large down wood, and percent cover of shrubs, herbs, and moss. Inferences on buffer performance were generated using linear mixed model analysis, equivalence-inequivalence tests, and two post-hoc comparisons. The results from this study show upland thinning led only to subtle changes in understory vegetation cover and composition with vegetation responses most prevalent with narrow buffer widths and particularly when adjacent to patch openings. There was a lack of significant change in down wood response to treatments.

Shade

Anderson et al., 2007

Anderson, P.D., Larson, D.J., Chan, S.S., 2007. Riparian buffer and density management influences on microclimate of young headwater forests of western Oregon. For. Sci. 53, 254–269. https://doi.org/10.1093/forestscience/53.2.254

The purpose of this study was to characterize variation in overstory density, canopy closure, and microclimate as a function of distance from headwater streams, and (2) determine differences in the ability of thinned stands and unthinned stands to maintain understory microclimate above the stream channel and in the riparian zone. The focus of this study was on second-growth (30- to 80-year-old) Douglas-fir forests characteristic of western Oregon. The study was located at four sites along the Oregon coast and at one site on the western Oregon Cascade Range. Stands were either thinned to approximately 198 trees per acre (TPA) or were left unthinned and ranged from 500-865 TPA. Within thinned stands, 10% of the area was harvested to create patch openings and 10% was left as clusters of "leave islands". Streams within treated stands were surrounded by buffers of either (1) one site-potential tree averaging 69 m (B1), (2) variable width buffer averaging 22 m (VB), or (3) streamside retention buffer averaging 9 m (SR-T). These six combinations of buffer width and adjacent density management were evaluated using univariate linear modeling and compared with untreated (UT) stands. Microsite and microclimate data were obtained through repeated transect measurements extending laterally from stream center and into the riparian zone and upland treated stand 2-5 years after treatment. The stand basal area was determined through variable radius plot sampling. Canopy cover was estimated through photographic techniques during the summer leaf-on period. The results from this study show that the ability of narrow streamside buffers (SR-T) at moderating stream microclimate in treated stands was questionable. Visible sky at stream center only differed significantly between SR-T (9.6%) and UT (4.2%) stands. The SR-T stands showed a +4.5°C difference in daily maximum temperatures just above stream center when compared to the UT stands. However, this difference was not statistically significant. The researchers report that SR-T had a weak temperature gradient (tested at 0-10 m and 10-30 m increments from stream center) indicating the stream center and buffer microclimates were nearly the same as upslope in the thinned stand. Within the riparian buffer zones daily maximum temperatures were higher in all treated stands when compared to UT stands. The differences in daily maximum temperatures ranged from 1.1°C (B1) to 4.0°C (SR-T), but the difference was only significant in one SR-T stand. The maximum air temperature within buffer zones adjacent to patch openings was 3.5°C higher than in UT stands. Soil temperature changes were only evident within patch openings ranging from 3.6 - 8.8°C higher than in UT stands. The researchers of this study conclude by saying that buffers with widths defined by the transition of riparian to upslope vegetation or significant topographic slope breaks appear sufficient at mitigating effects from upslope harvests on the above-stream microclimate. Their suggestions for further study center around cross-disciplinary research into the relationships between forest structure, microclimate, and habitat suitability on headwater riparian organisms.

Stream Temperatures

Cole & Newton, 2013

Cole, E., & Newton, M. (2013). Influence of streamside buffers on stream temperature response following clear-cut harvesting in western Oregon. Canadian journal of forest research, 43(11), 993-1005. https://doi.org/10.1139/cjfr-2013-0138

This study compares the changes in stream temperatures following a clearcut with three different buffer treatments – no tree buffer, predominantly sun-sided 12 m wide partial buffer, and a two-sided 15-30 m buffer (BMP for this area). The study was conducted on four small fish bearing streams in the area surrounding Corvalis, Oregon. Streams were dominated by both hardwood and conifers and were located at low- and mid-elevations. Each treatment alternated with unharvested references sections along study reaches spanning 1800-2600 meters. Stream temperature data adjacent to treatment and downstream of treatment were collected for 2 –years prior and 4 to 5 years following harvest. Time-series regression analysis was used to evaluate the change in temperatures between pre- and post-harvest. The researchers controlled for yearly fluctuations in temperatures by analyzing the difference in stream temperature entering and exiting the experimental reaches. Results showed significant increases in daily maximum, mean, and diel fluctuations in temperatures post-harvest for all no tree buffers (up to

3.8 °C). The no tree buffers also showed small but significant changes below predicted summer minima by as much as 1.2°C. The partial buffer units varied in their response to treatment exhibiting increases, decreases, and no change from preharvest trends. For example, at one site, there were no detectable changes in means, minima, or diel fluctuations but significantly lower maximum temperatures post-harvest ($p = 0.0021$; actual temperatures not reported). Partial buffers at another site reported lower trends in mean, maxima, and diel fluctuations in temperature post-harvest, and no difference in minima. Only one partial buffer site showed increases in all recorded trends (mean, minima, maxima, diel fluctuations). The BMP buffered treatment sites also showed variation in results. One site showed no detectable changes, one site showed small but significant ($p < 0.0350$; actual temperatures not reported) decreases in downstream temperatures. Only two BMP buffered sites showed significant ($p < 0.0499$) increases in mean, maxima, and diel fluctuations in temperatures. The highest increase in maxima for any BMP buffered site was 5.3°C. Changes in temperature trends in uncut reference post-treatment were minimal and attributed to downstream effects from the treatment reaches. However, when post-harvest trends in upstream treated sites were higher than pre-harvest temperatures tended to fall below pre-harvest values when passing through the unharvested downstream units. For within-unit trends, unharvested units downstream from no tree and partial buffers showed trends of significantly decreasing daily maximum temperatures. When the data was analyzed by 7-day moving mean maximum temperatures, the no tree buffers showed significant increases after harvest. The authors report that most partial and BMP buffers resulted in minimal increases or negligible changes to the 7-day moving mean maximum temperatures (actual values not reported). Significant changes in one or more temperature trends (mean, minima, maxima, diel fluctuations) were detected in all treatment stream post-harvest with only one exception at a BMP buffered site This was a well planned and executed experimental design that shows how changes in stream temperatures post-harvest are directly related to residual buffer treatment while also showing evidence that many other factors such as stream features (orientation, topography, ground water source) can compound or ameliorate these effects (I.e., changes in temperature were highly affected by site factors).

Stream Temperature

Johnson & Jones, 2000

Johnson, S. L., & Jones, J. A. (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. https://doi.org/10.1139/f00-109

This paper is a study of the changes in mean stream temperature minimum, maximum, diurnal fluctuation, and interannual and seasonal variability following harvest in three small basins of the H.J. Andrews experimental watershed between 1962 and 1966. The experimental design used historic stream temperature data to examine changes in stream temperature following clear-cut (no buffer) and burning in one watershed; patch cutting and debris flows (resulted in the removal of all streamside vegetation 3 years after cut) treatments in another watershed; and one old-growth uncut reference watershed. All watersheds were dominated by 450-year-old Doug-fir forests prior to harvest. Data was analyzed for the period 1959-1997. Mean weekly temperature maximum, minimum, and annual fluctuations were compared between all three watersheds using a complete factor analysis of variance (ANOVA). The experiment also involved long-term monitoring to evaluate time until recovery of pre-treatment temperature fluctuations. Results showed a significant increase in stream temperatures in both treatment watersheds after treatment compared to the unharvested site. The unharvested watershed showed higher interannual variability in maximum stream temperatures ranging from 15 to 19°C. The two treatment watersheds, despite differences in disturbances, (clear-cut and burn vs. Patch cut and debris-flow) followed similar trajectories from 1966-1982. Stream temperature summer maximums reached 23.9°C and 21.7°C 1-2 years post-harvest (clear-cut/burn and patch-cut/debris flow respectively) and returned to pre-harvest summer temperatures by 1980 (~15 years post-harvest). Both treatment watersheds exhibited significant increases in mean weekly minimum and maximum stream temperatures in the summer months immediately following harvest and for at least 3 years compared to the unharvested reference. The clear-cut and burn watershed's weekly maximum summer temperatures ranged between 5.4 and 6.4°C higher, and mean weekly minimum ranged 1,6-2.0°C higher than the reference streams for 4 years post-harvest. The patch-cut and debris-flow watershed exhibited mean weekly maximum stream temperatures3.5-5.2°C higher than in the reference stream for 3 years following harvest/disturbance. Prior to harvest and 30 years post-harvest the mean weekly maximum and minimum stream temperatures for both treatment streams differed less than 1.1°C from the reference stream. These differences in stream temperatures from treated and untreated sites were amplified during periods of high solar inputs and reduced during periods of cloud cover. Differences in stream temperatures were greatest during the end of July and beginning of June. Diurnal fluctuations in stream temperatures were also significantly higher in both treatment watersheds (6-8 ºC in the clearcut, and 5-6 ºC in the patch-cut) relative to the reference stream (1-2 ºC). Stream temperatures returned to pre-harvest levels after 15 years of growth.

Large Wood (LW)

Bahuguna et al., 2010

Bahuguna, D., Mitchell, S.J., Miquelajauregui, Y., 2010. Windthrow and recruitment of large woody debris in riparian stands. Forest Ecology and Management 259, 2048–2055. https://doi.org/10.1016/j.foreco.2010.02.015

The purpose of this paper was to evaluate the effect of riparian buffer width on windthrow and LW recruitment and to contrast data with unharvested controls. This paper also seeks to document the geometry of post-harvest windthrow from buffers of varying widths and to develop a model framework for incorporating supply of LW originating from windthrow to streams from riparian buffers. The focus of this paper is on dense young conifer-dominated forests originating from harvest followed by wildfire. This study is located in the Coast Mountains, approximately 60 km east of Vancouver, BC. Two buffer widths on each side of the stream (10 m and 30 m) along with an unharvested control were each replicated three times in the experiment. The researchers used a strip plot sampling method running parallel to the stream to collect data on species, diameter, height, and status (standing live/dead) beginning in the year prior to harvest and annually thereafter for seven years. A General Linear Model Procedure was used to determine the significance of variables. The Pearson correlation coefficient was used to assess correlations and potential predictor variables. Multiple linear regression was then used to determine the utility of the variables at determining LW height above the stream. Following harvest, 11% of initially standing timber was blown down in the first and second years in the 10 m buffer, compared to 4% in the 30 m buffer, and 1% in the unharvested controls. Following 8 years post-harvest, a significant amount of annual mortality occurred in the unharvested control at 30%, compared to 15% in both 30 m and 10 m buffers. 77% of LW was in the 10 cm - 20 cm diameter class while the mean diameter of standing trees in riparian buffers was 30 cm indicating small diameter trees were significantly more represented in streams. Only 3% of windthrown logs fell perpendicular to the stream with the majority falling diagonal-perpendicular relative to the stream. The researchers of this study conclude that recruitment of logs into streams lags behind the post-harvest pulse of windthrow by several years. The lag depends on the size, species, and condition of logs, and their direction of fall relative to stream valley geometry.

Species Richness

Baldwin et al., 2012 <u>(Removed from focal list)</u>

Baldwin, L.K., Petersen, C.L., Bradfield, G.E., Jones, W.M., Black, S.T., Karakatsoulis, J., 2012. Bryophyte response to forest canopy treatments within the riparian zone of high-elevation small streams. Can. J. For. Res. 42, 141–156. https://doi.org/10.1139/x11-165

The purpose of this study was to examine the influence of forest harvesting practices and distance from the stream on riparian-bryophyte communities. The experiment was limited to the montane spruce forest type which is considered moderately open and dominated by lodgepole pine in the uplands and by hybrid spruce in well-developed riparian areas. The study took place at five different watersheds located approximately 70 km from Kamloops, BC. Three primary treatments: clear-cut (n=7), two-sided buffer averaging approximately 15 m on both sides (n=10), and a continuous forest (n=6) were used to sample numerous environmental variables including elevation, aspect, slope, buffer width, and CWD decay class. Bryophytes (classified into life history strategies), stand structure, and microhabitat were also measured 1, 5, and 10 m from the streams edge. Additionally, the DBH of all conifer stems as well as percent vegetation cover were measured along transects. All data were collected in July-August of 2007 and 2008. Minimum time since disturbance for clearcut sites was 13 years versus a minimum of 5 years in buffered sites. An analysis of variance was used to compare environmental, stream, and stand structure characteristics among canopy treatments. Mean values were calculated for stand structure and substrate variables recording in transects. Bryophytes were analyzed within functional groups based on growth form, substrate affiliations, and life history. Linear models were used to evaluate the effects of distance to stream, forest canopy treatment, and their interaction on response variables. Overall CWD did not differ significantly among treatments, although buffer treatment sites had significantly higher volume of CWD in early decay classes compared to clearcut and continuous forests. The researchers suggest the early decay class CWD in buffer treated sites was likely the result of increased stem breakage. After accounting for distance from the stream, the richness and frequency of bryophyte functional communities was intermediate to continuous and clearcut sites. Compared to continuous sites, buffered sites featured significantly lower richness and frequency of many forest-associated groups. Furthermore, buffered sites also did not support increased richness or frequency of disturbance-associated species. Clearcut treatments featured higher levels of disturbance associated species including colonists, canopy species, and species typically found on mineral soil. Data from this study also showed bryophyte species richness and frequency decline with increasing distance from the stream. The authors conclude by noting that while bryophyte communities in buffered sites are significantly more diverse than communities in clearcut sites, reductions in forest-associated species as well as in the bryophyte mat as a result of large-scale forestry indicate that the ecological function of buffer-dwelling bryophyte communities may be hindered and could benefit alongside large uncut forest reserves.

Sediment

Mueller & Pitlick, 2013

Mueller, E. R., & Pitlick, J. (2013). Sediment supply and channel morphology in mountain river systems: 1. Relative importance of lithology, topography, and climate. *Journal of Geophysical Research: Earth Surface*, *118*(4), 2325-2342. https://doi.org/10.1002/2013JF002843

This study used correlation analysis to assess the relative impact of lithology, basin relief, mean basin slope, and drainage density on in stream sediment supply defined by the bankfull sediment concentration (bedload and suspended load). The study used sediment concentration data from 83 drainage basins in Idaho and Wyoming. Lithologies of the study area were divided into four categories ranging from hardest to softest- granitic, metasedimentary, volcanic, and sedimentary. The results showed the strongest correlation of bankfull sediment concentration was with basin lithology, and showed little correlation strength with slope, relief and drainage density. As lithologies become dominated by softer parent materials (volcanic and sedimentary rocks), bankfull sediment concentrations increased by as much as 100-fold. These results suggest that lithology can be more important in estimating sediment supply than topography. The authors discuss using a correlative analysis but give little description of what that analysis was or how they compare the values of each correlation strength to see if the differences were significant.

CWD Modeling

Benda et al., 2016

Benda, L.E., Litschert, S.E., Reeves, G., Pabst, R., 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. J. For. Res. 27, 821–836. https://doi.org/10.1007/s11676-015-0173-2

The purpose of this study was to develop a model which examines the effects of riparian thinning on in-stream wood recruitment in second growth stands. A secondary objective of this study was to model how manual felling of trees in no-harvest buffer zones impacts the effects of thinning. The study site was located within the Alcea watershed in central coastal Oregon. Silvicultural simulation treatments used the reach scale wood model (RSWM) and included: (1) no harvest control; (2) single entry thinning from below (thinning from below removes the smallest trees to simulate suppression mortality) with and without a 10 m width no-cut buffers; (3) double entry thinning from below with the second thinning occurring 25 years after the first with and without 10 m no-cut buffers (4) Each thinning treatment was also combined with some mechanical introduction of thinned trees into the stream encompassing a range between 5 and 20 % of the thinned trees. . The simulation model RSWM was run for 100 years in 5-year time steps. In the no-harvest control, the model output shows the density of live trees declines from 687 trees-per-hectare (tph) in 2015 to 266 tph in 2110 due to natural suppression mortality (-61 % from initial conditions). The single-entry thin reduces stand density to 225 tph in 2015 (-67 %) and declines further to 160 tph by 2110 (-77 %). The double entry thinning resulted in 123 tph after the second thinning in 2040 (-82%) and maintained that density until 2110. Both thinning treatments resulted in a substantial reduction of dead trees that could contribute to in-stream wood over time. The model output for single entry thinning treatments predicts a 33% or 66% reduction of in-stream wood over a century relative to the unharvested reference for harvest on one side or both sides of the stream, respectively. Adding the 10-m no cut buffer reduced total loss to 7 and 14%. Including mechanical tipping of 5,10,15, and 20% of cut stems without a buffer in the single entry thinning treatment changes the relative in-stream percentages of wood relative to the reference stream to –15, -6, +1, and +6%, respectively. To completely offset the loss of in stream wood due to single entry thinning mechanical tipping of 14 and 12% were required without and with buffers. Double entry thinning treatments without a buffer predicted further reduction in wood recruitment over a century of simulation with 42 and 84% reduction of in stream wood relative to the reference stream when one side and both sides of the channel were harvested. Adding a 10 m buffer reduced total reduction of in stream wood to 11 and 22% for thinning on one and both sides of the channel. To offset the predicted changes of in stream wood volume following double entry harvest would require tipping of 10 and 7% of cut stems without and with the 10-m buffer. The authors conclude that thinning without some mitigation efforts resulted in large losses of in stream wood over a century. However, by including a 10-m no cut buffer or a practice of mechanical tipping can offset these losses Although predictions from this study contribute to the in-stream wood recruitment conversation moving forward, the model contained limitations such as utilizing data from FIA plots which only approximate riparian forest conditions.

Modeling Stream Litter Delivery

Bilby & Heffner, 2016

Bilby, R.E., Heffner, J.T., 2016. Factors influencing litter delivery to streams. Forest Ecology and Management 369, 29–37. https://doi.org/10.1016/j.foreco.2016.03.031

The purpose of this study was to understand the relative influence of wind speed and direction, topography, litter type, species, and stand conditions on the distance from which litter is delivered to streams. This study utilized a combination of field experiments, literature, and simple models to estimate the width of a delivery areas. The effects of wind speed on litter delivery distance were measured on litter samples from two common species of the Pacific Northwest, Douglas-fir and red alder by releasing litter from a riparian tree canopy at various wind speeds and recording the distances traveled for each litter type at each wind speed. The relationship between distance of litter recruitment area and variables of interest (e.g., wind speed, topography, litter type...) were determined with a linear mixed effects model Data for wind speed and direction was recorded for one year in 30 min intervals along Humphrey Creek in the Cascade Mountains of western Washington. Results showed that under the wind conditions recorded at Humphrey Creek the majority of the litter recruited into the stream originated from within 10 m of the stream regardless of litter or stand type. No difference was found in delivery distance and litter type (needles or broadleaf) at young sites. However, needles released at mature sites had a higher proportion of cumulative input from greater distances than needles or alder leaves released at younger sites. This is likely due to the higher canopy and thus higher release position. Litter travel distance was linearly related to wind speed ($p < 0.0001$) Doubling wind speed at one site led to a 67-87% expansion of the riparian contribution zone in the study area. The results reveal a trend that suggests slope also contributes to the width of the litter contributing area. However, the authors did not apply statistical analysis to these values and only speculate that increasing the slope from 0-45% would increase the width of the litter contributing area by 70%. Overall, the results of this study show evidence that wind speed has a strong effect on the width of litter delivery areas within riparian areas, but that relationship is also affected stand age and litter type. Trends in the data also suggest that topography is an important factor, but it was not quantified.

Stream Temperature

Bladon et al., 2016

Bladon, K.D., Cook, N.A., Light, J.T., Segura, C., 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. http://dx.doi.org/10.1016/j.foreco.2016.08.021

The purpose of this study was to compare the effects of contemporary riparian forest harvest treatments under the Oregon Forest Practices Act (15 m riparian management area with a minimum of ~3.7 m^2 conifer basal area retained for every 300 m length of stream) with historical riparian forest harvest practices (no maintenance of streamside vegetation) on stream temperatures. This study took place in the Siuslaw National Forest in the Oregon Coast Range as part of the Alsea Watershed Study Revisited. Historical records of stream temperatures were sourced from the original Alsea Watershed Study that monitored stream temperature changes from 1958-1973, before and after streamside timber harvesting in 1966. Stream temperature data was collected for contemporary forest practices over a 6-year period (3 years pre- and 3 years post-harvest; 2006-2012). Data for the contemporary harvest was also compared with stream temperature changes in uhnharvested reference streams to support a Before-After-Control Impact (BACI) design. Stream temperature thermistors were installed, and data was taken at 30-minute intervals at three sections of both the harvested (2 within harvest boundary and 1 downstream) and reference sites. Mean canopy closure, as measured with a densiometer, along the stream channel in the harvested portion of Needle Branch was reduced from ~96% in the pre-harvest period to ~89% in the post-harvest period. Comparatively, mean canopy closure along the stream channel in the reference sites were ~92% in the pre-harvest period and 91% in the post-harvest period. Data was analyzed to assess whether there were changes in the 7-day moving mean of daily maximum stream temperature, mean daily stream temperature, and diel stream temperature following harvest. The results showed no significant changes in any of the three parameters measured following contemporary forest harvesting practices when analyzed across all catchments for all summer months (July to September). When the mean 7-day moving maximum temperature was constrained to the summer period between July 15 – August 15 across all sites there was a significant increase in stream temperatures in the harvested sites by 0.6 + 0.2°C following harvest. However, when the data was arranged for individual pair-wise comparisons with the unharvested sites, and intrinsic annual and site variability was accounted for, the increases in stream temperature (ranging from 0.3 ± 0.3°C to 0.8 ± 0.3°C) were not significant at any site. The only comparison made in the study to the original Alsea Watershed study was with the single day maximum stream temperatures for pre- and post-harvest. The contemporary practices showed a change of single day maximum stream temperatures from 15.7 °C to 14.7 °C (a reduction) from pre- to post-harvest. In contrast, the historical stream temperature data showed an increase in single day maximum stream temperatures from 13.9 °C (pre-harvest) to as much as 29.4 °C (2-years post-harvest). The authors caution that while these results support the conclusion that contemporary forest practices in Oregon are sufficient in maintaining stream temperatures after riparian forest harvest, and much more efficient than historical practices; these results should not be generalized to areas outside of coastal Oregon. The authors caution that the streams in this study have potential for a muted stream temperature response following harvest relative to other regions because of the (1) north-south stream orientation, which would maximize RMA effectiveness (2) steep catchment and channel slopes that can increase stream velocity and hyporheic exchange, (3) potential increases in groundwater contributions after harvest.

Stream temperature

Bladon et al., 2018

Bladon, K.D., Segura, C., Cook, N.A., Bywater-Reyes, S., Reiter, M., 2018. A multicatchment analysis of headwater and downstream temperature effects from contemporary forest harvesting. Hydrological Processes 32, 293–304. https://doi.org/10.1002/hyp.11415

The purpose of this study was to (1) examine the effects of contemporary forest harvesting practices on headwater stream temperature, (2) determine if increased temperatures from harvesting was detectable in downstream fish-bearing streams, and (3) examine the relative role of geology and forest management on influencing the differential stream temperature responses in both headwater and downstream reaches. This study took place at three paired watershed studies, of which two (Alsea, Trask) were located in the Oregon coast range, and one (Hinkle) was located in the western Cascades of Oregon. This study featured pre- and post-harvest measurements, as well as measurements within and downstream from harvested and reference sites. Buffer widths at harvested sites varied but averaged 20 m on either side of streams. Statistical models were generated which analyzed whether (a) the 7-day moving average of daily maximum stream temperature (7daymax) changed between pre- and post-harvest sites, and (b) whether post-harvest changes in 7daymax were detectable downstream. A regression analysis was also performed to assess the relative relationship between catchment lithology and percent catchment harvested on temperature at all sites. Statistical models were generated for each harvest site and reference pair. The pre-harvest relationship in stream temperatures for paired sites were used to create predicted changes in stream temperatures post-harvest. The post-harvest stream temperatures were then compared to the predicted values and the 95% prediction intervals. If post-harvest values of the 7daymax were outside the prediction interval the authors referred to these observations as statistical "exceedances". Results showed that the 7daymax exceeded the predictive interval at 7 of the 8 harvested headwater sites (within the harvested boundary) when analyzed across all harvest years. The exceedances were largest in the first year after harvest but diminished in the second and third year at two treatment sites. However, at one site, the elevated 7daymax continued for three years post-harvest. In 4 of the 7 harvested sites with exceedances, the exceedances were recorded between 22 and 100% of the time. Smaller increases in stream temperatures were detected in the other 3 streams with exceedances, the exceedances occurred < 15% of the time. There was no evidence of elevated stream temperatures beyond the predicted intervals in any of the downstream sites following harvesting. The magnitude of change in stream temperature and transmission of warmer water downstream were a function of percentage of catchment harvested and the underlying geology. Although, these relationships were scale dependent. At the upstream, harvested sites there was a strong relationship between stream temperature increases and catchment lithologies, but no statistically significant relationship between stream temperature changes and percent of catchment harvested. Sites downstream from harvested areas showed a strong relationship with the interaction of percentage of catchment harvested and the underlying lithologies. The greatest temperature increases at downstream sites were in areas with a higher percentage of catchment harvested and were underlain by more resistant lithologies. There was no evidence for increases in stream temperatures in catchments with a high percentage of harvest that were underlain by permeable geology. The authors suggest that this relationship may be due to the buffering effect of increases in summer low flows and greater groundwater or hyporheic exchange. They conclude that the variability of rock permeability and the relative contribution of groundwater during summer months, and their effect on stream temperatures following harvest should be investigated further.

Wood Loading

Burton et al., 2016

Burton, J.I., Olson, D.H., Puettmann, K.J., 2016. Effects of riparian buffer width on wood loading in headwater streams after repeated forest thinning. Forest Ecology and Management 372, 247–257. https://doi.org/10.1016/j.foreco.2016.03.053

The purpose of this study was to examine the relationship between in-stream wood loading and riparian buffer width in thinned stands in conjunction with several stand, site, and stream variables. This study is a part of a larger density management study which covered 6 sites along the coastal and western Cascade Range of Oregon. The sites used for this study were dominated by Douglas-fir and ranged in age from 30-70 years old. Two consecutive thinning treatments took place on a portion of each site, while the other portions were designated as an unthinned control. Treated sites featured one of four buffer width prescriptions: (1) ~ 70-m buffer representative of one site potential tree, (2) ~15-m buffer, (3) a 6-m buffer representative of trees immediately adjacent to the stream. Wood surveys were carried out at four times during the study: (1) prior to the first thinning, (2) five years after the first thinning, (3) 9-13 years after the first thinning and just prior to the second thinning, and (4) one year after the second thinning. At each site, the first thinning was to 200 trees per ha (tph), the second thinning (~10 years later) was to ~85 tph, alongside an unthinned reference stand ~400 tph. Spatial and geomorphic characterization were measured using a combination of field and geospatial data. Hierarchical linear mixed models were developed with repeated measures using a multi-step process to examine relationships between large wood volume in headwater streams over time and in-stream wood characteristics (decay stage, zone), buffer width, time since thinning, and reach and geomorphology (drainage basin area, width:depth ratio, gradient). Wood volume was found to increase exponentially with drainage basin area; for every 1-ha increase in drainage basin area, wood volume increased by 0.63%. Slightly higher volumes of wood were found in sites with a narrow 6-m buffer, as compared with the 15-m and 70-m buffer sites in the beginning 5 years after the first harvest and maintained through year 1 of the second harvest (end of study). The authors attributed this difference to a higher likelihood of logging debris and/or windthrow but was not analyzed. Low volumes of wood from stands in the stem-exclusion phase were found to contribute to overall in-stream wood. The results showed that between 82-85% of the wood with discernable sources (90% for wood in early stages of decay; 45% of wood in late stages of decay) came from within 15 m of the stream, and the relative contribution of wood to streams declined rapidly with increasing distance. The authors hypothesize that this finding in conjunction with their results, which show a positive relationship between basin area and wood volume suggests a greater role for other large wood recruitment processes such as creep, landslides, and debris flow.

Sediment

Bywater-Reyes et al., 2018

Bywater-Reyes, S., Bladon, K.D., Segura, C., 2018. Relative Influence of Landscape Variables and Discharge on Suspended Sediment Yields in Temperate Mountain Catchments. Water Resources Research 54, 5126–5142. 10.1029/2017WR021728

The purpose of this paper was to improve our ability to predict suspended sediment yields by quantifying how sediment yields vary with catchment lithography and physiography, discharge, and disturbance history. This study took place at the HJ. Andrews Experimental Site in the

Western Cascade Range of Oregon. The questions this paper sought to answer were (1) What is the relative association between discharge and catchment setting (i.e., lithology and physiography) and suspended sediment yields over an ~60-year period? (2) Is there an association between historical forest management activities (i.e., forest harvesting and road building) or extreme hydrologic events and the spatial and temporal trends in suspended sediment yield? Data was collected from 10 catchments, 8 within the Lookout Creek Watershed, 1 just below the Lookout Creek Watershed, and 1 that drains to the adjacent Blue River. The data set spanned a 60-year period from 1955-2015 Methods for determining suspended sediment concentration involved using either vertically integrated storm-based grab samples, or discharge-proportional composite samples where composite samples were collected every three weeks at the outlet of each catchment. A linear mixed effects model (log transformed to meet the normality assumption) was used to predict annual sediment yield. In this model, site was treated as a random effect while discharge and physiographic variables were treated as fixed variables. This allowed for the evaluation of the relationships between sediment yield and physiographic features (slope, elevation, roughness, and index of sediment connectivity) while accounting for site. To account for the effect of disturbance history a variable was added to the model when the watershed had a history of management or natural disturbances. If the models for the disturbed watersheds significantly underpredicted the sediment discharge, the timing of the sudden increases were further examined to assess whether it correlated with a disturbance event. Last, the authors considered changes in stage derived from comparing measured historic stage values to those predicted from current rating curves. Changes in stage were interpreted as a relative bed-elevation change resulting from changes in scour and deposition of material likely moved as bedload. The results of this study show that sediment yield varied greatly across space and time with the lowest annual yield occurring in 2001 (~0.2 t/km^2) at one catchment, and the highest annual yield (~953 t/km^2) occurring in 1969 at another catchment. Annual suspended sediment yield was most strongly correlated with the standard deviation of watershed slope ($r = 0.72$), Only moderately correlated with slope ($r = 0.32$), and with drainage area ($r = 0.38$). Standard deviation of slope was also strongly correlated with TPI (a surface roughness index), and standard deviation of index of connectivity. When considering disturbance, the largest magnitude changes in bed-elevation (I.e., sediment movement), were after floods with a $\geq$ 30-year return interval. The authors conclude that variability in watershed slope was the best predictor of annual suspended sediment yield relative to other physiographic variables. The authors report that the variability in watershed slope combined with cumulative annual discharge explained 67% of the variation in annual sediment yield across the 60-year data set. The results, however, show that annual sediment yields also moderately correlated with many other physiographic variables and caution that the strong relationship with watershed slope variability is likely a proxy for many processes, encompassing multiple catchment characteristics. For example, the strong relationship between watershed slope standard deviation and surface roughness. For the relationships between disturbance and sediment yield the authors conclude that the few anomalous years of high sediment yield occurred in watersheds with high slope variability and within a decade of forest management and a large flood event. The authors further caution that the high variability of sediment yield over space and time indicate that the factors tested in this study should be tested more broadly to investigate their utility to forest managers.

LW, Wildfire

Chen et al., 2005

Chen, X., Wei, X., Scherer, R., 2005. Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. Forest Ecology and Management 208, 101–114. doi:10.1016/j.foreco.2004.11.018

The purpose of this study was to compare the components of in-stream LW features between wildfire and forest harvesting disturbances. This study focuses particularly on the change in biomass and carbon pool among LW under different disturbances. This study was located in the central Okanagan Valley, Kelowna, British Columbia. A total of 19 forest streams, first and second order, within the study area were divided into four categories based on disturbance history of the adjacent upland forest and included: (1) riparian forest harvested 10 years ago; (2) riparian forest harvested 30 years ago; (3) riparian forest burnt ~ 40 years ago; and (4) undisturbed old-growth riparian forests that had a mean forest age of 163 years.. All harvested streams were clear-cut to the stream edge. New trees had established on these sites within 1-3 years of harvest (planted or natural growth) and resulted in lodgepole pine being the dominant species. The wildfire streams included those that had been burnt ~40 years ago with no post-fire harvest or salvage logging. In stream LW was recorded for analysis if it had a minimum diameter of 10 cm and length of 1.0 m and were situated within the bankfull width. LW biomass was determined through the conversion of wood density and wood volume. LW was also categorized by decay class (3 classes), species, orientation submergence, and distance from the beginning of the study reach. Sampling took place during the period between July and October 2003 along a 150 m study reach for each stream. An analysis of variance was used to determine the relationships between the chosen variables. When significant differences were found, the data was further analyzed with the data was fitted with a linear regression model to obtain correlations between the three variables (volume, biomass, and carbon). Results from this study show that on average the riparian sites disturbed by wildfire had the highest biomass, volume, and carbon content for individual LW pieces, followed by the 10-year harvest, then the old-growth forest; the 30-year harvest had the lowest of all streams for all parameters. Mean LW biomass of each individual piece of wood was significantly higher in sites which had been burned than in harvested sites. Biomass values were, on average, 31 kg in the wildfire sites, compared to 21 kg and 19 kg for sites harvested 10 years ago and 30 years ago, respectively. The volume of individual pieces in wildfire sites was significantly higher than in old-growth sites, and nearly significantly higher than in sites harvested 30 years ago. No statistical significance was found comparing piece volume in wildfire sites to sites harvested 10 years ago. The average carbon content of individual pieces of wood was also highest in the wildfire sites but the differences were not significant. The authors present data that the LW found in the wildfire and 30-year harvest sites was mostly in the third decay class (most decayed), with less than 1% of LW in the class 1 decay class. Statistical significance was not discussed in the results for differences in decay class. The authors conclude that streams adjacent to wildfire disturbed and recently harvested (10-years post-harvest) forests contained significantly higher LW individual pieces and total volume than old-growth and 30-year post-harvest sites. Further because biomass, volume, and carbon were significantly higher in the 10-year post harvest sites, but there was no difference in the 30-year post-harvest sites and the old-growth sites; the authors speculate that harvest can increase the abundance of LW in the short-term from leaving harvest residues but reduces the abundance of LW over the long-term (~30 years post) due to a lack of recruitment from the young forests, and loss of in-stream LW from decomposition. The three main takeaways presented by the authors for this paper were (1) LWD input in old growth forested streams was relatively stable, (2) timber harvesting activities would cause a short-term increase of LWD stocks and might greatly reduce LWD loadings over a long-term, and (3) wildfire disturbance would delay LWD recruitment because not all burnt trees would fall in the stream immediately after the wildfire.

LW

Chen et al., 2006

Chen, X., Wei, X., Scherer, R., Luider, C., Darlington, W., 2006. A watershed scale assessment of in-stream large woody debris patterns in the southern interior of British Columbia. Forest Ecology and Management 229, 50–62. https://doi.org/10.1016/j.foreco.2006.03.010

The purpose of this study was to (1) determine the spatial distribution and variation of LW characteristics (size, amount, volume, mass, orientation, position) within different order streams of forested watersheds; (2) to examine the relationship between LW characteristics and stream features through channel networks; and (3) to estimate the total density, volume and mass of LW at the watershed scale using a combination of field surveys and GIS data. This study took place at three different watersheds located in the south-central interior of British Columbia near Kelowna. A total of 35 study reaches with stream orders ranging from first- through fifth-order were selected to measure spatial distribution and variability of LW characteristics. Data collected for each reach was binned into 4 stream size categories (I = first order; II = second to third order; III = third to fourth order; IV = fourth to fifth order). Study sites were selected based on the following criteria. (1) the streams were in areas of intact mature riparian forests (>80 years); (2) the stream side forests were not disturbed by human activities, such as harvesting, road building;

(3) the streams were not salvaged. Therefore, the results from this study provide a baseline of LWD characteristics in intact mature riparian forests in the southern interior of British Columbia. LW in this study is defined as having a diameter of > 0.1 m and a length > 1.0 m. LW characteristics (decay class, orientation, position within channel, distance from downstream end of channel) were recorded for any piece of LW that was within or above the bankfull width of the channel. Watershed features and the distribution of stream orders were derived from remotely sensed data. Mean values of LW density, volume, and biomass were compared between stream size classes with an analysis of variance (ANOVA). Results from this study show that LW size, volume, and biomass generally increased with increasing stream size. For example, the mean LWD diameter in stream size I (16.4 cm) was lower than that in stream size III (20.6 cm) and size IV (20.5 cm), respectively. Mean LW length also increases with stream size from 2.3 m in size I, 2.9 m in size II, 3.1 m in size III, and 3.9 m in size IV. Stream IV had the highest mean volume (0.18 m^3), significantly higher than stream size I (0.06 m^3). LW volume was also significantly lower than in stream sizes II, and III. LW density (pieces per 100 m2 of stream area), however, decreased as stream size increased. For example, LW density (defined as piece numbers per 100 m^2) numbers were 19, 17, 12, and 4 for stream size I, II, III, and IV respectively. Increases in channel bankfull width ($R^2 = 0.52$) and stream area ($R^2 = 0.58$) was found to be strongly inversely correlated with LW density. Taken together, this study shows that spatial variation and distribution of LW characteristics vary as a function of stream size. From their results the authors conclude that in small sized streams, LW exhibit high density (number of pieces per 100 m^2), low volume and biomass per unit area of stream. While in large sized streams, LW number, volume and biomass per unit of stream area are low but mean individual LW size was high.

Stream Temperature Response to Harvesting

Gravelle & Link, 2007

Gravelle, J.A., Link, T., 2007. Influence of Timber Harvesting on Headwater Peak Stream Temperatures in a Northern Idaho Watershed. Forest Science 53, 189–205.

The purpose of this study was to examine the effects of clearcutting and partial cutting on summer peak water temperatures in downstream fish-bearing streams, and to measure direct harvesting impacts on peak water temperature within headwater catchments. This study took place at the Mica Creek Experimental Watershed in Northern Idaho. Three headwater drainages were used to assess harvesting impacts on stream temperatures: (1) Watershed 1 which had 50% of the drainage area clearcut in 2001; (2) Watershed 2 which was thinned to a 50% target shade removal in Fall 2001; (3) and an unimpacted control. Riparian buffers were applied adjacent to the streams under the Idaho Forest Practices Act. This means, for fish-bearing streams the riparian management area must be at least 75 ft (22.9 m) wide on each side of the ordinary high-water mark (definable bank). Harvesting is still permitted, but there is a restriction where 75% of existing shade must be left. There are also leave tree requirements, which is a target number of trees per 1,000 linear feet (305 m), depending on stream width. For non-fish-bearing streams there is a 30 ft (9.1 m) equipment exclusion zone on each side of the ordinary high-water mark (definable bank). There are no shade requirements and no leave tree requirements, but skidding logs in or through streams is prohibited. Stream temperature data and canopy cover percentage data were collected at multiple sites within and downstream of treatment areas between 1992-2005. However, for the non-fish-bearing, headwater sites pre-treatment data was only collected one season prior to treatment. Temperature data was summarized as maximum daily temperature and was analyzed using simple linear regression to estimate changes in stream temperature following harvest during the summer months (July 1 – September 1). Results from this study show that there is no strong evidence of a posttreatment increase in stream temperature at long-term downstream sampling points for each harvest treatment. In general, the downstream sites showed a cooling effect between –0.2 and –0.3°C. The estimated cooling effect could not be attributed to any cause (e.g., increase in water yield), but the authors conclude that there was no post-harvest increase in peak summer temperatures at the downstream sites. For streams immediately adjacent to the clearcut treatment (headwater streams) a significant increase in temperature was detected at 2 sites ranging between 0.4 and 1.9°C, while a marginally significant decrease in temperature was detected at the third site (-0.1°C, $p = 0.06$). At the sites located immediately adjacent to partial cuts, results showed mixed results with decreases in temperature (-0.1°C; non-significant) at one site and significant but minimal changes at another site (0.0-3.0°C) across the individual post-harvest years. Overall, there were minimal to no changes in stream peak temperatures following treatment in the partial-cut riparian areas. The authors go on to point out that headwater stream temperatures were highly variable, and that the shade value of understory vegetation may be an important factor contributing to results.

SED

Bywater-Reyes et al., 2017

Bywater-Reyes, S., Segura, C., Bladon, K.D., 2017. Geology and geomorphology control suspended sediment yield and modulate increases following timber harvest in temperate headwater streams. Journal of Hydrology 548, 754–769. https://doi.org/10.1016/j.jhydrol.2017.03.048

The purpose of this study was to assess the influence of natural controls (basin lithology and physiography) and forest management on suspended sediment yields in temperate headwater catchments. The study sought to achieve three objectives: (1) Quantify how suspended sediment yield varies by catchment setting in forested headwater catchments, (2) Determine whether contemporary forest management practices impact annual suspended sediment yield (SSY) in forested headwater catchments (3) Determine whether there are natural catchment settings that result in different levels of vulnerability or resilience to increases in suspended sediment yield associated with disturbances (e.g., harvest activities). This study analyzed 6 years of data from the Trask River Watershed in Northeastern Oregon and included data from harvested and unharvested sub-catchments underlain by heterogenous lithologies. Baseline SSY data collection began in water year 2010 and continued through water year 2015, with road upgrades (July–August 2011) and harvest (May–November 2012) occurring in the middle of the study period. Generalized least square candidate models quantifying the parameters from each site were used to test differences in the relationship between suspended sediment yield and catchment setting. Results from this study indicate that site lithology was a first order control over SSY with SSY varying by an order of magnitude across lithologies observed. Specifically, SSY was greater in catchments underlain by Siletz Volcanics ($r = 0.6$), the Trask River Formation ($r = 0.4$), and landslide deposits ($r = 0.9$) and displayed an exponential relationship when plotted against percent watershed area underlain by these lithologies, combined. In contrast, the site effect had a strong negative correlation with percent area underlain by diabase ($r = 0.7$), with the lowest SSY associated with 100% diabase independent of whether or not earthflow terrain was present. Following timber harvest (water year 2013), increases in SSY occurred in all harvested catchments. The SSY in both PH4 (clearcut with buffers) and GC3 (clearcut without buffers) declined to pre-harvest levels by water year 2014. Interestingly, the SSY in UM2 (clearcut without buffers) increased annually throughout the post-harvest period, ultimately resulting in the highest SSY of all catchments during the final two years of the study after producing the lowest SSY in the pre-harvest period. Catchment physiographic variables (hypsometry, slope, standardized topographic position index (SD TPI), and sediment connectivity (IC)) appeared to be good indicators of the underlying lithology of each site. Principle component analysis constructed from physiographic variables separated sites underlain by resistant diabase from those underlain by mixed lithologies along the PC1 axis. While sites along the second axis (PC2) were separated by relative values of earthflow terrain (high proportion vs. Little to none). Sites with low SSY and underlain by more resistant lithologies were also resistant to harvest-related increases in SSY. The authors conclude that sites underlain with a friable lithology (e.g., sedimentary formations) had SSYs an order of magnitude higher, on average, following harvest than those on more resistant lithologies (intrusive rocks). In general, sites with higher SSY also had 1) lower mean elevation and slope, 2) greater landscape roughness, and 3) lower sediment connectivity (potential for sediment transport based on physiography). The authors suggest that their research be undertaken in different regions with different disturbance types to broadly apply their findings.

Plant Communities

D'Souza et al., 2012

D'Souza, L.E., Six, L.J., Bakker, J.D., Bilby, R.E., 2012. Spatial and temporal patterns of plant communities near small mountain streams in managed forests. Can. J. For. Res. 42, 260–271. https://doi.org/10.1139/x11-17

The purpose of this study was to examine spatial and temporal patterns in plant communities along fish-bearing streams in western Washington. The focus of this study is on areas which were harvested to the streambank within the last 100 years. The study took place in the western Cascade Mountains of Washington. Sites were randomly selected using a geographic information system. Stands that had been impacted by road development were excluded. Stands were stratified into a chronosequence of age classes: young (31-51 years), mature (52-70 years), old (>100 years). Due to availability, the sample sizes included 11 young stands, 10 mature stands, but only 4 old stands. Vegetation characteristics were captured in each stand using 0.16 ha plots located 30 m from stand edges to limit the influence of adjacent stands. Transects perpendicular to the stream were used 10 m apart and extended 80 m upslope. Vegetation and physical features along each transect were sampled using a series of subplots at 10 m intervals from the channel. The authors found little variation in riparian landform type and or canopy cover and were not included in the analysis for their effect on vegetation. Plant communities were examined spatially as a function of distance to stream and temporally by using the chronosequence of stand ages. Three distinct plant communities were observed in the shrub and herb layer (riparian: 0-9 m; transitional: 10-29 m; and upslope: 30-80 m) and their composition differed significantly between communities. A total of 12 species were identified as indicators of these communities. For the shrub layer, community composition differed between old stands and young and mature stands. In the herb layer, community composition differed between all age classes. The results from this study suggest that plant communities along small fish-bearing streams have distinct changes in community with distance to stream, but also reflect successional status in nearby forests. The authors conclude by suggesting increased research in understanding the effects of forest management on streamside vegetation.

LW Residence Time

Hyatt & Naiman, 2001

Hyatt, T.L., Naiman, R.J., 2001. The Residence Time of Large Woody Debris in the Queets River, Washington, Usa. Ecological Applications 11, 191–202. https://doi.org/10.1890/1051-0761(2001)011[0191:TRTOLW]2.0.CO;2

The purpose of this study was to determine the depletion rate of LW by examining differences in size and species composition in the Queets River compared to the adjacent forest. This study took place in the Queets River Watershed located on the west slope of the Olympic Mountains in Washington. Field sampling was carried out at 25 transects and four different sites. Increment cores from in-stream LW were cross-dated against cores from riparian conifers to estimate the time which LW was recruited into the channel. LW pieces which were in a heightened state of decay were dated using carbon-dating techniques. the most common tree species (> 30 cm diameter) in the riparian zone is red alder, followed by Sitka spruce and western hemlock, whereas the most common species of LWD (> 30 cm diameter) is Sitka spruce, followed by red alder and western hemlock. Each of the hardwood species is better represented among standing trees than among LWD, and each of the conifers are better represented as LW than among trees in the riparian zone. The depletion curve developed in the results was based only on conifer LW because hardwood LW was either too small or too young to provide accurate estimates of residence time in the stream. Based on the depletion curve developed for all available LW showed that wood typically disappears from the active channel within the first 50 years, while some pieces may remain for several hundred years. By cross-referencing the LW depletion curves with field notes the authors suggest that the longer residence time, beyond 50 years, was dependent on more than one process such as burial. Decay class was not an accurate predictor of LW age. Also, Dependent vegetation on or around LWD was a poor and often misleading indicator of residence time. Many LWD pieces that had 1–5 year old vegetation growing on or around them were discovered to have died and presumably recruited to the channel 20 years previous. The authors conclude that LW originating from hardwoods is depleted faster than conifers. Considering the depletion rate curve, the authors speculate that the majority of LW is transported out of the system within 50 years, while pieces of LW that are buried or jammed in the river floodplain may remain for hundreds of years. Overall, ~80% of LW residing in the active channel were living within 50 years of the study. The authors explain there are several caveats to the depletion curve created for this study (1) the depletion constant was developed for a large, mostly alluvial river and should probably not be applied to smaller streams (mean bankfull width at study transects on the Queets is 165 m and the range is 51–398 m; mean key LWD length is 23.4 m, and the range is 5.3–69.0 m). Also, from the data the authors infer that alluvial channel trap wood from upstream, and constrained channels export LWD downstream, so it is not to be expected that the LWD resident in a channel was recruited from the riparian zone in that reach. In general, the authors conclude that for this study the depletion curve shows that the half-life of LW is ~20 years and thus all resident LW will be exported, buried, or broken down within 3-5 decades. Also, hardwood LW will be depleted from the channel more rapidly than conifers.

Litter Input

Hart et al., 2013

Hart, S.K., Hibbs, D.E., Perakis, S.S., 2013. Riparian litter inputs to streams in the central Oregon Coast Range. Freshwater Science 32, 343–358. https://doi.org/10.1899/12-074.1

The purpose of this study was to understand how riparian vegetation composition, understory density, and topography affect the quantity and quality of litter input to streams throughout the annual cycle. This study took place within 5 contiguous watersheds located in the central Coast Range of Oregon. At each of the study sites uniform areas along a $\leq$300 m stream reach, 3 plots were delineated on 1 side of the stream, each 8x 25 m along the stream. Three treatments were applied: (1) a no cut or fence control; (2) cut and remove a 5 x 8 m section adjacent to stream plants < 10 cm DBH and >12 cm height every 2 months; and (3) 5 m fence extending underground and parallel to the stream to block litter moving downslope from reaching stream. Vertical and lateral litter traps were installed at each site and collected monthly between August 2003-August 2004. Variation of riparian vegetation and woody debris characteristics were analyzed with a 3-way ANOVA using overstory, treatments, and sections and their interactions. Two-way ANOVA with repeated measures was used to compare seasonal and monthly control and treatment inputs for different overstory and litter types. 1-way ANOVA was used to test for differences in nutrient concentration flux between overstory type. Results from this study show that deciduous forests dominated by red alder delivered significantly greater vertical and lateral inputs to stream than did coniferous forests dominated by Douglas-fir. Deciduous-site vertical litter input (mean, 95% CI; 504 g m-1 y-1, 446.6–561.9) exceeded that from coniferous sites (394 g m-1 y-1, 336.4–451.7) by 110 g/m2 (28.6–191.6) over the full year. Annual lateral inputs at deciduous sites (109 g m-1 y-1, 75.6–143.3) were 46 g/m (1.2– 94.5) more than at coniferous sites (63 g m-1 y-1, 28.9– 96.6). Lateral inputs calculated for a 3-m-wide stream accounted for 9.6% (5.4–12.5) of total annual inputs at coniferous sites and 12.7% (10.2–14.5) of total inputs at deciduous sites. Composition of litter also differed significantly by overstory type. Annual lateral inputs at coniferous sites were dominated by deciduous leaves (,33%), twigs (,23%), and leftover (,18%) litter types, whereas annual lateral inputs at deciduous sites were deciduous leaves (,61%) and leftover (,15%) litter types. Leftover litter types were defined as those that were too small or decayed to identify, bark, moss, or lichens. Vertical litter inputs at deciduous sites were dominated by deciduous leaves (,65%) and deciduous-other (,15%) litter types. While deciduous leaves (,33%), coniferous needles (,24%), and twigs (,21%) composed the annual vertical litter inputs at coniferous sites. The strongest deciduous inputs to streams occurred in November. Annual lateral litter input increased with slope at deciduous sites (R2 = 0.4073, p = 0.0771), but showed no strong relationship at coniferous sites (R2 = 0.1863, p = 0.2855). Total nitrogen flux to streams at deciduous sites was twice as much as recorded at coniferous sites. However, there was seasonal effect where the N fluxes in deciduous sites was only higher in autumn. The authors of this study conclude by suggesting management in riparian areas consider utilizing deciduous species such as red alder for greater total N input to aquatic and terrestrial ecosystems along with the increased shade and large woody debris provided by coniferous species.

Effect of Contemporary Management on Nutrient Concentration and Cycling

Gravelle et al., 2009

Gravelle, J.A., Ice, G., Link, T.E., Cook, D.L., 2009. Nutrient concentration dynamics in an inland Pacific Northwest watershed before and after timber harvest. Forest Ecology and Management 257, 1663–1675. https://doi.org/10.1016/j.foreco.2009.01.017

The purpose of this study was to assess the effects of contemporary forest harvesting practices on nutrient cycling and concentrations. This study took place at the Mica Creek Experimental Watershed in Northern Idaho. Seven steel Parshall flumes were installed at select locations within the watershed to assess the effects of clearcut to stream and partial cut (50% shade retention) harvesting practices. All harvesting was conducted in compliance with the Idaho Forest Practices Act. Within fish-bearing streams (Class I) Harvesting is permitted, but 75% of existing shade must be retained. There are also leave tree requirements for a target number of trees per 1000 linear feet (305 m), depending on stream width. In Mica Creek, this was roughly 200 trees in the 3–12 in. (8–30 cm) diameter class per 305 m of the riparian management zone (RMZ). Along non-fish-bearing streams (Class II) the RMZ is 30 feet (9.1 m) of equipment exclusion zone on each side of the ordinary high-water mark (definable bank); skidding logs in or through streams is prohibited. There are no shade requirements and no requirements to leave merchantable trees. Two-sided riparian buffers were left on all Class I streams during harvest operations. Timber was removed from both sides of the Class II streams. In the post-harvest and post-burn conditions, Class II streams in clearcut treatments had only a small amount of green tree retention within the riparian zone, while in partial cut treatments equal amounts of canopy cover (approximately 50%) were removed from both sides of the stream. This study followed the BACI design and featured a pre-treatment measurement phase (1992-1997), a post-road construction phase (1997-2001), and a post-harvest phase (2001-2006). A students t-test was used to analyze the data between the observed and predicted values of post-treatment sites for several nitrogen and phosphorus compound concentrations (Kjeldahl nitrogen (TKN), nitrate + nitrite (NO3 + NO2), TP, total ammonia nitrogen (TAN) consisting of unionized (NH3) and ionized (NH4+) ammonia, and unfiltered orthophosphate (OP) samples). Results from the post-road construction period showed no significant changes in concentrations of any nutrients analyzed. Results from this study show statistically significant increases in NO3 and NO2 concentrations following clearcut and partial harvest cuts in headwater streams. Increases at the clearcut treatment site were greatest, where mean monthly concentrations increased from 0.06 mg-N L -1 during the calibration and post-road periods to 0.35 mg-N L -1. There was also an observable seasonal effect on NO3 + NO2 concentrations with the peak concentration of 0.89 mg-N L-1 occurred at F1 in April 2004, with mean monthly concentrations of 0.43 mg-N L-1 and 0.59 mg-N L -1 in water years (October–September) 2004 and 2005, respectively. Similar results were also observed at sites further downstream although changes were smaller which, the authors point out this may be due to in-stream uptake and/or dilution. No significant changes of in-stream concentration of any other nutrient recorded were found between time periods and treatments except for one downstream site that showed a small increase in orthophosphate by 0.01 mg P L –1. In general, the results of this study show that forest management influences in-stream NO3 + NO2 immediately adjacent to treatment and downstream of treatment. The authors conclude by suggesting future research in understanding variability in nutrient concentrations and cycling as affected by seasons and storm runoff events.

Organic Matter Inputs

Kiffney & Richardson, 2010

Kiffney, P.M., Richardson, J.S., 2010. Organic matter inputs into headwater streams of southwestern British Columbia as a function of riparian reserves and time since harvesting. Forest Ecology and Management 260, 1931–1942. https://doi.org/10.1016/j.foreco.2010.08.016

The purpose of this paper was to assess how differences in riparian buffer width and timing since harvest affect terrestrial particulate organic matter flux into streams. The focus of this paper was on 1st and 2nd order headwater streams located approximately 45 km east of Vancouver in British Columbia, Canada. Sites were measured over an 8-year period and included clear-cut (n=3), 10-m buffered reserve (n=3), 30-m buffered reserve (n=2), and uncut control (n=2) treatments. For streams receiving a 10 or 30-m reserve, there was no logging on either side of the stream within these reserves. Study reaches were approximately 200m long. Vertical litter inputs were collected monthly and at approximately 6–8-week intervals during each season for years 1,2,6,7, and 8 years after harvest. Litter was separated into broadleaf deciduous, twig, needles, and other (seeds, cones, and moss) categories following collection and subsequently dried and weighed using a microbalance. A mixed-model analysis of covariance was used for Fall data with riparian treatment as a fixed effect and year as a covariate. Secondarily, ordinary least squares regression was used to quantify the functional relationship between reserve width and litter flux within each year. Results show riparian treatments having significant effects on the quantity and composition of litter input into streams. Inputs consisting of needles and twigs were significantly lower while deciduous inputs were higher in clearcuts compared to other treatments. Differences in litter flux relative to riparian treatment persisted through year 7, while a positive trend between reserve width and litter flux remained through year 8. For example, one-year post-treatment, needle inputs were 56x higher during the Fall into control and buffered treatments than into the clearcut. Needle inputs remained 6x higher in the buffer and control sites through year 7, and 3-6x higher in year 8 than in the clearcut sites. Twig inputs into the control and buffered sites were ~25x higher than in the clearcut sites in the first year after treatment. There was no significant difference in treatment for deciduous litter but a trend of increasing deciduous litter input in the clear cut was observed in the data. For example, one-year post-treatment deciduous litter was lowest in the clearcut, but by year 8 deciduous litter was highest in the clearcut sites relative to control and buffered sites. The linear relationship between reserve width and litter inputs was strongest in the first year after treatment, explaining ~57% of the variation, but the relationship could only explain ~17% of the variation in litter input by buffer width by year 8 (i.e., the relationship degraded over time). The authors interpret these results as evidence that riparian reserves showed a similar litter flux to streams when compared to uncut controls. They also conclude that litter flux from riparian plants to streams, was affected by riparian reserve width, time since logging, and potentially channel geomorphology.

In-stream Wood Loads

Jackson & Wohl, 2015

Jackson, K.J., Wohl, E., 2015. Instream wood loads in montane forest streams of the Colorado Front Range, USA. Geomorphology 234, 161–170. http://dx.doi.org/10.1016/j.geomorph.2015.01.022

The purpose of this study was to examine in-stream wood loads and geomorphic effects between stands of different ages and stands with different disturbance histories The first objective of this study was to determine whether instream wood and geomorphic effects differ significantly among old-growth, younger, healthy, and beetle-infested forest stands. The second objective of this study was to determine whether instream wood loads correlate with valley and channel characteristics. The authors hypothesized that streams in old-growth montane forests have (1) significantly larger in stream and floodplain wood loads than those in younger stands, (2) greater frequency of volume of jams than those in younger forests, and (3) more wood created geomorphic effects. They also hypothesized that instream wood loads in healthy montane forests are significantly smaller than in beetle-infested forests. Last, they hypothesized that instream wood load correlates with lateral valley confinement, with unconfined valleys having the greatest in-stream and total wood loads. This study took place within the Arapaho and Roosevelt National Forests in Colorado. Sediment storage, channel geometry, in-stream wood load, and forest stand characteristics were measured along 33 pool-riffle or plane-bed stream reaches (10 located in old-growth (> 200 years); 23 located in younger forests (age range not reported)). LW characteristics were recorded for all in-stream wood $\geq$ 10 cm diameter and $\geq$ 1 m in length. Pair-wise t-test or Kruskall-Wallis tests were used to check for significant differences in wood load, logjam volume, and logjam frequencies. To test for significant differences in wood created geomorphic effects a principal component analysis was used. Results indicated that channel wood load (OG = 304.4 $\pm$ 161.1; Y = 197.8 $\pm$ 245.5 m^3 /ha), floodplain wood load (OG = 109.4 $\pm$ 80; Y = 47.1 $\pm$ 52.8 m^3 /ha), and total wood load (OG = 154.7 $\pm$ 64.1; Y = 87.8 $\pm$ 100.6 m^3

/ha) per 100 m length of stream and per unit surface area were significantly larger in streams of old-growth forests than in young forests. Streams in old-growth forests also had significantly more wood in jams, and more total wood jams per unit length of channel than in younger forests (jam wood volume: OG = 7.10 + 6.9 m^3; Y = 1.71 + 2.81 m^3). When standardized to stream gradient, old-growth streams had significantly greater pool volume and significantly greater sediment volume than younger stands. No significant difference was detected in in-stream wood loads between healthy and beetle-infested stands. Although wood load in streams draining from pine beetle infested forests did not differ significantly from healthy forests, best subset regression (following principal component analysis) indicated that elevation, stand age, and pine beetle infestation were the best predictors of wood load in channels and on floodplains. The authors speculate that beetle infestation is affecting in-stream wood, but perhaps not enough time has passed since the infestation for the affected trees to fall into the stream. Time since beetle-infestation was not reported.

LW Recruitment

May & Gresswell, 2003

May, C.L., Gresswell, R.E., 2003. Large wood recruitment and redistribution in headwater streams in the southern Oregon Coast Range, U.S.A. Can. J. For. Res. 33, 1352–1362. https://doi.org/10.1139/x03-023

The purpose of this study was to understand the relative influence of processes that recruit and redistribute wood into channels and to understand how these processes vary spatially. Specific research questions included the following:(i) Do processes that deliver and redistribute wood differ in small colluvial channels compared with larger alluvial channels? (ii) Do proximal and distal controls on wood delivery differ for colluvial and alluvial channels? (iii) How do input and redistribution processes influence the functional role of wood in the channel? The focus of this research is specifically on differences between small colluvial channels and large alluvial channels in the southern Oregon Coast Range. All downed wood exceeding 20 cm mean diameter and 2 m in length, and in contact with the bank-full channel were measured in three second order and one third-order stream. Large wood was categorized based on the various mechanisms delivering it to the stream channel. Categories included (i) direct delivery from local hillslopes and riparian areas, (ii) fluvial redistribution, (iii) debris flow transported, or (iv) an unidentified source. Results from this study show that stream size and topographic position strongly influence processes that recruit and redistribute wood in channels. Processes of slope instability were shown to be important conveyors of wood from upland forests to small colluvial channels. In the larger alluvial channels, windthrow was found to be the dominant recruitment process from adjacent riparian area. Results showed that Wood derived from local hillslopes and riparian areas accounted for the majority of pieces (63%) in small colluvial channels. The larger alluvial channel received wood from a greater variety of sources, including recruitment from local hillslopes and riparian areas (36%), fluvial redistribution (9%), and debris flow transported wood (33%). However, because pieces recruited from local sources (hillslope and riparian area) were larger, these sources of wood had a disproportionately large contribution to volume of wood in the stream. For example, wood recruited from the local hillslopes and riparian areas accounted for 36% of wood pieces in the alluvial stream, which accounted for 74% of the total volume of wood. Slope instability and windthrow were the dominant mechanisms for wood recruitment into small colluvial channels. Windthrow was the dominant recruitment mechanism for wood recruitment into larger alluvial channels. Distributions of the source distance of wood pieces were significantly different between colluvial and alluvial channels. In colluvial streams, 80% of total wood and 80% of total wood volume recruited originated from trees rooted within 50 m of the channel. In the alluvial channel, 80% of the pieces of wood and 50% of the total volume originated from trees which came from 30 m of the channel. The primary function of wood in smaller colluvial channels was sediment storage (40%) and small wood storage (20%). The primary function of wood in larger alluvial channels is bank scour (26%), stream bed scour (26%), and sediment storage (14%). Recruitment and redistribution processes were shown to affect the location of the piece relative to the channel/flow direction, thus influencing its functional role. The authors conclude that wood recruited from local sources is variable by position in the stream network because of differences in recruitment processes, degree of hillslope constriction, and slope steepness.

Sediment

Macdonald et al., 2003

Macdonald, J. S., Beaudry, P. G., MacIsaac, E. A., & Herunter, H. E. (2003). The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. Canadian Journal of Forest Research, 33(8), 1397-1407. https://doi.org/10.1139/x03-110

(BACI, only single year pre-harvest)

This study investigates the changes in suspended sediment concentration and stream discharge during freshet (spring snowmelt) at two harvest intensities relative to each other and an unharvested control watershed, pre- and post-harvest. The design included three small sub-boreal, first order, forest streams (<1.5 m width) in the central interior of British Columbia (Baptiste watershed). Both treatment streams received a 55% harvest treatment; one (low-retention) removed all merchantable timber >15 cm DBH for pine and > 20 cm DBH for spruce within 20 m of the stream; the other treatment (high-retention) removed all merchantable timber > 30 cm within 20 m of the stream; and an un-harvested control. Data for stream flow and total suspended sediments (TSS) was collected using Parshall flumes downstream from the treatment and control sites for one-year pre- and four-years post-harvest during snowmelt periods. Regression analysis was used to analyze relationships between treatment and control reaches pre- and post-treatment to estimate and compare predicted changes in TSS. The results showed an increase in freshet discharge for both treatments above predicted values for the entirety of the study. During the year prior to treatment, TSS relationships of both treatment watersheds during freshet closely matched those of the control. Immediately following harvest TSS concentrations increased above predicted values for both treatment streams. Increased TSS persisted for two-years post-harvest in the high-retention treatment, and for 3-years in the low-retention. The authors speculate that the treatment areas may have accumulated more snow (e.g., more exposed area below canopy) than in the control reaches leading to the increase in discharge. This study shows evidence that harvest intensity (low vs. high retention) is proportional to the increase in stream discharge, TSS, and recovery time to pre-harvest levels.

LW

Fox & Bolton, 2007

Fox, M., & Bolton, S. (2007). A regional and geomorphic reference for quantities and volumes of instream wood in unmanaged forested basins of Washington State. North American Journal of Fisheries Management, 27(1), 342-359. https://doi.org/10.1577/M05-024.1

This study uses in-stream LW values from 150 stream segments located in unmanaged watersheds, across all of Washington State, to investigate the relationships between geomorphology, forest zone, and disturbance regimes with LW recruitment. The purpose of this study was to create a base-line value of central tendency for in-stream LW values in “natural” streams for which salmonids are theoretically adapted. The authors define natural and unmanaged as streams that (1) had no part of the basin upstream of the survey site ever logged using forest practices common after European settlement and (2) the basin upstream of the survey site contains no roads or human modifications to the landscape that could affect the hydrology, slope stability, or other natural processes of wood recruitment and transport in streams. Sites were stratified to capture the variations in forest types, channel morphologies, and hydrological origins. The authors used descriptive statistics to establish and evaluate correlations between wood loading and watershed characteristics to reveal the highest valued variables influencing wood loading. Following this analysis, the variables with the highest mechanistic values in determining wood loading were evaluated and compared using simulation modeling.

Results showed that in-stream wood volume increased with drainage area and as streams became less confined. However, bank full width (BFW) was a significantly better predictor of wood parameters than basin size. There was observational evidence that alluvial channels contained more wood volume on average than bedrock channels. However, due to limits in sample size following stratification, statistical analysis could not be completed. Sample sizes for isolating gradient and confinement were also too small to apply statistical analyses. Fire was found to influence in-stream wood quantities and volumes west of the Cascade crest; In-stream wood volume increased with adjacent riparian timber age as determined by the last stand replacing fire. Other disturbances such as debris flow, snow avalanche, and flooding were too few in frequency in the study area to be analyzed statistically. From these results the authors developed thresholds for expected "key piece volume (m^3)" (pieces with independent stability) of wood for three BFW classes (20-30 m, >30 – 50 m, > 50 m width) per 100 m stream length for streams with BFW greater than 20 m. From percentile distributions the authors recommend minimum volumes, defined by the 25th percentiles, of approximately 9.7 m3 for the 20- to 30-m BFW class, 10.5 m3 for the 30- to 50-m3 BFW class, and 10.7 m3 for channels greater than 50 m BFW per 100 m length of stream. The results of this study suggest that BFW is the single greatest predictor of in-stream wood quantity and volume relative to other predictor variables. However, this result comes with the caveat that other processes and geomorphologies (e.g., channel bed form, gradient, confinement) are also important in the mechanisms for wood recruitment, modeling in this study showed too much inconsistency with these predictor variables too draw strong conclusions. Further the authors warn that these values for reference conditions are only applicable to streams with bank-full widths between 1 and 100 m, gradients between 0.1% and 47%, elevations between 91 and 1,906 m, drainage areas between 0.4 and 325 km2, glacial and rain- or snow-dominated origins, forest types common to the Pacific Northwest.

LW and sediment

Gomi et al., 2001

Gomi, T., Sidle, R. C., Bryant, M. D., & Woodsmith, R. D. (2001). The characteristics of woody debris and sediment distribution in headwater streams, southeastern Alaska. Canadian Journal of Forest Research, 31(8), 1386-1399. https://doi.org/10.1139/x01-070

This study investigated different riparian conditions related to harvest and disturbance (landslides), their influence on woody debris and sediment distributions, and their related functions in headwater streams. This study examined the effects of recent and past timber harvests on woody debris abundance and distribution, landslides and debris flow on woody debris abundance and sediment accumulations, and the function of in-stream woody debris on sediment storage. The researchers examined 15 steep headwater streams in the Maybeso

Experimental Forest and Harris River basin in the Tongass National Forest, Prince of Wales Island, southeastern Alaska. Treatments of headwater streams included five management or disturbance regimes: old growth (OG), recent clear-cut (CC; 3 years), young growth conifer forest (YC; 37 years after clear-cut), young growth alder (YA; 30 years after clear-cut), and recent landslide and debris flow channels (LS). Three headwater streams were sampled for each of the 5 treatments, 15 streams total. Analysis of covariance (ANCOVA) was used to compare LW quantity and distribution, and sediment quantity and distribution, across plots nested within each treatment site. Results showed in-channel numbers of LW pieces were significantly higher in YC and CC sites when compared to OG, YA, and LS sites. The number of LW pieces was highest in YC streams even though logging concluded 3 decades prior to sampling. No significant differences in LW volume were found among OG, CC, and YC streams. However, LW volume per 100 m of stream length in YC was twice that in OG. The total volume of LW per 100 m associated with CC channels was half that in OG channels. However, the majority of the LW volume in OG systems was outside of the bank-full area. When the data was stratified by channels that experienced landslides (LS and YA), the number of LW pieces among OG, YA, and LS was not statistically significant. However, the in-channel volumes of LW in LS and YA channels were significantly lower than in OG sites because individual LW pieces in the OG sites were relatively larger than in the LS and YA sites. There was high variability among sites in the amount of sediment stored within streams. The authors conclude that timber harvesting and related landslides and debris flows affect the distribution and accumulation of LW and related sediment accumulation in headwater streams. These effects are summarized as (i) inputs of logging slash and unmerchantable logs significantly increase the abundance of in-channel woody debris; (ii) in the absence of landslides or debris flows, these woody materials remain in the channel 50–100 years after logging; (iii) relatively smaller woody debris initially stores sediment; (iv) when landslides and debris flows occur 3–15 years after logging because of intensive rain and weakening of root strength (Sidle et al. 1985), woody debris is evacuated from headwater streams and deposited in downstream reaches; (v) although less woody debris remains in the scour zone, woody debris pieces and jams contribute to sediment storage in both the scour and deposition zones of landslide and debris flow channels; (vi) red alder stands actively recolonize riparian zones of headwater streams for 20–50 years after mass movement and recruit woody debris and organic materials, which in turn provide sediment storage sites; and (vii) subsequent sediment movement after landslides and debris flows are affected by residual woody debris and newly introduced debris.

LW and sediment

Johnson et al., 2000 (removed from focal list)

Johnson, S. L., Swanson, F. J., Grant, G. E., & Wondzell, S. M. (2000). Riparian forest disturbances by a mountain flood—the influence of floated wood. Hydrological processes, 14(16-17), 3031-3050. https://doi.org/10.1002/1099-1085(200011/12)14:16/17<3031::AID-HYP133>3.0.CO;2-6

This study examined the differences in riparian forest responses to a 100-year flood event along eight third- to fifth-order streams in the Cascade Mountain Range of Oregon. Disturbance intensities were grouped into three categories: purely fluvial (high water flow only), fluvial with uncongested wood transport, and fluvial with congested wood transport. Riparian forest responses were heavily influenced by pre-flood forest structure and disturbance/harvest history, especially the characteristics of LW presence within streams and along channels. The quantity and severity of toppled trees (fully uprooted vs. partially uprooted) during the flood event was proportional to the quantity and congestion of LW already present (i.e., higher volumes of LW already present during the flood event increased the frequency of toppled trees and newly deposited LW in streams). Further, stands that experienced higher frequencies of toppled trees also showed higher frequencies and magnitudes of debris flow. The authors concluded that the land use practices, and disturbance histories influenced the age and structure of the riparian forests, but also the availability of the agents of disturbance (presence of LW) during the 100-year flood event. This paper is a good discussion of how pre-disturbance structure affects the response of riparian forests to disturbances (in this case, flood), however, there is no statistical analysis discussed in the methods. This is purely descriptive science that involves an intensive survey of before and after riparian forest structures.

Sediment

Yang et al., 2022 (removed from focal list)

Yang, Y., Safeeq, M., Wagenbrenner, J. W., Asefaw Berhe, A., & Hart, S. C. (2022). Impacts of climate and forest management on suspended sediment source and transport in montane headwater catchments. Hydrological Processes, 36(9), e14684. https://doi.org/10.1002/hyp.14684

This paper investigates the changes in annual hysteresis patterns for in-stream suspended sediment in 10 headwater streams at 2 sites, Providence Creek (rain-snow-dominated, transitional), and Kings River Experimental Watershed (snow-dominated). Aside from precipitation pattern differences in the two catchments, the researchers also compared differences in hysteresis patterns for forested riparian control, burn-only, thin-only, and thin-and-burn combined areas. The differences in the proportion of clockwise-loop hysteresis patterns for suspended sediments in the warmer rain-snow-transition sites compared to the colder snow-dominated sites suggests that warming temperatures may cause the snow-dominated basins to receive sediment from extended source areas and for longer periods if they transition to rain dominated catchments. The results found no discernable difference in hysteresis loops between the control, burn-only, thin-only, and thin-and-burn combined areas. Further, there seemed to be little change in the hysteresis loops during drought, average, and excessively wet years. The authors speculate that local conditions will be more important in understanding the impacts of climate change than changes in precipitation patterns or average annual temperatures alone. Mainly, there is evidence that if snow-dominated watersheds become warm enough to transition to rain-dominated, there is potential for disruption to sediment discharge frequency, rates, and source distance. The indiscernible difference in hysteresis loops for the different treatments also suggests that management practices imposed to ameliorate these changes may not be completely effective.

Nutrients

Vanderbilt et al., 2003

Vanderbilt, K. L., Lajtha, K., & Swanson, F. J. (2003). Biogeochemistry of unpolluted forested watersheds in the Oregon Cascades: temporal patterns of precipitation and stream nitrogen fluxes. Biogeochemistry, 62(1), 87-117. DOI:10.1023/A:1021171016945

This study uses long-term datasets (ranging from 20-30 years) from six watersheds in the H.J. Andrews Experimental Watershed (HJA) in the west-central Cascade Mountains of Oregon to investigate patterns in dissolved organic nitrogen (DON) and dissolved inorganic nitrogen (DIN) export with watershed hydrology. The objectives of this study were to 1) characterize long-term patterns of N dynamics in precipitation and stream water at the HJA, 2) analyze relationships between annual output of N solutes and annual stream discharge, 3) analyze relationships between seasonal stream water N solute concentrations and precipitation and stream discharge, and 4) compare results with those from other forested watersheds. Precipitation data were collected at three-week intervals from 10/1/1968 until 5/24/1988 and at one-week intervals thereafter. Stream chemistry samples were collected weekly for the entirety of the study. Stream discharge was measured continuously throughout the study. The researchers used regression analysis of annual N inputs and outputs with annual precipitation and stream discharge to analyze patterns. The results showed DON was the largest component of N input at the low-elevation collector, followed by PON (particulate organic N), NO3-N, and NH4-N. At the high-elevation collector, NO3-N input was higher than at low elevation and was the largest component of N in bulk and wet-only inputs, followed by NH4-N, DON, and PON. For annual stream outputs, DON was the largest fraction of annual N output, followed by PON, NH4-N and then NO3-N. Total annual discharge was a positive predictor of annual DON export in all watersheds with r2 values ranging from 0.42 to 0.79. In contrast, significant relationships between total annual discharge and annual export of NO3-N, NH4-N, and PON were not found in all watersheds. No systematic long-term average seasonal trends were observed for NO3-N or PON concentrations. Elevated concentrations of NH4-N occurred in spring and early summer in all three watersheds, although they are not convincingly synchronous. DON concentrations increased in the fall in every watershed. The increase in concentration began in July or August with the earliest rain events, and peak DON concentrations occurred in October through December before the peak in the hydrograph. DON concentrations then declined during the winter months. The authors conclude that total annual stream discharge was a positive predictor of DON output suggesting a relationship to precipitation. Also, DON had a consistent seasonal concentration pattern. All other forms of N observed showed variability and inconsistencies with annual and seasonal stream discharge. The authors speculate that different factors may control organic vs. Inorganic N export. Also, DIN may be strongly influenced by terrestrial or in-stream biotic controls, while DON is more strongly influenced by climate. Last, the authors suggest that DON in streams may be recalcitrant, and largely unavailable to stream organisms. The authors emphasize the importance of analyzing data from multiple watersheds in a single climactic zone to make inferences about stream chemistry.

Stream temperature

Roon et al., 2021b

Roon, D. A., Dunham, J. B., & Torgersen, C. E. (2021). A riverscape approach reveals downstream propagation of stream thermal responses to riparian thinning at multiple scales. Ecosphere, 12(10), e03775. https://doi.org/10.1002/ecs2.3775

This study uses a riverscape approach to evaluate the effects of streamside forest thinning on stream temperatures at multiple spatiotemporal scales. This study addresses the question of how thinning second-growth riparian forests influences local and downstream temperatures at watershed extents. This study attempts to answer this question by addressing four objectives: (1) quantify pretreatment spatial and temporal variability in stream temperature conditions; (2) evaluate local responses in stream temperature to riparian thinning; (3) assess the spatial extent and temporal duration of downstream effects to local responses in temperature; and (4) characterize local and downstream responses to thinning with a conceptual framework based on waveforms. The researchers compared upstream, local, and downstream, stream temperature fluctuations following different intensities of streamside forest thinning at 10 treatment reaches across three watersheds in the redwood forests of northern California. Treatments varied by landowners. In two watersheds thinning treatments were intended to reduce 50% of canopy closure within the riparian zone along a 200 m reach on both sides of the active channel. This treatment resulted in a reduction in effective shade over the stream between 19-30%. In the other treatment watershed, thinning treatments reduced basal area by as much as 40% on both sides of the active channel along a 100 m long reach. Reductions in effective shade over the stream in these sites ranged from 4-5%. The analysis considered each reach both individually and collectively to understand how site and treatment heterogeneity may affect thermal responses at local and watershed extents. Temperature data were collected before, during, and after treatment and in the thinned experimental reaches and in adjacent unthinned control reaches with digital temperature sensors. Temperature data was collected for only 1-year pre-treatment and 1-year post-treatment. For data analysis, semivariograms of summer degree days were used to determine the presence of spatial autocorrelation. To control temporal variations in local and downstream responses summer cumulative degree-days were plotted for pre- and post- treatment temperatures and along a longitudinal gradient. A Lagrangian framework was used to track changes in temperature through space and time. Results showed that increases in thermal heterogeneity occurred in the treatment reaches, in the year following treatment (20° to 139°C), compared to the pre-treatment year (66° to 112°C). Local changes in stream temperature were dependent on thinning intensity, with higher levels of canopy cover reduction leading to higher increases in local stream temperatures. In the reaches with higher reductions in shade (19-30%) there was accumulation of 45° to 115°C additional degree days from pre- to post treatment years, while the reaches with lower reductions in shade (4-5%) only accumulated 10° to 15°C additional degree days. Travel distance of increased stream temperatures also appeared to be dependent on thinning intensity. The lower shade reduction reaches had an increased temperature effect downstream with travel distance of 75-150 m, while the high shade reduction sites had a downstream travel distance of 300- ~1000 m. In the high shade reduction sites, treatment reaches that were further apart (> 400 m) showed dissipation in increased stream temperatures downstream, while in parts of the stream where treatments were <400 m apart, temperature increases did not always dissipate before entering another the next treatment reach. The analyses with the conceptual framework based on waveforms showed there was no evidence of cumulative watershed effects at the downstream extent. The authors conclude that their results show evidence that riparian forest management impacts may extend beyond local stream environments. Further, the authors propose that riparian forest management that uses a holistic approach may be more effective in preserving some functions (e.g., shade).

Sediment

Wissmar et al., 2004

Wissmar, R.C., Beer, W.N. & Timm, R.K. (2004) Spatially explicit estimates of erosion-risk indices and variable riparian buffer widths in watersheds. Aquat. Sci. 66, 446–455 . DOI: 10.1007/s00027-004-0714-9

The purpose of this study is to use management records, the spatial distribution, and the variability of different landcover types that can contribute to unstable conditions to develop erosion-risk indices and variable riparian buffer widths in watersheds of different drainages in the State of Washington. The objectives of this study were to 1) define erosion risk indices based on “different land cover types,” 2) evaluate erosion risk indices with sediment inputs into streams, 3) use erosion risk categories to define locations of stream reaches that are susceptible to different levels of erosion 4) use categories to identify distribution of channels requiring variable width buffers for protection 5) Test procedure by applying ground-truthed data from the upper Cedar River drainage near Seattle, Washington. The land cover types used to assess risk included unstable soils, immature forests, roads, critical slopes for land failure, and rain-on-snow events. Based on available data, the researchers developed a map of these land cover features with sediment input values to define erosion risk indices. The indices were used to categorize the landscape into 6 levels of erosion risk. Results of the mapped erosion risk categories explained 65% of the variation associated with sediment inputs. The highest-risk areas contained a combination of all landscape cover factor combinations (rain-on-snow zone, critical failure slope, unstable soil, immature forests, and roaded areas). The lowest risk categories contained only rain-on-snow zones, and critical failure slopes. Roaded areas and unstable soils were only present in risk categories 3-6. This paper shows the importance of investigating multiple factors when evaluating the controls on sediment discharge and stream inputs. Further, when factors influencing erosion combine in an area, their effects are compounded.

Nutrient and forest structure

Devotta et al., 2021 (removed)

Devotta, D. A., Fraterrigo, J. M., Walsh, P. B., Lowe, S., Sewell, D. K., Schindler, D. E., & Hu, F. S. (2021). Watershed Alnus cover alters N: P stoichiometry and intensifies P limitation in subarctic streams. Biogeochemistry, 153(2), 155-176. DOI:10.1007/s10533-021-00776-w

This study investigates how coverage of alder species affects the aquatic N and P availability across a natural alder coverage gradient in 26 streams of southwestern Alaska. Alder coverage in the Alaskan streams was inversely related to elevation (i.e., lower coverage at higher elevations). To identify the presence of alder as the N and p contributing factor, the researchers analyzed resin lysimeter samples from select watershed soils supporting variable percent coverages of alder. Soils supporting alders leached, on average, three times more N and two times more P than soils not containing alders. The relationship between alder coverage and N and P values was not linear. Still, the authors identified 30% alder coverage as a transitional threshold from low to markedly higher soil N and p availability. The higher soil N and P resulted in higher dissolved N in streams, but the higher soil P under alder coverage did not translate to higher stream P availability. The authors speculate that soil chemistry or local soil biota may be immobilizing the soil P from transport into the streams. This led to a high N:P ratio in the spring and summer stream chemistry of reaches supporting >30% alder coverage. As climate change causes increasing temperatures, alder may begin to expand its range into higher elevations. This, in turn, may lead to increased N availability, but higher P limitations in high-elevation montane streams.

Sediment and lithology

Fratkin et al., 2020 (removed from focal, scope and results not relevant to review)

Fratkin, M. M., Segura, C., & Bywater-Reyes, S. (2020). The influence of lithology on channel geometry and bed sediment organization in mountainous hillslope-coupled streams. Earth Surface Processes and Landforms, 45(10), 2365-2379. https://doi.org/10.1002/esp.4885

This study compares the differences in channel form patterns, sediment flow, grain size, and sheer stress thresholds between two gravel-bed streams, one on basalt and one on sandstone parent material in the Oregon Coast Range. Study sites were in a region where widespread landslides and debris flows occurred in 1996. The researchers compared channel geomorphologies (e.g., slope, valley width, channel geometry, etc.) to evaluate thresholds and channel bed adjustments since the 1996 events. The results showed similar sediment coarsening patterns in the first several kilometers indicating hillslope influence, but downstream fining was lithology dependent. The authors hypothesized threshold channel conditions in the basalt basin, and non-threshold conditions in the sandstone basin with a tendency to expose bedrock, based on the relative competencies (i.e., basalt = high-competency, sandstone = low-competency). However, results showed evidence of threshold conditions for over 60% of the streams in both basins. The authors inferred a cycle adjustment to correct the assumed sediment delivery from the 1996 flood season. The authors speculate that the basalt basins would act as threshold channels over longer time periods despite a higher debris flow frequency. This paper provides some evidence that lithologies impose control on channel adjustments driven by different rock competencies. This difference in rock competency ultimately controls the grain size fining rates and bed load transport (sediment availability).

Nutrient and species composition

Whigham et al., 2017 (removed from focal)

Whigham, D. F., Walker, C. M., Maurer, J., King, R. S., Hauser, W., Baird, S., ... & Neale, P. J. (2017). Watershed influences the structure and function of riparian wetlands associated with headwater streams–Kenai Peninsula, Alaska. Science of the Total Environment, 599, 124-134. https://doi.org/10.1016/j.scitotenv.2017.03.290

This field study was designed to test the hypothesis that alder cover in watersheds influences the structure and function of riparian wetlands adjacent to headwater streams. The researchers compared biomass production, biomass distribution (aboveground vs. belowground), decomposition rates, and chemical characteristics of interstitial groundwater, between watersheds with and without alder coverage. Study sites were located on two headwater streams located in the Kenai Peninsula in south-central Alaska. The results showed that aboveground biomass was higher in watersheds with alder cover, but the largest differences were in the litter layer and the belowground biomass. Watersheds without alder had significantly higher belowground root biomass. The litter overhanging the stream was higher in N content at the alder sites than in the no-alder sites. The quantity of litter overhanging the stream was higher in the no-alder sites. Interstitial groundwater was significantly higher in dissolved N at the alder sites. The results of this study show that species composition within the riparian area can have a considerable effect on nutrient concentrations which consequently affect stream chemistry, biomass production, vegetation structure, and decomposition rates.

LW

Wing & Skaugset, 2002

Wing, M. G., & Skaugset, A. (2002). Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences, 59(5), 796-807. https://doi.org/10.1139/f02-052

This study investigated the relationships of land use, land ownership, and channel and habitat characteristics with LW quantity and volume in 3793 stream reaches in western Oregon State (west of Cascade crest). This study analyzed an extensive spatial database of aquatic habitat conditions created for western Oregon using stream habitat classification techniques and a geographic information system (GIS). The overall objectives of this study were to identify the database factors most strongly related to LWD abundance and to determine whether ownership and land use patterns are related to LWD abundance. Regression tree analysis is an exploratory regression analysis that allows for the inclusion of multiple explanatory variables. LW counts (by piece, and by key pieces (logs at least 0.60 m in diameter and 10 m long)) and volume were used as the response variables and explanatory variables included morphology of active channel (hillslope, terrace, terrace hillslope, unconstrained), lithology (e.g., alluvium, basalt, etc.), Land use and land cover (e.g., young timber, old timber, rural resident, agriculture, etc.), ownership (private industrial (PI), private non-industrial (PNI), state, federal (BLM, USFS)), vegetation type, and other channel characteristics. The analysis was run at the reach scale. Results showed that the most important predictor for LW volume was land ownership with PNI split from all other ownership types. Mean LW volumes in stream reaches with PNI ownership were 3.1 m^3 while mean volume of LW in reaches in all other ownerships (PI, state, BLM, USFS) were 17.9 m^3. However, this was likely because the PNI lands held a disproportionally higher percentage of unforested lands compared to all other ownership types. When the ownership and land use variables were removed, stream gradient became the most import explanatory variable for LW volume. The split for stream gradient occurred for reaches with < 2.3% gradient averaged 5.8 m^3 while higher gradient streams averaged 17.9 m^3 per reach. When ownership and land use were included but non-forested lands were removed, stream gradient again was the most important predictor with the split occurring for stream reaches with gradients less than 4.7% averaging 11.5 m^3 , which was less than half of the average found at higher gradient reaches (25.2 m^3); in this model the stream gradient split explained 11% of the variation observed of instream LW volume. For LW pieces in forested stream reaches bankfull channel width was the most important explanatory variable with the split occurring for streams channels less than 12.2 m wide. LW pieces for streams <12.2 m wide averaged 11.1 LW pieces per reach while larger channels averaged 4.9 pieces per reach; in this model the BFW split explained 7% of the variation in LW pieces found in forested streams. For key LW pieces (logs at least 0.60 m in diameter and 10 m long) in forested reaches, stream gradient was again the most important explanatory variable with the split occurring at a slope of 4.9%. The streams with a gradient < 4.9% averaged 0.5 key LW pieces per reach while streams with higher gradients averaged 0.9 key LW pieces per reach; in this model stream gradient explained 8% of the variation in key LW pieces found in streams. For forested streams, lithology caused second, third or fourth level splits after stream gradient or BFW. In three of these four splits, Mesozoic sedimentary and metamorphic geologies, located in southern Oregon stream reaches, were grouped and split from basalt, cascade, and marine sedimentary geologies. In stream reaches in Mesozoic sedimentary and metamorphic geologies, the quantity of LWD was roughly half the amount found in other geologies. The only exception to this grouping was for LW volume in larger stream reaches, where basalt and marine sedimentary geologies were grouped separately from all other geologies in a fourth-level split and contained more LW volume. The authors conclude that the geomorphic characteristics of stream reaches, in particular stream gradient and bankfull width, in forested areas correlated best with LW presence.

LW and plant communities

Rot et al., 2000

Rot, B. W., Naiman, R. J., & Bilby, R. E. (2000). Stream channel configuration, landform, and riparian forest structure in the Cascade Mountains, Washington. Canadian Journal of Fisheries and Aquatic Sciences, 57(4), 699-707. https://doi.org/10.1139/f00-002

This study investigates the hierarchical relationships between the "five key elements", valley constraint, riparian landform, riparian plant community, channel type, and channel configuration. for 21 sites in mature old-growth riparian forests of the western Cascade Mountains in Washington State. The objective of this article is to expand this perspective over several spatial scales and the temporal life span of a conifer by examining how channel configuration interacts with valley constraint, streamside landform, channel bedform, and successional processes within the riparian forest. Stepwise regression was used to examine the relationship between physical and biological characteristics and the individual elements of channel configuration. Channel configuration is the channel elements at the habitat unit scale, including channel units (total number of pool–riffle habitat units per 100 m of channel length), LW pieces (per 100 m of channel length), LW volume (cubic meters per 100 m of channel length), pool spacing, percent pools, and percent LW-formed pools. Results showed that significantly more total LW pieces were found in forced pool–riffle channels than in the bedrock and plane-bed channels (Kruskal–Wallis, $p < 0.05$). Forced pool–riffle channels averaged 16.4 pieces per 100 m, bedrock 10.8 pieces, and plane-bed 10.1 pieces. The volume of LW (cubic meters per 100 m) followed a similar trend. The percentage of deep pools (>0.5 m) formed by LW increased with stand age ($r^2 = 0.36$). LW diameters were significantly smaller for ages 55–220 than for ages 333–727 (Kruskal–Wallis, $p = 0.01$). The authors conclude that scale is an important consideration for management of aquatic habitat. At the largest spatial scale, results showed valley constraint significantly influenced off-channel habitat (plant communities associations and landform categories) and in-stream LW volume within forced pool-riffle channels. At the smallest scale, channel type (bedrock, plane-bed, and forced pool-riffle) was most closely related to LW volume, density, and the number of LW-formed pools. The diameter of the in-channel LW increased with riparian forest stand age. Streams adjacent to old-growth forests in-channel LW diameter were equivalent to or greater than the average standing riparian tree diameter at all sites. In younger stands, the relationship of in-stream LW diameter had a mixed relationship with riparian tree average diameters. The authors speculate this may be due to many in-stream LW pieces being relics from previous old-growth communities. In this area, four landform classes differentiated the riparian communities (floodplain, low terrace, high terrace, slope). Most were dominated by conifers, except the floodplain landforms, which supported a higher density of deciduous species, but a higher basal area of conifer species. The results of this study provide more evidence, similar to other studies, that channel geomorphology and valley constraint are important predictors of LW abundance (quantity and volume) in streams. The novelty in this study is how the riparian area landforms lead to different riparian plant communities, which consequently affect the input of LW.

Nutrients

Yang et al., 2021

Yang, Y., Hart, S. C., McCorkle, E. P., Stacy, E. M., Barnes, M. E., Hunsaker, C. T., ... & Berhe, A. A. (2021). Stream water chemistry in mixed-conifer headwater basins: role of water sources, seasonality, watershed characteristics, and disturbances. Ecosystems, 24(8), 1853-1874. DOI:10.1007/s10021-021-00620-0

This study investigated the effects of drought and forest thinning operations (independently and combined) on water chemistry from multiple basin water sources (snowmelt, soil solution, stream water) in the Mediterranean climate headwater basins of the Sierra National Forest. Data on water chemistry was taken 2 years prior and 3 years following drought and thinning operations in two watersheds, each with thinned and control stands. This data was analyzed to answer 3 questions: 1. How does the chemistry of different water sources (that is, snowmelt, soil solution at two depths, stream water) vary monthly and interannually prior to drought and thinning? 2. How does drought alone and drought combined with thinning impact water chemistry? 3. Can watershed characteristics predict stream water chemistry over contrasting water years? The authors used general linear models to analyze differences in chemistry by water source, repeated measures analysis of variance for effects of drought and thinning on water chemistry, and linear regression to predict water chemistry based on watershed characteristics. Results showed that monthly concentrations of dissolved C and N varied among different water sources prior to drought and thinning. For dissolved organic carbon (DOC) soil solution at 13 cm depth (mean ± SE of 25.97 ± 2.75 mg l^{-1}, across months for 2 years) had higher monthly concentrations than soil solution collected at 26 cm depth (16.93 ± 1.55 mg l^{-1}). Snowmelt (9.67 ± 0.89 mg l^{-1}) and stream water (5.33 ± 0.52 mg l^{-1}) had the lowest concentrations. For total dissolved Nitrogen (TDN) and dissolved organic nitrogen (DON), soil solution at 13 cm depth (1.72 ± 0.57 and 1.66 ± 0.57 mg l^{-1}, respectively), soil solution at 26 cm depth (0.94 ± 0.32 and 0.92 ± 0.32 mg l^{-1}), and snowmelt (0.94 ± 0.17 and 0.73 ± 0.18 mg l^{-1}) had higher concentrations than stream water (0.11 ± 0.02 and 0.08 ± 0.01 mg l^{-1}). For dissolved inorganic nitrogen (DIN), snowmelt (0.25 ± 0.05 mg l^{-1}) had the highest concentration followed by the soil solution at 13 cm depth (0.06 ± 0.01 mg l^{-1}). Soil solution at 26 cm depth (0.03 ± 0.01 mg l^{-1}) and stream water had the lowest values (0.04 ± 0.01 mg l^{-1}). For pH, snowmelt (pH 6.09 ± 0.06) was more acidic than soil solutions at both depths (7.52 ± 0.23 at 13 cm depth and 7.79 ± 0.11 at 26 cm depth) and stream water (7.37 ± 0.07). Drought alone altered DOC in stream water, and DOC:DON in soil solution in unthinned (control) watersheds. Volume-weighted concentration of DOC was 62% lower ($p < 0.01$) and DOC:DON was 82% lower ($p = 0.004$) in stream water in years during drought (WY 2013–2015) than in years prior to drought (WY 2009 and 2010). Drought combined with thinning altered DOC and DIN in stream water, and DON and TDN in soil solution. For stream water, volume-weighted concentrations of DOC were 66- 94% higher in thinned watersheds than in control watersheds for all three consecutive drought years following thinning. No differences in DOC concentrations were found between thinned and control watersheds before thinning. Watershed characteristics explained inconsistently the variation in volume-weighted mean annual values of stream water chemistry among different watersheds. The authors conclude that their results showed evidence that the influences of drought and thinning are more pronounced for DOC than for N in streams.

Geology

Kusnierz and Sivers, 2018 (removed from focal)

Kusnierz, P.C., Sivers, E., 2018. How important is geology in evaluating stream habitat? J Soils Sediments 18, 1176–1184. DOI:10.1007/s11368-017-1885-z

The purpose of this study was to assess the importance of considering geology when evaluating stream habitat conditions. Stream habitat data were collected from 424 sites on federally managed lands in western Montana, USA. These sites represented a variety of ecoregions, stream types, management practices, and geologies. The importance of accounting for geology in data analysis was evaluated using five sediment-related habitat variables and three analyses that examined (1) differences across geology for the entire dataset and for sites in reference and managed watersheds; (2) differences between reference and managed sites within geologies; and (3) the relative strength of geology as a factor when accounting for the effects of management, stream type, and ecoregion. This objective was pursued by using five sediment-related habitat variables (Log instability index, Log roughness-corrected index of relative bed stability, Median substrate size, Percent pool tail fines < 6 mm, Percent stable banks). Five sediment-related habitat variables were collected from 424 sites on federally managed lands between 2009-2012.Factorial ANOVA on ranks was performed to evaluate the relative importance of geology when other factors were taken into account. Results from this study show that differences in sediment-related habitat variables did not differ significantly according to geology; however, observed differences were typically drawn from managed sites. The authors conclude by advising against using geology as the sole means of stratifying habitat data when attempting to account for between-site variability.

Stream Temperatures

Leach et al., 2017 (removed from focal list)

Leach, J.A., Olson, D.H., Anderson, P.D., Eskelson, B.N.I., 2017. Spatial and seasonal variability of forested headwater stream temperatures in western Oregon, USA. Aquat Sci 79, 291–307. DOI:10.1007/s00027-016-0497-9

This study is a case study of thermal regimes for headwater streams in the Keel Mountain Study area. This study examined (1) forested headwater stream temperature variability in space and time; (2) relationships between stream temperature patterns and weather, above-stream canopy cover, and geomorphic attributes; and (3) the predictive ability of a regional stream temperature model to account for headwater stream temperature heterogeneity. Stream temperature data was collected at 48 sites within a 128-ha watershed in western Oregon between 2012 and 2013. Spatial statistical modeling was used to relate stream temperature patterns to site characteristics (elevation, stream width, catchment area, slope, aspect, channel substrate, and terrain shading), a cluster analysis was used to capture the full variability in annual stream temperatures. Results from this study show considerable variability in stream temperature over relatively small areas, and between seasons. The greatest spatial variability existed during summer (up to 10 Celsius) and during cold and dry winter periods (up to 7.5 Celsius). Geomorphic attributes typically used in stream temperature models were not good predictors of variability at headwater scales.

Stream Temperatures

Groom et al., 2011b

Groom, J.D., Dent, L., Madsen, L.J., Fleuret, J.(2011b). Response of western Oregon (USA) stream temperatures to contemporary forest management. Forest Ecology and Management 262, 1618–1629. https://doi.org/10.1016/j.foreco.2011.07.012

The objective of this paper was to assess the riparian characteristics that best predict shade, and to determine the stream temperature changes that result following harvest. This study took place in the Oregon Coastal Range at 33 sites (15 state-owned and 18 private-owned). The 33 sites studied were approximately 50-70 years old and predominately composed of Douglas-fir and red alder. Private sites (n = 18) followed FPA rules whereby the riparian management area (RMA)s are 15 and 21 m wide on small and medium fish-bearing streams, with a 6 m no-cut zone immediately adjacent to the stream. Harvesting is allowed in the remaining RMA to a minimum basal area of 10.0 (small streams) and 22.9 (medium streams) m^2/ha. State sites (N = 15) followed the state management plan whereby a 52 m wide buffer is required for all fish-bearing streams, with an 8 m no cut buffer immediately adjacent to the stream. Limited harvest is allowed within 30 m of the stream only to create mature forest conditions. Harvest operations within this zone must maintain 124 trees per hectare and a 25% Stand Density Index. Additional tree retentions of 25–111 conifer trees and snags/hectare are required between 30 and 52 m. A site's control reach was located immediately upstream of its treatment reach. The control reaches were continuously forested to a perpendicular slope distance of at least 60 m from the average annual high-water level. Reach lengths varied from 137 m to 1,829 m with means of 276 m and 684 m for the control and treatment reaches, respectively. Temperature recording stations were located upstream and downstream of both control and treatment sites. Stream temperature data was summarized to provide daily minimum, maximum, mean, and fluctuation for analysis. The temperature data was modeled using mixed-effects linear regression. Shade analysis included trees per hectare, basal area per hectare, vegetation plot blowdown, and tree height. A linear regression analysis of shade data (n = 33) was performed and compared small-sample AIC values to determine relative model performance among 8 a priori models. Results showed that average, minimum, and diel stream temperatures increased on private sites following harvest, suggesting a relationship between decreased shade derived from buffer width and an increase in stream temperature. Outputs from the model predicted an increase of ~2 °C for minimum shade conditions and a decrease of ~ -1 °C for maximum shade conditions. For sites that exhibited an absolute change of shade > 6% from pre-harvest to post-harvest experienced an increase in maximum temperatures. Further, the model predicted an increase in stream temperature proportional to treatment reach length. The authors estimate an increase in maximum and minimum temperatures of 0.73 and 0.59 °C per km, respectively. Following harvest, maximum temperatures at private sites increased relative to state sites on average by 0.71 °C. Similarly, mean temperatures increased by 0.37 °C (0.24 - 0.50), minimum temperatures by 0.13 °C (0.03 - 0.23), and diel fluctuation increased by 0.58 °C (0.41 - 0.75) relative to state sites. A comparison of within site changes in maximum temperatures pre-harvest to post-harvest showed an overall increase at private sites, but not all sites behaved the same and some had decreases in maximum temperatures. The average of maximum state site temperature changes = 0.0 ºC (range = -0.89 to 2.27 ºC). Observed maximum temperature changes at private sites averaged 0.73 ºC (range = -0.87 to 2.50 ºC) and exhibit a greater frequency of post-harvest increases from 0.5 to 2.5 ºC compared to state sites. Private site shade values also appeared to decrease pre-harvest to post-harvest. Private post-harvest shade values differed from pre-harvest values (mean change in Shade from 85% to 78%); however, no difference was found for state site shade values pre-harvest to post-harvest (mean change in Shade from 90% to 89%). They did not find evidence that shade differed if one or both banks were harvested for private sites although the sample size for single sided harvests was low. Similarly, private site shade values did not appear to differ between medium or small streams. Results from this study also show that between 68% and 75% of variability in post-harvest shade may be accounted for by basal area within 30 m of the stream, tree height, and potentially blowdown. The authors speculate that their results suggest sites with shorter trees have higher post-harvest shade and this may be due to the negative correlation between crown ratios and tree heights. Overall, this study shows that buffers managed by state sites were sufficient at mitigating the effects of upland harvesting on stream temperature. Increases in stream temperature on private sites were related to decreases in shade, which were related to decreases in basal area on sites with greater tree heights. The authors suggest that their results are likely relevant to other high-rainfall low-order Douglas-fir dominated streams in the Pacific Northwest that are subject to similar harvest practices.

Litter

Yeung et al., 2019

Yeung, A. C., Stenroth, K., & Richardson, J. S. (2019). Modelling biophysical controls on stream organic matter standing stocks under a range of forest harvesting impacts. Limnologica, 78, 125714. https://doi.org/10.1016/j.limno.2019.125714

This study investigates the relative impact of major biophysical controls (stream temperature, riparian litterfall, and stream discharge) on in-stream CPOM (coarse particulate organic matter) quantity across a variety of streamside timber harvest intensities using simulation modeling. The CPOM model used was developed by Stenroth et al., 2014, for similar stream types and conditions of coastal rainforest streams of British Columbia. The model was calibrated using data from multiple published studies from, primarily the Pacific Northwest region, and several other North American regions, that quantified stream flow, temperature, and CPOM following different timber harvest intensities within 4 years of harvest. The model used an estimated response of low, moderate, high, and very high severity timber harvest for litterfall (-10%, -30%, -50%, -90%), peak flows (+20%, +40%, +100%, +300%), and stream temperature (+1°C, +2°C, +4°C, +6 °C). These changes in litterfall, peak flow, and stream temperature were modeled and analyzed individually and cumulatively to estimate their relative and combined effects on in stream CPOM standing stocks. Results of the model showed that in general the standing stocks of CPOM decreased under the independent effects of reduced litterfall and elevated peak flows and increased with higher stream temperatures. Along the gradient of harvest severities, litterfall reductions on depleting CPOM standing stocks were at least an order of magnitude greater than those of elevated peak flows. At low severity, litterfall reductions led to a 13.5% reduction of CPOM stocks while peak flow increases at high severity harvest only led to a 5% reduction in CPOM stocks. The magnitude of CPOM changes induced by litterfall reductions was consistently greater than stream temperature increases, but their differences in magnitude became smaller at higher levels of disturbance severity. For example, at low severity, stream temperatures only led to an increase on CPOM stocks by 1.1% while litter fall reductions led to a reduction of CPOM by 13.5%. However, at the high intensity treatment CPOM stocks changed by –90.24%, and +72.07% for litterfall, and stream temperature respectively. For scenarios involving perturbations of multiple model drivers (combined effects), the effect size of disturbance was significantly negative (indicating significantly lower CPOM standing stocks than in undisturbed conditions) whenever litterfall reductions reached 50% or above (i.e., high severity). When litterfall reductions were 30% or below, the effect size of disturbance varied with the relative changes in peak flows and stream temperature. Only the effects of litterfall-temperature interactions on CPOM standing stocks were significant ($p < 0.001$). The authors interpret these results as evidence that litterfall reduction from timber harvest was the strongest control on in-stream CPOM quantity for 4 years post-harvest. Further, the authors propose that the decreased activity of CPOM consumers caused by increasing stream temperatures may be enough to offset the loss of litterfall inputs on CPOM stocks. The caveat of this study is that it did not include LW dynamics in preserving CPOM post-harvest. As other studies have shown, harvest can increase in-stream LW, and in-stream LW can act as a catchment for CPOM.

Drought Frequency

Wise, 2010

Wise, E. K. (2010). Tree ring record of streamflow and drought in the upper Snake River. Water Resources Research, 46(11). https://doi.org/10.1029/2010WR009282

This study used newly collected tree-ring data augmented with existing chronologies from sites at three headwater streams in the Snake River Basin to estimate streamflow patterns for the 1600-2005 time-period. The reconstructed chronologies were tested for significant correlations with streamflow patterns during the 1911-2005 time period prior to extrapolation. Streamflow patterns derived from instrumental data and from reconstructed chronologies were compared with other streamflow reconstructions of three other western rivers in similar climates to examine synchronicity among the rivers and gain insight into possible climatic controls on drought episodes. The reconstruction model developed for the analysis explained 62% of the variance in the instrumental record after adjustment for degrees of freedom. Results showed evidence that droughts of the recent past are not yet as severe, in terms of overall magnitude, as a 30-year extended period of drought discovered in the mid-1600s. However, in terms of number of individual years of < 60% mean-flow (i.e., low-flow years), the period from 1977-2001 were the most severe. Considering the frequency of consecutive drought years, the longest (7-year-droughts), occurred in the early 17th and 18th centuries. However, the 5-year drought period from 2000-2004 was the second driest period over the 415-year period examined. The author explains that the area has continued to experience a drought period, but its severity could not be calculated as it hadn't ended by the time of the study (2010). The correlative analysis of the chronologies developed for the upper Snake River with other rivers of the West (the upper Colorado, the Sacramento, and the Verde Rivers) showed mixed results with periods of positive and negative correlations. The author interprets these results as evidence that drought frequency in general, in this area appears to be increasing in severity and that mean annual flow appears to be reducing in the latter half of the 20th and the beginning of the 21st century. The exceptions being the 1930's dustbowl, and an unusually long dry period in the early 1600s.

Shade and structure

Warren et al., 2013

Warren, D. R., Keeton, W. S., Bechtold, H. A., & Rosi-Marshall, E. J. (2013). Comparing streambed light availability and canopy cover in streams with old-growth versus early-mature riparian forests in western Oregon. Aquatic sciences, 75(4), 547-558. DOI:10.1007/s00027-013-0299-2

This study investigates the differences in canopy cover and streambed light availability between paired reaches in old-growth (> 500 years old) and secondary-growth (~40-60 years old) riparian forests on canopy cover and streambed light exposure in four second order fish-bearing streams in the H.J. Andrews Experimental Forest. Streams were paired based on reach length and bankfull width and north (n =2), and south (n=2) facing watersheds. The overall mean percentage of canopy cover was estimated using a convex spherical densiometer every five meters along the thalweg of each stream reach. At each point densiometer readings were taken from four directions (upstream, downstream, left bank, right bank) The amount of light reaching the bottom of the stream was estimated every five meters using fluorescent dye that degrades overtime from light exposure. Differences in light availability and canopy cover were analyzed separately for each of the four reaches using a single factor ANOVA. To avoid the inclusion of overlapping canopy images from adjacent densiometer sampling locations, the canopy cover data from sites every 15 m (rather than every 5 m) were used in the comparison of canopy cover between the two age classes along each reach. Linear regression was used to compare values from mean densiometer readings with mean dye photodegradation site (every 5 meters). To evaluate the hypothesis that light availability in old-growth forested streams would be more variable than in second-growth forested streams, the standard deviations of the mean densiometer readings and mean photodegradation values were compared between old-growth and second-growth forested streams with an ANOVA. Results showed that the differences in stream light availability and percent forest cover between old-growth and second-growth reaches were significant in both of the south-facing watersheds in mid-summer at an alpha of 0.01 for the dye results and 0.10 for the cover results. For the north-facing watersheds differences in canopy cover and light availability (alpha = 0.01, and 0.10 respectively) were only significant at 1 of the two reaches. Overall, three of the four paired old-growth reaches had significantly lower mean percent canopy cover, and significantly higher mean decline in fluorescent dye concentrations The authors interpret these results as evidence that old-growth forest canopies were more complex and had more frequent gaps allowing for more light availability and lower mean canopy cover, on average, than in adjacent mature second-growth forests.

LW

Teply et al., 2007

Teply, M., McGreer, D., Schult, D., & Seymour, P. (2007). Simulating the effects of forest management on large woody debris in streams in northern Idaho. Western Journal of Applied Forestry, 22(2), 81–87. https://doi.org/10.1093/wjaf/22.2.81

This paper uses simulation modeling to estimate the effects of timber harvest, under the Idaho Forest Plan (IFP), on in-stream LW loading for Class I streams (fish-bearing streams) of the Priest Lake Watershed in northern Idaho relative to unharvested riparian forest streams. Under the IFP, class one streams have a 25-foot no-cut-buffer that extends out from the high-watermark, and an additional 50 feet beyond the edge of the no-cut-buffer where harvest requires retention of 88-trees-per-acre that are greater than 8-in diameter at breast height (DBH). This study used the Riparian Aquatic Interaction Simulator (RAIS) to estimate the potential wood loading for 58 randomly selected north Idaho stream segments with and without harvest. Stream segments were measured in the field along the stream centerline from the upstream starting point (0 ft) to a downstream ending point (200 ft). Riparian stand conditions were measured within 75 ft-long by 10-ft-wide strips oriented perpendicular to the stream at 25, 75, 125, and 175 ft downstream of the upstream starting point on each side of the stream segment to provide a total of eight strips for each stream segment. Along each strip, live trees and snags greater than 8 in dbh within the strip were located and measured. Three circular subplots, each 10 ft in diameter, were located along each 75-foot strip plot at 12.5, 37.5, and 62.5 ft from the stream edge. Within the subplots, smaller live trees (less than 8-in. dbh) were tallied by 1-in. dbh classes. Instream LW loads were surveyed along the same 200-ft stream segments located for measuring riparian stand conditions. Qualifying LW (greater than 4-in diameter and longer than 6.6 ft) occurring within the high-water mark along the entire extent of the segment was tallied. Observed instream LW loads ranged from 10 to 710 pieces per 1,000 ft of stream. Stream size measured by bank full width covered a wide range (1 ft to 190 ft), averaging 32.5 ft (SD = 28.1). The authors determined that active streambank erosion was uncommon in the study area and did not include it as a LW recruitment mechanism in their analysis. Simulation was based on a four-step process applied to each riparian stand: 1) Harvest the stand according to riparian management prescriptions, 2) Predict stand characteristics using growth and yield simulators, 3) Estimate the number of trees that fall due to mortality in each time step, 4) Calculate the probability that a tree would deliver LWD to the stream. The simulation evaluated both a harvest and a no-harvest scenario to predict mean in-stream LW loads after 30, 60, and 100 years. The results predicted mean LW loads at 30 years for the 58 segments studied were 151.1 pieces per 1,000 ft for the no-harvest scenario (SD = 76.2) and 145.1 pieces per 1,000 ft for the harvest scenario (SD = 75.6), which were not significantly different ($P = 0.67$). However, on a pairwise basis, loads predicted for these segments using the harvest scenario were significantly lower by an average of about 6.0 pieces per 1,000 ft than those predicted via the no-harvest scenario (P < 0.001). Compared to the initial surveyed LW loads, LW loads at 30 years predicted in the no-harvest scenario decreased by an average of 19.5 pieces per 1,000 ft, representing a significant (P < 0.007) downward shift in the distribution. Predicted mean LW loads at 60 years were 136.1 pieces per 1,000 ft in the no-harvest scenario (SD = 49.2) and 128.3 pieces per 1,000 ft under the harvest scenario (SD = 48.3). At 100 years, predicted mean LW loads were 122.5 (SD = 35.4) and 116.7 (SD = 35.8), respectively. Based on 20-piece LW classes, the frequency distributions of predicted loads between the scenarios were not significantly different at either time step. However, on a pairwise basis, predicted loads for the harvest scenario were significantly lower than the no-harvest scenario by an average of 7.8 (P < 0.001) and 5.8 (P < 0.001) pieces per 1,000 ft at 60 years and 100 years, respectively. Compared to LW loads predicted at 30 years and 60 years, LWD loads decreased significantly on a pairwise basis by an average of 15.1 (P < 0.001) and 13.6 (P < 0.001) at 60 and 100 years, respectively. The authors note that the collective effect of the assumptions made for the simulation is likely to underestimate the number and variability of LW pieces recruited and retained in the streams sampled. The authors interpreted these results as evidence that the IFP prescriptions for class I Idaho streams were sufficient in maintaining LW recruitment potential.

Shade

Swartz et al., 2020

Swartz, A., Roon, D., Reiter, M., & Warren, D. (2020). Stream temperature responses to experimental riparian canopy gaps along forested headwaters in western Oregon. *Forest Ecology and Management*, *474*, 118354. https://doi.org/10.1016/j.foreco.2020.118354

This study tested the effects of adding canopy gaps within young, regenerating forests of western Oregon on stream light availability and stream temperatures. The addition of gaps in the young regenerating forests were used to theoretically mimic the natural disturbance regimes and the higher canopy complexity of late-successional forests. The researchers used a before-after-control-impact design on six replicated streams within the Mckenzie River Basin. In the experimental reaches 30 m gaps were created, centered on a tree next to the stream and at least 30 m in from the beginning of the reach. The study reaches were located on second- and third-order fish-bearing steep step-pool and cascade dominated headwater streams with boulder substrate that ranged from 2.2 to 6.4 m in bankfull width and were lined by 40- to 60-year-old riparian forests. Study sites in each stream encompassed two 120 m reaches with no large tributary inputs within or between the study reaches, and reference and treatment reaches were separated by a buffer section of 30–150 m. In each treatment reach, gaps were designed to create openings in the canopy that were approximately 20 m in diameter. Gaps were centered on a tree next to the stream at approximately meter 30 along each reach. The gaps sizes were intended to mimic naturally occurring gaps from an individual large tree mortality or small-scale disturbance events found in these systems which range from 0.05 to 1.0 gap diameter to tree height ratio with smaller gaps occurring more frequently. Using the Douglas-fir canopy height of 50 m, gaps were created in the 0.4–1.0 gap diameter to tree height ratio range (approximately 314 m2 – 1,963 m2). Actual gap sizes varied across sites from approximately 514 m2 to 1,374 m2 (0.45 – 0.74 gap ratios) with a mean of 962 m2 (mean gap ratio 0.61). Riparian shade was quantified with hemispherical photos. Light reaching the stream was quantified using photodegradation of fluorescent dyes placed at 5 m intervals, over a 24 -hour period. Stream temperature was recorded continuously, at 15-minute intervals, using HOBO sensors to quantify the seven-day moving average of mean and maximum temperatures. Data was collected for one year pre-harvest, during harvest year (harvest took place in late fall 2017), and one-year post-harvest. To determine the effects of experimental canopy gaps on stream light as well as reach responses a linear mixed-effects model was fit to the data. The results showed that after gaps were cut, the BACI analysis showed strong evidence for significant increase in mean reach light ($p < 0.01$) to a mean of 3.91 (SD ± 1.63) moles of photons m^{-2} day^{-1}. overall resulting in a mean change in light of 2.93 (SD ± 1.50) moles of photons m^{-2} day^{-1}. Mean stream shading could not be evaluated in the full BACI analysis because post-treatment hemispherical photographs could not be taken at all sites due to fire impeding access in 2018. For the remaining sites, the areas beneath each gap had notable localized declines in shade, through the entirety of the treatment reach mean shading declined by only 4% (SD ± 0.02%). Overall, the gap treatments did not change summer T 7DayMax or T 7DayMean significantly across the 6 study sites. The mean response (change in reach difference before and after the cut) indicated an increase on average across the six sites in T7DayMax of 0.21 °C (±0.12 °C) and in the T7DayMean of 0.15 °C (±0.14 °C); however, there was not statistical support of the BACI effect for either metric. The light response was not correlated with T 7DayMax responses ($r2 < 0.01$, $p = 0.69$), nor was gap area ($r2 = 0.01$, $p = 0.63$), but there was a significant relationship between discharge ($r2 = 0.73$, $p = 0.03$), and bankfull width ($r2 = 0.93$, $p < 0.01$) and the T7DayMax response. Wetted width was also highly correlated with T 7DayMax responses, but the relationship was not as strong with this stream size metric as with discharge or bankfull width ($r2 = 0.65$, $p = 0.05$). In contrast to the summary values, results from the analysis of individual days throughout the full 40-day summer period identifying differences in the relationships of daily maximums and daily means between reaches showed a statistically significant effect of the gap for average daily maximums ($p < 0.01$) and for average daily means ($p = 0.02$). The regression comparison reveals there will be on average an additional 0.12 °C/⁰C increase in daily maximum temperature in the reach with a gap. Likewise, for the daily mean, for every degree increase in the shaded reference reach, an average additional increase of 0.05 °C in a reach with a small gap is expected. The authors conclude that adding gaps to young regenerating forests only minimally increases temperatures, dependent on stream size, and that riparian canopy gaps may be a viable management strategy that can be implemented with minimal effects on stream temperatures. This paper does not quantify changes in stream productivity, also expected from the increase in available light.

Shade

Sugden et al., 2019

Sugden, B. D., Steiner, R., & Jones, J. E. (2019). Streamside management zone effectiveness for water temperature control in Western Montana. International Journal of Forest Engineering, 30(2), 87-98. https://doi.org/10.1080/14942119.2019.1571472

This study investigates the effects of riparian forest timber harvest, under the Montana Streamside Management Zone (SMZ) laws, on stream temperature in Class 1 streams (fish-bearing, or flow more than 6 months per year and are connected to downstream waters). Montana state law requires timber be retained within a minimum of 15.2 m of the class 1 streams, with equipment exclusion zones extended on steep slopes for up to 30.5 m. Within the SMZ no more than half the trees greater than 204 mm (8 in) diameter at breast height (DBH) can be removed, and trees retained must be representative of the pre-harvest stand. In no case, however, can stocking levels of leave trees be reduced to less than 217 trees per hectare. The objectives of this study were to fill the information gap in this region by: (1) evaluating the performance of 15.2 m SMZs retained during harvest activities for protecting against adverse changes in summer maximum stream temperatures, (2) quantifying the level of timber removal occurring within operational SMZs that may help explain any observed changes, and (3) Evaluating fish response that may be associated with a stream temperature change. Data for stream temperature and fish population response was collected for 30 harvest reaches in western Montana (northern Rocky Mountain Region), for a minimum of one-year pre- and one-year post-harvest. Data for stream temperatures and fish populations were also collected from unharvested references reaches upstream from the harvest sites as a control. Temperature data was collected with Optic StowAway™ and StowAway TidBit™ digital temperature loggers manufactured by Onset Computer Corporation. Shade over the stream surface was not directly measured in this study. Canopy cover was estimated using a combination of simulation modeling and using a concave spherical densiometer. Fish populations were estimated for 100 m reaches at study sites using an electro-fishing pass of capture method. Linear mixed effects models were used to analyze the relationship between year, stream position, harvest, fish populations and stream temperatures. The results showed that within harvest areas, the mean basal area (BA) declined from 30.2 m2/ha pre-harvest to 26.4 m2/ha post-harvest (mean = –13%, range from -32% to 0%). Windthrow further reduced the mean BA to 25.9 m2/ha (mean = -2%, range = -32% -0%). Changes in mean canopy cover were not significant based on the simulation modeling (-3%), or densiometer readings (+1%). Results of the model for the effect of harvest on stream temperature showed no detectable increase in treatment streams relative to control streams. The estimated mean site level response in maximum weekly maximum temperatures (MWMT) varied from –2.1 °C to +3.3 °C. Overall, 20 of 30 sites had estimated site level response within ±0.5 °C. There were five sites that had an estimated site-level response greater than 0.5 °C (i.e.

warming) and five sites that had an estimated site level response less than –0.5 °C (i.e. cooling). Results for the fish population showed approximately 7% increase in trout population from pre-harvest to post-harvest, but this difference was not significant. The authors conclude that the results suggest that Montana's 15.2 m SMZs retained during timber harvest activities are highly protective (change <0.5°C) of stream temperatures.

LW

Sobota et al., 2006

Sobota, D. J., Gregory, S. V., & Sickle, J. V. (2006). Riparian tree fall directionality and modeling large wood recruitment to streams. Canadian Journal of Forest Research, 36(5), 1243–1254. https://doi.org/10.1139/x06-022

The objectives of this study were to evaluate patterns of riparian tree fall directions in diverse environmental conditions and evaluate correlations with tree characteristics, forest structural variables, and topographic features. Specifically, the authors were interested in correlations between fall directionality and tree species type, tree size, riparian forest structure, and valley topography (side slope). Data was collected from 21 field sites located west of the Cascade Mountains crest (11 sites: Coast Range and west slopes of the Cascades), and in the interior Columbia Basin (10 sites: east slopes of the Cascades, Blue Mountains, and Northern Rockies) of Oregon, Washington, Idaho, and Montana, USA. Streams were second- to fourth-order channels and had riparian forests that were approximately 40 to >200 years old. The location of specific study reaches (200–300 m stream length) on each stream were selected randomly. Minimum size criteria for a fallen tree in this study were diameter at breast height (DBH) of 0.1 m and height of 5 m. All fallen trees up to 50 m slope distance from stream or the first 100 trees were measured at all sites. Tree fall direction was standardized among sites by streamside location (upstream = 0° and 360°; toward stream = 90°; downstream = 180°; away from stream = –90° and 270°). Spearman rank correlations were used to compare site level statistics of tree fall directions with physical and riparian forest characteristics. Then trees were pooled among sites and classified by species for analysis of species, tree size, and valley side slope effects. To avoid small sample sizes species were grouped by side slope categories (< 40%, >40%). Average direction of tree fall by site was significantly correlated with valley constraint (Spearman r = –0.53; P = 0.02). Average direction of tree fall by site was weakly correlated with active channel width, tree stem density, and basal area (P > 0.05), with Spearman r coefficients of 0.22, –0.21, and 0.39, respectively. Trees on valley side slopes >40% for each species had a 95% CI that only included falls directly towards the stream channel; trees on side slopes <40% had a 95% CI for mean fall direction that included directly upstream, downstream, away from the stream, towards the stream, or all four directions simultaneously (consistent with random fall directions), depending on species. Tree size was only different between side slope categories for coastal Douglas fir on >40% side slopes which had a median DBH 1.2 to 1.9 times greater than trees on <40% side slopes. Also, red alder trees on side slopes > 40% had a median DBH 1.1 to 1.6 times greater than on side slopes < 40%. Model projections of LW recruitment calibrated with the results of the spearman rank correlations estimated that sites with uniform steep side slopes (>40%) produced between 1.5 (first resolution) to 2.4 (second resolution) times more in stream LW by number of tree boles than sites with uniform moderate side slopes (< 40%). The authors interpret their results as evidence that edaphic, topographic, and hydrologic characteristics are related to greater variability of tree fall directions on moderate slopes than on steep slopes. The authors conclude that models that use tree fall directions in predictions of LW recruitment should consider stream valley topography. The authors warn that while side slope categories (>40%, <40%) was the strongest predictor of tree fall direction in this study, they believe the differences in tree fall direction between these categories mainly characterized differences between fluvial (88% of moderate slope sites) and hillslope landforms (71% of steep slope sites). They suggest that the Implications from this study are most applicable to small- to medium-size streams (second- to fourth-order) in mountainous regions where sustained large wood recruitment from riparian forest mortality is the significant management concern.

LW

Schuett-Hames & Stewart, 2019a

Schuett-Hames, D., & Stewart, G. (2019a). Post-Harvest Change in Stand Structure, Tree Mortality and Tree Fall in Eastern Washington Riparian Buffers: Comparison of the Standard and All Available Shade Rules for the Fish-Bearing Streams in the Mixed Conifer Timber Habitat Type Under Washington's Forest Practices Habitat Conservation Plan. Cooperative Monitoring Evaluation and Research Report CMER. Washington State Forest Practices Adaptive Management Program. Washington Department of Natural Resources, Olympia, WA.

This report is a comparative analysis of the differences in strand structure, tree fall, and LW recruitment between riparian sites of eastern Washington harvested under the current Standard Shade Rule (SR), under the All-Available Shade rule (AAS), and unharvested reference sites (REF). Both shade rules have a 30-ft no-cut buffer (core zone) immediately adjacent to the stream. The SR prescription allows thinning in the buffer zone 30-75 feet (inner zone) from the stream while the AAS prescription requires retention of all shade providing trees in this area. Post-harvest surveys were completed at each site one−two years and five years post-harvest. A census was done of all standing trees ≥4 inches diameter at breast height (DBH) within 75 feet (horizontal distance) of the channel on both sides of the stream in each treatment and reference reach. The condition (live or dead), species, canopy class, and DBH were recorded for each tree.

Dead or fallen trees with a decay class of 1 or 2 were classified as post-harvest mortality and a mortality agent was recorded (e.g. wind, erosion, suppression, fire, insects, disease, and physical damage). Metrics were calculated separately for regulatory zones defined by horizontal distance from the channel, including the core zone (0–30 feet) and inner zone (30–75 feet) and the combined core and inner zone (the full RMZ). Mixed model analysis was used to evaluate differences in treatment response. Results showed Cumulative wood recruitment from tree fall over the five-year post-harvest interval was highest in the SR group, lower in the AAS group and lowest in the REF group. The SR and AAS rates by volume were nearly 300% and 50% higher than the REF rates, respectively. The mixed model comparisons indicated that the frequency of wood input from fallen trees was significantly greater in SR group compared to both the REF and AAS groups ($p < 0.001$), while the difference between REF and AAS groups was not significant. Over 60% of pieces recruited from AAS and SR fallen trees consisted of stems with attached rootwads (SWAR), double the proportion in the REF sites. The REF-AAS and REF-SR differences in recruitment of SWAR pieces were significant ($p < 0.001$). Most recruiting fallen trees originated in the core zone (76%, 72%, and 64% for the REF, AAS and SR groups, respectively), while the proportion from the inner zone (30–75 feet from the stream) was ~10% greater for the SR group compared to the AAS and REF groups. The authors interpret the results and conclude that harvest of the adjacent stand outside the RMZ appeared to alter the spatial pattern of wood recruitment from fallen trees, increasing recruitment from trees located farther from the stream. Recruitment of fallen trees from the inner zone of the AAS and SR sites were two and four times the rate for the inner zones of the unharvested reference sites due to increased tree fall from wind disturbance in the buffers after harvest of the adjacent stand, as reported in other studies. It is important to note that this was a short-term study (5 years). The authors note that LW recruitment is a process that can change over decadal time scales. Adding that thinning and post-harvest mortality also reduced the standing stock of trees available for wood recruitment in the SR and AAS RMZs compared to unharvested REF RMZs.

Litter and LW

Six et al., 2022

Six, L. J., Bilby, R. E., Reiter, M., James, P., & Villarin, L. (2022). Effects of current forest practices on organic matter dynamics in headwater streams at the Trask River watershed, Oregon. Trees, Forests and People, 8, 100233. https://doi.org/10.1016/j.tfp.2022.100233

This study investigates the effects of different riparian timber harvest intensities on changes in canopy cover, and litter input into streams and litter transport downstream. The objective of this study was to investigate whether differing levels of tree retention adjacent to the channel altered coarse particulate organic matter (CPOM) delivery, retention, and transport. The authors hypothesized an inverse relationship between tree removal and litter delivery (i.e., increase in tree removal adjacent to the channel would result in a reduction of litter delivery). Data was collected for leaf litter in streamside litter traps, canopy cover percentage using hemispherical photos in-stream LW, and litter retention in stream flume litter traps pre- and post-treatment at five watersheds of the Trask River in the northern Oregon Coast range. The experimental design included three treatment watersheds: clearcut with no leave trees or retention buffer (CC), clearcut with leave trees (CC w/LT; retention of 5 trees per hectare/2 trees per acre), and clearcut with 15 m wide retention buffer (CC c/B) and two uncut references (REF 1, and 2) along headwater streams. Because there were no replication sites for treatments, data was analyzed using descriptive and graphical summaries of the data (i.e., no quantitative statistical analysis). Results showed a reduction of canopy cover from 91.4% to 34.4% in the clearcut treatment with no leave trees, from 89.8% to 76.1% in the clearcut treatment with leave trees, and from 89.5% to 86.9% in the clearcut treatment with the 15 m retention buffer. Change in canopy cover in the reference streams was < 1% for both reaches. Post harvest litter delivery decreased for the clearcut with no leave trees but increased for both the clearcut with leave tree and clear cut with retention buffer. The number of logjams, the total weight of logjams, and the volume of LW in streams increased for all treatment sites. The results of this study were consistent with similar studies and provide supporting evidence that riparian timber harvest can affect litter and LW delivery into and retention in streams.

Shade and LW

Schuett-Hames et al., 2011

Dave Schuett-Hames, Ashley Roorbach, Robert Conrad. 2011. Results of the Westside Type N Buffer Characteristics, Integrity and Function Study Final Report. Cooperative Monitoring Evaluation and Research Report, CMER 12-1201. Washington Department of Natural Resources, Olympia, WA.

This report presents the results from the Washington State Westside Type N Buffer Characteristics, Integrity and Function (BCIF) study. The purpose of the study was to evaluate the effects of westside riparian timber harvest prescriptions for Type Np (perennial non-fish-bearing) streams on resource objectives (riparian stand tree mortality, wood recruitment, channel debris, shade, and soil disturbance) described in the Forest and Fish Report of 1999. Three treatment prescriptions were evaluated, 1) clearcut harvest to the edge of the stream (CC) at eight sites, 50-foot-wide no-cut-buffers (50-ft) at 13 sites, and 56-foot radius circular no-cut-buffer at the perennial initiation point (PIP) at three sites (not used in statistical analysis due to small sample sizes). Each treatment site was paired with an uncut reference site as a control. The CC and 50-ft treatments were compared with treatment sites at three time periods (the first 1-3 years,

years 4-5, and the whole 5-year period). Differences in variable mean values were checked for statistical significance between treatment and reference streams using non-parametric Mann-Whitney U tests. Tree fall rates (annual fall rates of live and dead standing stems combined) was over 8 times and 5 times higher in the 50-foot buffers than in the reference buffers 3 years after treatment when compared as a percentage of standing trees and as trees/acre/yr, respectively. These differences were significant for both metrics ($p \leq 0.001$). In the period 4-5 years post treatment rate of tree uprooting decreased but rate of stem breakage increased in the 50-foot buffer. For this period only the percentage of broken trees were significantly different (higher) than what was observed in the reference buffers. Over the entire five-year period, the percentages of standing trees that were uprooted and broken (as well as the combined total) were significantly greater in the 50-foot buffer. Wind was the dominant tree fall process, accounting for nearly 75% of combined fallen trees, 11% fell from other trees falling against them and 1.8% of fallen trees fell from bank erosion. Differences in mortality followed a similar pattern to tree fall rates. In the 50-foot buffer sites mortality rates were significantly higher (3.5 times higher) than in the reference sites for the first three years following harvest. However, in years 4-5 mortality rates increased in the reference buffers after high-intensity storms resulting in non-significant differences in mortality during this period. The cumulative percentage of live trees that died over the entire five-year period was 27.3% in the 50-ft buffers compared to 13.6% in the reference reaches, but the difference was not statistically significant. This was likely because of the high variability in mortality between sites in the 50-foot buffers. LW recruitment into the channel after treatment was higher in the 50-ft buffers than in the reference patches during the first three years after harvest, over 8 times higher in pieces/acre/yr and over 14 times higher in volume/acre/yr. In years 4-5 after harvest LW recruitment decreased in the 50-ft buffers and increased in the reference patches, and the number of recruited LW pieces/acre/yr was greater in the reference patches, although the volume of LW recruited was greater in the 50-ft buffers. For the entire first 5 years after harvest, the 50-ft buffers recruited about twice the number of LW pieces recruited in the reference patches, and over 3 times the volume. The CC treatment, unsurprisingly, had significantly lower LW recruitment following harvest relative to the reference streams. Mean overhead shade (from trees and tall shrubs) was 13% lower in the 50-ft treatment, and 77% lower in the CC treatment relative to reference streams. The CC treatment, however, increased by 25% five years after harvest relative to values recorded 1-year following harvest. The implications of these results suggest that immediate and direct changes in stand structure, canopy cover, and LW are most severe for clear-cut treatments, but that the 50-foot buffer treatment showed an increase in LW and stand mortality, and a decrease in shade over the five-year period. Limitations of this study were the lack of pre-harvest data and the relatively short time-period (5-years) in evaluating impacts that may last for several decades.

Schuett-Hames & Stewart, 2019b (BCIF)

Schuett-Hames, D & Stewart, G. (BCIF), (2019). Changes in stand structure, buffer tree mortality and riparian-associated functions 10 years after timber harvest adjacent to non-fish-bearing perennial streams in western Washington. Cooperative Monitoring Evaluation and Research Report. Washington State Forest Practices Adaptive Management Program. Washington Department of Natural Resources, Olympia, WA.

This paper presents a 10 -year follow-up to the results of the BCIF report (Schuett-Hames et al., 2012) that originally presented 5-year post-treatment results. Over the 10-year period stand mortality in the 50-ft buffer treatment stabilized and showed a cumulative 14.1% reduction in live basal, while the reference stands showed a 2.7% increase in live basal area. The differences in these values were not significant. Cumulative LW recruited into stream channel over the 10-period was double in the 50-ft treatment streams than in the reference streams. However, the majority of the LW recruited in the 50-ft treatment streams came to rest above the streams, providing shade but not affecting streamflow, pool formation, or sediment storage. Further, while the 50-ft buffer treatment provided more LW recruitment in the short-term (10-years), the authors speculate there is a reduction in future LW recruitment potential given the removal of trees outside the 50-ft buffer. Canopy cover in the 50-ft treatment streams recovered to similar percentages as the reference's streams by the end of the 10-year period. The authors speculate that the 50-ft buffer was better at maintaining resource objectives than the clearcut but propose that the narrow buffers presented variable increases in mortality (specifically increased susceptibility to windthrow) and recommend further research before drawing definitive conclusions.

Riparian thinning effects on shade, light, and temperature

Roon et al., 2021a

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

The purpose of this study was to evaluate the effects of riparian thinning on shade, light, and temperature in three watersheds located in second-growth redwood stands in northern California. The objectives of this study were to evaluate: 1) the effects of experimental riparian thinning treatments on shade and light conditions; 2) how changes in shade and light associated with thinning affected stream temperatures at a reach-scale both locally and downstream; 3) how thermal responses varied seasonally; and 4) how these thermal responses were expressed across the broader thermal regime to gain a more complete understanding of thinning on stream temperatures in these watersheds. This study took place between 2016 and 2018 with thinning treatments applied during 2017 giving 1-year pre-treatment and 1-year of post-treatment data.

Two study sites prescribed treatment on one side of the stream of a 45 m buffer width with a 22.5 m inner zone with 85% canopy retention and a 22.5 m outer zone that retained 70% canopy cover (Green Diamond Resource Company, Tectah watershed). At the third treatment site thinning prescriptions included removal of up to 40% of the basal area within the riparian zone on slopes less than 20% on both sides of the channel along a ~100–150 m reach (Lost Man watershed, Redwood national park). Control reaches were located upstream from treatment reaches. Data analysis was conducted separately for each experimental watershed (i.e., 1 Lost man site, 2 Tectah sites). Stream temperature was collected using digital sensors; solar radiation was measured using silicon pyranometers; riparian shade was measured using hemispherical photography. A classical BACI analysis was performed to test the effects of riparian thinning on shade, light, and stream temperature using linear-effects models. Results for the Tectah watershed showed a significant reduction in canopy closure by a mean of 18.7%, (95% CI: -21.0, -16.3) and a significant reduction of effective shade by a mean of 23.0% (-25.8, -20.1) one-year post treatment. In the Lost man watershed, a non-significant reduction of mean shade by 4.1% (-8.0, -0.5), and mean canopy closure by 1.9% was observed in 2018. Results for below canopy light availability showed significant increases by a mean of 33% (27.3, 38.5) in the Tectah watershed, and non-significant increases in Lost man watershed of 2.5% (-1.6, 5.6) by 2018. Results for stream temperature changes showed variation seasonally and between watersheds. The Lost Man watershed showed no significant changes in average daily maximum, maximum weekly average of the maximum (MWMT), average daily mean, or maximum weekly average of the mean (MWAT). In the Tectah watershed, MWMT increased during spring by a mean of 1.7˚C (95% CI: 0.9, 2.5), summer by a mean of 2.8˚C (1.8, 3.8), and fall by a mean of 1.0˚C (0.5, 1.5) and increased in downstream reaches during spring by a mean of 1.0˚C (0.0, 2.0) and summer by a mean of 1.4˚C (0.3, 2.6). Thermal variability of streams in the Tectah watershed were most pronounced during summer increasing the daily range by a mean of 2.5˚C (95% CI: 1.6, 3.4) and variance by a mean of 1.6˚C (0.7, 2.5), but also increased during spring (daily range: 0.5˚C; variance: 0.3˚C) and fall (daily range: 0.4˚C; variance: 0.1˚C). Increases in thermal variability in downstream reaches were limited to summer (daily range: 0.7˚C; variance: 0.5˚C). Again, no significant changes in stream and downstream temperature variability were detected in the Lost Man watershed. In the Techtah watersheds the frequency of days with temperatures greater than 16˚C increased in summer by a mean of 42.9 more days (95% CI: 31.5, 53.8) in thinned reaches and a mean of 16.3 more days (6.1, 27.4) in downstream reaches. Temperatures greater than 16˚C persisted for a mean duration of 31.1 more consecutive days (21.0, 41.1) in thinned reaches and 11.6 more consecutive days (3.9, 20.0) in downstream reaches under the BACI analysis. The authors conclude that responses to the experimental riparian thinning treatments we evaluated differed greatly depending on treatment intensity. For example, they interpret their results as evidence that that changes in shade of 5% or less caused minimal changes in temperature while reductions in shade of 20–30% resulted in much larger increases in temperature. However, the authors warn that their data only evaluated immediate (1-year-post-treatment) changes in stream shade and temperatures. Also, the study was conducted in relatively small (< 10 km^2) coastal watersheds and may not apply to larger watersheds of different regions.

Sediment

Safeeq et al., 2020

Safeeq, M., Grant, G.E., Lewis, S.L., Hayes, S.K., 2020. Disentangling effects of forest harvest on long-term hydrologic and sediment dynamics, western Cascades, Oregon. Journal of Hydrology 580, 124259. https://doi.org/10.1016/j.jhydrol.2019.124259

The purpose of this study was to separate and investigate the effects of changes in streamflow and sediment supply due to disturbances (specifically timber harvest), on sediment transport into streams. Timber harvest affects both streamflow and sediment supply simultaneously. The researchers used a reverse regression technique to evaluate the relative and absolute importance of changes in streamflow versus changes in sediment supply on sediment transport. The technique was applied to long-term data collected from two paired experimental watersheds in the H.J. Andrews Experimental Forest, Oregon. The two watersheds were paired by size, aspect, and topography. The treatment watershed was 100% clearcut during the period from 1962-1966, broadcast burned in 1966, and re-seeded in 1968. Streamflow, and sediment data were taken intermittently, and after large storm events from 1952 (pre-harvest) through 1988 for suspended sediment data, and 2016 for sediment bedload. The control watershed was forested, and had no treatments (e.g., harvest) during the study period. The results that considered the effects of harvest on streamflow alone showed an increase in annual water yield in the treatment watershed by 10% (136 mm/year) over the 51-year post-treatment period. There were no significant changes in precipitation patterns before or after harvest. Further, the patterns of streamflow in the control watershed showed diverging patterns in streamflow after the harvest period. The authors state that these patterns strongly suggest that the increase in streamflow in the treatment watershed was caused by timber harvest. The results for post-treatment sediment yields showed suspended load declined to pre-treatment levels in the first two decades following treatment, bedload remained elevated, causing the bedload proportion of the total load to increase through time. Changes in streamflow alone account for 477 Mg/km2 (10%) of the suspended load and 113 Mg/km2 (5%) of the bedload over the post-treatment period. Increase in suspended sediment yield due to increase in sediment supply is 84% of the measured post-treatment total suspended sediment yield. In terms of bedload, 93% of the total measured bedload yield during the posttreatment period can be attributed to an increase in sediment supply. The authors interpret these results as evidence that while streamflow alone can cause a modest increase in sediment transport, it is negligible compared to the increases in sediment transport following harvest. Following harvest, changes on streamflow alone was estimated in being responsible for < 10% of the resulting suspended sediment transported into streams, while the increase in sediment supply due to harvest disturbance was responsible for >90%. The authors suggest these results provide evidence for a need to investigate thresholds for specific watershed management regimes to ameliorate these impacts following harvest, or thinning treatments. Also, the sharp increases in sediment transport following logging can be confidently attributed to the increase in sediment supply and delivery to streams due to the ground disturbances associated with logging rather than increased streamflow.

Stream Temperature

Reiter et al., 2020

Reiter, M., Johnson, S. L., Homyack, J., Jones, J. E., & James, P. L. (2020). Summer stream temperature changes following forest harvest in the headwaters of the Trask River watershed, Oregon Coast Range. Ecohydrology, 13(3), e2178. https://doi.org/10.1002/eco.2178

This paper investigates the effects of different riparian forest harvest treatments on stream temperature. Stream temperature data was collected from 2006 to 2016 for multiple small (<50 ha), non-fish-bearing headwater stream watersheds in the Trask River Watershed of the northwestern Oregon Coast range. The experiment followed a BACI design with four treatments, 1) clearcut, no buffer (CC_NB; n = 4), 2) clearcut with 10-m no cut buffer (CC_B; n = 3), 3) Thinning with 10 m no-cut buffer (TH_B; n =1), and 4) unharvested, reference streams (REF; n = 7). Temperature data was collected at 30-minute increments for all streams using continuously recording thermistors. Harvest operations occurred in the Summer of 2012 giving 6 summers of pre-treatment and 4 summers of post-treatment data collection. Temperature data was separated into 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th} percentiles, with each percentile being treated as independent response variables in a linear mixed model. Treatments were compared to reference watersheds to check for significant differences in temperature percentiles. For ecological context, the researchers also quantified the percentage of summer where temperatures where above 16 and 15 ºC, the preferred thermal regime limits for two local amphibian larvae (coastal tailed frog, coastal giant salamander). Results showed that even the small (10 m buffer; CC_B, TH_B) buffer was efficient in maintaining similar temperature changes throughout the summers compared to reference streams. There were no significant changes in the buffered watersheds with temperature responses in these watersheds ranging from negative values to negative values close to zero. The treatments with no buffer (CC_NB), however, showed significant increases in temperature for all percentiles with the greatest increases occurring in the 95^{th} percentile, showing a mean increase of 3.6 ºC (SE = 0.4). For the 5^{th} percentile, the CC_NB also showed a mean temperature response 1.7°C (SE = 0.3; range from 1.5 - 2.8°C). Temperature changes were more severe in the CC_NB watersheds with no leave trees (4.2 and 4.4°C), however, this difference was not analyzed. The percentage of time the post-harvest, no-buffer treatments spent above the 16 and 15 ºC thresholds were 1.3% and 4.7%, respectively. This was an increase from pre-harvest values that showed no instances of temperatures above 16°C, and only 0.2% of the recorded time above 15°C. The authors conclude that their evaluation of temperature responses as potential biologically significant changes adds context to the changes and fluctuations observed in each harvest design. While significant changes in mean and percentile changes in temperature were observed, the amount of time spent above critical temperature thresholds for important amphibian species was minimal.

SHD, Stream temperature

Chan et al., 2004 (Removed from focal list, significant results only apply to fauna)

Chan, S.S., Anderson, P.D., Cissel, J., Larsen, L., Thompson, C., 2004. Variable density management in Riparian Reserves: lessons learned from an operational study in managed forests of western Oregon, USA. USDA Forest Service. https://doi.org/10.1016/j.foreco.2013.06.055

The purpose of this study was to assess the ability of variable retention thinning and riparian buffers at accelerating late-seral habitat, facilitating rare species management, and maintaining ecological functions within riparian zones of 40–70-year-old headwater forests in western Oregon. This study evaluated 13 separate sites each averaging ~ 100 ha whereby 4 buffer width treatments adjacent to variable retention thinning prescriptions were assessed. Buffer treatments include: (1) one site potential tree; (2) two-site potential trees; (3) variable buffer width based on vegetation and/or topographic site factors; (4) streamside buffer of only the first tree whereby thinning treatments applied up to 6 m of stream. Thinning treatments included: (1) Unthinned control - 500-750 trees per hectare; (2) High density retention - 70-75% of area thinned to 300 TPH, 25-30% unthinned riparian reserves or leave islands; (3) Moderate density retention - 60-65% area thinned to 200 TPH, 25-30% unthinned riparian reserves or leave islands with 10% circular patch openings; (4) Variable density retention - 10% area thinned to 100 TPH, 25-30% thinned to 200 TPH, 25-30% thinned to 300 TPH, 20-30% unthinned riparian reserves or leave islands with 10% circular patch openings. Variables measured include stand development metrics, understory vegetation, microclimate, aquatic ecology, invertebrates, lichens, and bryophytes. Early findings from this study show that relatively small changes in the riparian environment are attributed to different residual thinning densities and different buffer widths. According to the results, the most suitable habitat for many species of fauna is consistently found within 5 m of the stream. The largest changes in relative humidity in warm and dry summer conditions occur within 15 m of the stream channel and begin to stabilize at 25 m. In summary, the early findings of this study indicate the near-stream riparian environment provides critical functions and habitat for a wide variety of organisms.

Sediment

Reiter et al., 2009

Reiter, M., Heffner, J. T., Beech, S., Turner, T., & Bilby, R. E. (2009). Temporal and Spatial Turbidity Patterns Over 30 Years in a Managed Forest of Western Washington 1. *JAWRA Journal of the American Water Resources Association*, *45*(3), 793-808. https://doi.org/10.1111/j.1752-1688.2009.00323.x

This study evaluates the efficacy of the changes in a forest practices plan developed in 1974 to reduce sediment inputs into streams in the Deschutes River watershed of western Washington. To test this, the researchers analyzed 30 years of data (1975-2005) on water levels, discharge, suspended sediment, turbidity, and water and air temperature from four permanent sampling sites representing a range of basin sizes from small tributary headwaters to the mainstem of the Deschutes River. In the 1970s roughly 30% of the watershed had been harvested and approximately 63% of the existing road network had been constructed. Timber harvest continued until the early 1990s and the road network was completed in the late 1970s but updated to include culverts and sediment traps in the early 2000s. The researchers used turbidity as a proxy for suspended sediment correlation and corrected for typical seasonal increases in streamflow. The results showed a declining trend in turbidity at all permanent sampling sites during the study period even with active forest management. Following the road construction and harvest activities of the 1980s turbidity levels continued to decline until the year 2000 when they returned to pre-logging levels. The authors interpret these results as evidence that management's increased attention to reducing sediment is responsible for the reduction in sediment transport.

Effect of debris torrents on shade, vegetation, and stream temperature

D'Souza et al., 2011

D'Souza, L.E., Reiter, M., Six, L.J., Bilby, R.E., 2011. Response of vegetation, shade and stream temperature to debris torrents in two western Oregon watersheds. Forest Ecology and Management 261, 2157–2167. https://doi.org/10.1016/j.foreco.2011.03.015

The purpose of this study was to examine the effects of debris torrents on vegetation, shade, and stream temperature eight years after an extreme storm-related disturbance. This study examined two separate managed watersheds which were affected by storm-related debris torrents in 1996. This study addressed several questions regarding the patterns and rate of vegetation, shade and water temperature change post-disturbance: (1) What is the relationship between vegetation and local landform and substrate types along the study streams? (2) Does vegetation composition and structure, stream shade and water temperature in debris torrented streams differ between the two watersheds? and (3) How does recovery of stream temperature relate to vegetation and shade recovery and does this differ through time between watersheds? Data was gathered from multiple headwater streams following the disturbance in 1996 at 2 managed watersheds: the Williams River watershed (WRW), and the Calapooia River watershed (CRW). Data for stream temperature, to analyze stream temperature recovery, was collected immediately following the disturbance event in 5 streams, 3 at the CRW (2 disturbed; 1 reference), and 3 at the WRW (1 disturbed, 1 reference) and for 8 years through the summer of 2004. Eight years post-disturbance 12 disturbed streams (n = 6 for each watershed) were selected for data collection to examine the relationships between riparian vegetation, shade, and stream temperatures. Data on landform, substrate, and vegetation (density, species, and seedlings) were collected at each stream. Stream shade was estimated using hemispherical photographs taken 1 m above the stream center during summer and winter months and compared using t-tests. Stream temperature data was collected using continuously recording thermistors. Data were averaged and analyzed using t-tests, chi-square tests, simple linear regression, Pearson's correlation coefficient, and analysis of covariance. Results from this study show early successional species red alder and willow species dominated areas affected by debris torrents. All red alder variables (density, basal area, and height) showed a significant relationship with vegetation-related shade. Red alder showed a significantly higher density ($p = 0.0277$) and basal area ($p = 0.0367$) in the WRW sites. While stem density of red alder was similar in both watersheds, the size of the trees differed suggesting that colonization and/or growth of red alder in the WRW occurred more rapidly than in the CRW. However, there was no statistical difference in landforms or site factors between watersheds that explained these differences. The only correlations found were a negative relationship between alder density and rock; and a positive relationship between alder basal area and moss suggesting a relationship between moisture availability and red alder establishment and growth. The authors note that the WRW sites experienced greater precipitation in the years following disturbance and may have contributed to the greater growth rates of red alder, but no analysis was conducted. Total shade was also significantly higher in the WRW ($p = 0.0049$). Mean maximum daily temperature fluctuations ($p = 0.0483$), and 7-day maximum temperatures ($p=0,0483$) were also significantly lower in the WRW streams. Mean max daily stream temperatures were lower in the WRW streams but the difference was not significant ($p = 0.0779$). The authors conclude that even though the debris torrents resulted in poor soil conditions, the ability of red alder to thrive in these conditions resulted in rapid recovery of shade and thermal control.

Stream temperature, shade and climate

Reiter et al., 2015

Reiter, M., Bilby, R. E., Beech, S., & Heffner, J. (2015). Stream temperature patterns over 35 years in a managed forest of western Washington. JAWRA Journal of the American Water Resources Association, 51(5), 1418-1435. https://doi.org/10.1111/1752-1688.12324

This study was an analysis of long-term stream temperature data in a western Washington watershed to evaluate the effects of forest management, before and after implementation of riparian forest best management practices, and climate change on stream temperatures. Stream temperature data from four permanent sampling stations in the Deschutes River Watershed. Stream and air temperature data was analyzed on a monthly basis from 1975-2009. This long-term dataset allowed for the examination of changes in stream temperature in four basins of varying size across a period from before stream buffers were implemented, during their implementation, and several instances of buffer expansion. Because the study period covered such a long time the changes in stream temperature based on climate change needed to be accounted for as well. The recovery of shade was estimated using the shade recovery function developed by R. Summers of Oregon State University (1983), whereby stream shade is estimated by angular canopy density (ACD) as a function of the age of stream-adjacent harvest units. To detect correlations of stream and air temperature change with land management activity separately from climate changes the data was fit to a model that included the effects of climate. The researchers accomplished this with a technique for deriving the residuals between stream temperature and climate called locally weighted scatterplot smoothing (LOWESS). The four watersheds varied in size from small (2 sites: Hard Creek, 2.4 km2; Ware Creek, 2.9 km^2), medium (1 site: Thurston Creek, 9.3 km^2), and large (1 site: The Deschutes River Station, 150 km^2). In the 1970s nominal buffer widths were required along fish-bearing streams, which expanded in the 1980s (requirements not listed), again in the mid-1990s to 23 m, and again to 30 m in 2001. Methods for stream temperature data collection varied at different periods resulting in a margin of error for monthly temperatures of 0.14°C for 1975 - 1983, 0.09°C for 1984 – 1999, and 0.02°C. for 2000 – 2009. Because these margins of error were smaller than what the authors expected from climate and management, they were not accounted for in confidence intervals and p-values. The results for air temperature changes showed a statistically significant ($p \leq 0.05$) increasing trend in regional air temperatures for July TMAX_AIR and June and July TMIN_AIR. The trend for TMAX_AIR for July resulted in a trend magnitude of +0.07°C per year, for a total increase of 2.45°C over the 35-year record. For minimum air temperatures the magnitude of the June trend was +0.03°C per year while July TMIN_AIR had a trend magnitude of +0.04°C per year. The resulting increases in minimum temperatures for the period of record are 1.05°C and 1.40°C for June and July TMIN_AIR, respectively. Results for trends in stream temperature over the 35-year study period without adjustment for climate change showed no statistically significant trend in water temperature changes for the large watershed, while the medium watershed (Thurston Creek) showed decreasing trends in TMAX_WAT for June, July, and August, ranging in magnitude from 0.05°C (August) to 0.08°C (July) per year. For the smaller watershed, Hard Creek (Ware Creek was not included in this analysis), had significant decreasing trends in TMAX_WAT for July, August, and September. The magnitude of these trends was yearly decreases of TMAX_WAT by 0.05, 0.08, and 0.05°C, for July, August, and

September, respectively. Significant changes in trends for TMIN_WAT were only found for the large basin site with yearly increases of 0.04, 0.03, and 0.04°C for July, August, and September, respectively. Results for stream temperature trends after adjusting for changes in air temperature (climate) showed significant decreasing trends in TMAX_WAT for the large basin by 0.04, 0.03, and 0.04°C yearly, for July, August, and September, respectively. For the medium basin, trends showed yearly decreases in TMAX_WAT of 0.07, 0.08, 0.06, and 0.03 for June, July, August, and September, respectively. For the small basin, climate adjusted trends in TMAX_WAT showed significant decreases in yearly trends by 0.05, 0.08, and 0.05 for July, August, and September, respectively. When stream temperature was examined with its correlation with estimated annual shade recovery from initial harvest (indexed by ACD). Significant correlations were found for monthly temperature metrics that were adjusted for climate, for all basins. The strongest correlations were for the smallest basin (Ware Creek) with correlation coefficients for climate adjusted maximum water temperatures (CTMAX_WAT) with ACD valuing –0.66, -.078, -0.65, and – 0.69 for June, July, August, and September, respectively. Correlation coefficients for Ware Creek CTMIN_WAT with ACD were –0.46, -0.64, -0.71, and –0.52 for June July, August, and September respectively. The largest basin (The Deschutes River) only showed significant correlations of CTMAX_WAT with ACD with July (-0.39) and August (-0.25); and only showed significant correlations of CTMIN_WAT with ACD for the months of August (+0.27), and September (+0.37). The authors interpret their results as evidence that following canopy recovery after implementation of riparian harvest rules the larger mainstem of the Deschutes River decreased in average maximum temperatures by approximately 1.3 °C when accounting for climate driven changes. The effects of canopy closure cooling were even more dramatic in the smaller headwater streams by 2.67 and 1.6 °C during the study period when accounting for climate driven changes (this includes a 0.5 °C correction based on climate warming). However, following re-initiation of timber harvest in 2001 for the area, when riparian protection buffers of 30 m minimum were required, there was no detectable change in stream temperatures. The authors conclude that the results of this study show evidence that implementation of protection buffers in this area were sufficient in maintaining stream temperatures. Conversely, this study also shows evidence that despite these protections from land management induced stream temperature changes, these protections have been somewhat offset by the warming climate conditions.

Overstory structure effects on understory light and vegetation

Giesbrecht et al., 2017 (removed from focal, not relevant to questions, essentially a case study)

Giesbrecht, I.J.W., Saunders, S.C., MacKinnon, A., Lertzman, K.P., 2017. Overstory structure drives fine-scale coupling of understory light and vegetation in two temperate rainforest floodplains. Can. J. For. Res. 47, 1244–1256. dx.doi.org/10.1139/cjfr-2016-0466

The purpose of this paper was to characterize the overstory structure and understory light regimes of temperate rainforest floodplains, and to assess the role of light and other site variables in driving stand vegetation patterns and processes. This study took place along two 1-ha coastal BC, Canada floodplain sites. These sites were selected as representative examples of floodplain forests in the Coastal Temperate Rainforest (CTR) as part of a larger network of long-term, old-growth monitoring plots. These sites were in the submontane variant of the very wet maritime subzone of the Coastal Western Hemlock zone (CWHvm1) of the B.C. coast. In each stand, the largest overstory trees are Picea sitchensis (Bong.) Carr., with several individuals taller than 60 m in height (maximum of 62 to 93 m). Based on coring a sample of main canopy trees, stand age at Kitlope is at least 95 years. Stand age at Carmanah is at least 350 years, based on a core from a 50 m tall P. sitchensis. All trees ≥ 5 cm were measured along with all understory vegetation within 25 2m x 2m subplots. Stand characteristics were recorded as well as information on gap origins. Hemispheric canopy photographs were taken to estimate understory light penetration. Visual estimations of organic material, mineral layer, CWD, and other substrates were taken in each vegetation subplot. Relationships among measures of light transmission, vegetation structure, and diversity were analyzed with linear correlation analysis. Nonmetric multidimensional scaling was used to describe variation in species composition on multivariate axes. Results from this study show both sites as having a relatively high degree of canopy openness (11-11.6%) and light transmission (median 18% full sun) compared to many other tropical and temperate forests. Light transmission at both sites is however significantly lower than a number of old-growth sites in Quebec and northern BC. The origins of canopy openness and stand shade differ between both sites indicating distinct stand processes and different stages of stand development. Further, light levels vary substantially within short distances at each site reflecting a complex overstory structure. Although results from this study are reflective specifically of the coastal temperate rainforests of BC, the descriptive assessment of these two separate floodplain forests reveal a natural disturbance history which fostered a high degree of canopy openness and structural heterogeneity which may ultimately aid in informing future temperate rainforest floodplain restoration efforts.

LW

Reid & Hassan, 2020

Reid, D. A., & Hassan, M. A. (2020). Response of in-stream wood to riparian timber harvesting: Field observations and long-term projections. Water Resources Research, 56(8), e2020WR027077. https://doi.org/10.1029/2020WR027077

This paper proposes a conceptual model of wood storage response to different harvesting intensities. The model predicts how LW in streams is expected to change spatially and temporally following three different harvest patterns. The model was developed with 45 years of LW data retrieved from the Pacific coastal region of Vancouver Island, British Columbia. The Carnation Creek watershed, which supports gravel bed forested streams, contains riparian forests that have received a wide range of harvest plans implemented. During logging in the 1970s and '80s riparian forests of one region were harvested with buffer widths ranging from 1 – 70 meters in upstream reaches, and another region with near complete or complete removal of vegetation to the streams edge in downstream reaches. In-stream wood volume and characteristics data has been collected in eight of these study reaches since 1973 (pre-harvest). The researchers used this data with simulation modelling to develop a reach-scale wood budget model that predicts wood loss and recover patterns for 300 years (1900-2200). This paper has two objectives: (i) to use this field data and modeling approach to examine LW storage changes, the time to minimum wood load, and wood load recovery times as a result of riparian timber harvesting and forest regeneration, and (ii) to describe the characteristics of in stream wood, with particular focus to spatial and temporal patterns in wood storage over the multidecade scale following harvesting in riparian areas. The model was based upon the proposed response outlined by Murphy and Koski (1989). Wood budget responses were estimated using three management scenarios. Scenario 1 is a no harvest scenario, in this configuration, the loss of wood supply from the landscape has little to no impact on input from wood mortality or bank erosion, and therefore in-stream storage, decay, and transport of wood is not affected. Scenario 2 represents partial loss of forested area in the riparian zone, which will lead to a near-immediate reduction in wood recruitment to the channel from mortality and bank erosion along harvested areas. Wood decay and other components of wood loss will exceed rates of input, leading to a reduction in storage until time Tmin, the point where wood recruitment equals losses as the forest regrows in riparian areas and the greatest overall reduction in storage has occurred (ΔSmax). Wood storage increases thereafter, eventually recovering to preharvest levels after time Trec. Scenario 3 represents an intensive harvest scenario where most of the riparian area has undergone harvesting over a short period of time, a major reduction of input from bank erosion and mortality occurs. This greater reduction leads to a much larger ΔSmax than in Figure 1b as wood losses exceed recruitment. However, as the dominant wood sources recover at the same rate, the time to Tmin and Trec is similar under both the moderate and intensive harvest scenarios. Results of the model show evidence that wood storage in streams of harvested reaches, hits its minimum value in 50 years or more following loss of LW input, decay, and export of current stock. Recovery of LW volume in-streams following harvest is estimated to take approximately 150-200 years. The pattern and intensity of the harvesting operation had little effect on LW loss and recovery times but did affect the estimated magnitude of LW volume loss in the first 50 – 80 years. These results show evidence that timber harvest has a long-term effect on LW storage and loading dynamics even with protective buffers. However, buffers can ameliorate the magnitude of LW loss during the recovery period. The one caveat of this model is it doesn't account for as much variability on stream configuration or valley morphologies that are likely to affect LW storage.

Buffers and LW Recruitment

Grizzel et al., 2000 (Removed)

Grizzel, J., McGowan, M., Smith, D., Beechie, T., 2000. STREAMSIDE BUFFERS AND LARGE WOODY DEBRIS RECRUITMENT: EVALUATING THE EFFECTIVENESS OF WATERSHED ANALYSIS PRESCRIPTIONS IN THE NORTH CASCADES REGION (Timber/Fish/Wildlife Monitoring Advisory Group and the Northwest Indian Fisheries Commission). fp_tfw_mag1_00_003

This study analyzed the effectiveness of the Washington Watershed Analysis (WWA) prescriptions at recruiting large woody debris. This study took place at 10 riparian sites distributed across 5 watershed administrative units in the Northern Cascades of Washington. Ten sites were randomly chosen with gradients and buffer width classes in compliance with WWA indices. To analyze WWA effectiveness, debris frequency and size at each site were compared to targets derived from WWA. In addition, debris recruitment was compared between three buffer width classes. Geometric mean diameter and geometric mean length of debris was calculated based on measurements of midpoint diameter and total lengths. This data was then compared to targets derived from a channel width-dependent regression. Results show post-harvest mortality substantially decreasing stand density at several sites. In stream frequency targets were met at most sites; however, debris categorized as "good" for habitat was only achieved at four out of ten sites. At the time of data collection, a large portion of debris recruited from buffers was either above or outside the bankfull flow zone. The authors point out that the degree to which the debris will influence fluvial processes in the future will depend on whether or not they are recruited into the stream and will also depend on the size and state of decay. The size of debris recruited from buffers was significantly smaller than recruited from unmanaged old-growth stands. Interestingly, data shows recruitment occurring from the outermost margins of the widest buffers (20-30 m, >30 m), suggesting narrow buffers may limit recruitment. The authors point out that the large degree of variability in recruitment from site to site suggests windthrow as an important causal factor. In channels oriented perpendicular to damaging winds (east-west), there was a higher likelihood of potential recruitment as compared to channels oriented parallel to damaging winds. The authors conclude with multiple recommendations for future study. First, they suggest integrating habitat inventory with recruitment to achieve a better understanding of relationships. Second, they suggest future study into the fate of debris suspended above channels given much of our current understanding is based on assumptions of decay and breakage. Finally, they recommend study into factors influencing windthrow in riparian buffers.

Sediment

Rachels et al., 2020

Rachels, A. A., Bladon, K. D., Bywater-Reyes, S., & Hatten, J. A. (2020). Quantifying effects of forest harvesting on sources of suspended sediment to an Oregon Coast Range headwater stream. Forest Ecology and Management, 466, 118123. https://doi.org/10.1016/j.foreco.2020.118123

This study uses sediment source fingerprinting techniques to quantify the proportional relationship of sediment sources (hillslope, roads, streambanks) in harvested and un-harvested watersheds of the Oregon Coast Range. The researchers used sediment traps, and chemical analysis to estimate the origin of suspended sediment in the stream and to quantify magnitude of sediment stored in protection buffers. The study included one catchment (Enos Creek) that was partially clearcut harvested in the summer of 2016 and an unharvested reference catchment (Scheele Creek) located ~3.5 km northwest of Enos Creek. The paired watersheds had similar road networks, drainage areas, lithologies and topographies. The treatment watershed was harvested with a skyline buffer technique in the summer of 2016 under the Oregon Forest practices Act policy that requires a minimum 15 m no-cut buffer. The proportion of suspended sediment sources were similar in the harvested (90.3 ± 3.4% from stream bank; 7.1 ± 3.1% from hillslope) and unharvest (93.1 ± 1.8% from streambank; 6.9 ± 1.8% from hillslope) watersheds. However, the harvested watershed contained a small portion of sediment from roads (3.6 ± 3.6%), while the unharvested reference watershed suspended sediment contained no sediment sourced from roads. In the harvested watersheds the sediment mass eroded from the general harvest areas (96.5 ± 57.0 g) was approximately 10 times greater than the amount trapped in the riparian buffer (9.1 ± 1.9 g), and 4.6 times greater than the amount of sediment collected from the unharvested hillslope (21.0 ± 3.3 g). These results suggest that the riparian buffer was efficient in reducing sediment erosion relative to the harvested area. The caveat of this study was the limited sample size (1 treatment, 1 paired reference watershed) and does not incorporate the effects of different watershed physiography on sediment erosion.

SED

Puntenney-Desmond et al., 2020

Puntenney-Desmond, K. C., Bladon, K. D., & Silins, U. (2020). Runoff and sediment production from harvested hillslopes and the riparian area during high intensity rainfall events. Journal of Hydrology, 582, 124452. https://doi.org/10.1016/j.jhydrol.2019.124452

This study uses simulation modeling to evaluate the differences in run-off rates, sediment concentrations, and sediment yields between watershed harvested areas, along the interface of harvested areas and riparian buffers, and within riparian buffers during periods of high-intensity rainfall events. The model simulations were calibrated with soil and watershed characteristic data collected from the Star Creek catchment located in southeastern Alberta. Fifteen plots were selected for rainfall simulations along three transects on a north facing hillslope (aspect: ~358°) and along two transects on a southeast facing hillslope (aspect: ~129°). Each transect consisted of three plots that were spaced ~20 m apart along the planar hillslopes. Each plot was one square-meter, which was bounded by a three-sided steel frame that was inserted into the soil with the open side facing down the slope. The plots were located either (a) within the general harvest area, (b) along the edge of the riparian buffer at the interface with the harvested area, or (c) within the riparian buffer. The high-intensity rainfall events were calibrated to mimic 100-year, or greater, storm events of the Northern Rocky Mountains (1-hour high intensity rainfall). The results showed runoff rates and surface and shallow subsurface were greatest in the buffer areas than in the harvested areas or in the harvest-buffer interfaces especially during dry conditions. During the dry condition rainfall simulations, the general pattern of runoff rates (surface/shallow subsurface flow) was riparian buffer (175.6 ± 17.3 [SE] ml min^{-1}) > harvest-riparian edge (125.8 ± 18.2 ml min^{-1}) > general harvest area (37.2 ± 8.5 ml min^{-1}). Mean runoff rates within the riparian buffer plots were greater than within the general harvest area plots ($t= 2.90$, $p =.03$). Runoff ratios were only statistically greater in the riparian buffer plots (13.9 ± 3.1%) relative to the general harvest area (2.9 ± 1.5%) during the dry conditions. All runoff ratios declined during the wet condition rainfall simulations relative to the dry condition simulations with no evidence for differences between any of the plot positions ($p > .27$ for all pairwise comparisons). During the dry condition rainfall simulations, the general patterns of sediment concentrations and sediment yields were opposite of the runoff rates, with the general harvest area > harvest-riparian edge > riparian buffer. The sediment concentration was (a) 424.8 mg l^{-1} (151.0–1195.3 mg l^{-1}) in the general harvest area, (b) 100.9 mg l^{-1} (45.8–222.1 mg l^{-1}) along the harvest riparian edge, and (c) 26.9 mg l^{-1} (12.2–59.1 mg l^{-1}) in the riparian buffer. Statistically, there was strong evidence for differences in sediment concentrations between the general harvest area and along the harvest-riparian edge ($t = 3.21$, $p = .01$) and between the harvest area and the riparian buffer ($t = 6.17$, $p < .001$). Statistically, there was no evidence for differences in sediment yields between any of the plot positions. Sediment concentration among plot positions remained the same during the wet rainfall simulations as the dry rainfall simulations—general harvest area > harvest-riparian edge > riparian buffer. The geometric mean and 95% confidence intervals (back-transformed) for the sediment concentration was (a) 285.7 mg l^{-1} (67.9–1201.5 mg l^{-1}) in the general harvest area, (b) 79.6 mg l^{-1} (36.5–173.5 mg l^{-1}) along the harvest-riparian edge, and (c) 22.3 mg l^{-1} (3.5–141.7 mg l^{-1}) in the riparian buffer. However, while sediment concentrations differed most strongly between the general harvest area and the riparian buffer ($t = 3.51$, $p = .01$), other pairwise comparisons were not significant ($p > .20$). Statistically, there was no evidence for differences in sediment yields between any of the plot positions for rainfall simulations during wet conditions. The authors speculate this was likely due to the greater soil porosity in the disturbed, harvested areas. Sediment concentration in the runoff, however, was approximately 15.8 times higher for the harvested area than in the riparian buffer, and 4.2 times greater than in the harvest-buffer interface. Total sediment yields from the harvested area (runoff + sediment concentration) were approximately 2 times greater than in the buffer areas, and 1.2

times greater in the harvest-buffer interface (however, these proportions were not statistically different). Replication of the model showed high levels of variability in total run off rate, sediment concentrations, and sediment yields but the relationships between timing and relative magnitudes between the three experimental areas were consistent. The authors speculate that these results will become more relevant as climate change is expected to increase the frequency of high-intensity rainfall events following dry periods in this area. They suggest expanding similar methods to understand these effects in areas of different hydro-climatic settings.

Stream Temperature

Pollock et al., 2009

Pollock, M. M., Beechie, T. J., Liermann, M., & Bigley, R. E. (2009). Stream temperature relationships to forest harvest in western Washington 1. JAWRA Journal of the American Water Resources Association, 45(1), 141-156. https://doi.org/10.1111/j.1752-1688.2008.00266.x

This study investigates the effect of watershed harvest percentage, and time since harvest on summer stream temperatures at different scales in the Olympic Peninsula, Washington. The researchers examined recorded stream temperature data in 40 small watersheds that experienced a range of harvest from 0 – 100% (7 unharvested, 33 harvested between 25-100%), with regrowth age groups binned for analysis as recently clear cut (< 20 years old) and less recently clearcut (mostly < 40 years old). Unharvested sites were estimated as being >150-years old. Clearcut is defined in this paper as removing any protective canopy cover for streams. This study tested 3 hypotheses: (1) the condition of the riparian forest immediately upstream of a site primarily controls stream temperature, (2) the condition of the entire riparian forest network affects stream temperature, and (3) the forest condition of the entire basin affects stream temperature. These hypotheses were test by examining correlations of stream temperature with the condition of the immediate upstream riparian forest, or more correlated with forest conditions more spatially distant and on a coarser scale, such as the entire upstream riparian forest network or the forest condition of the entire basin. To avoid site effects in their analysis sites were chosen from a narrow range of subbasin sizes (approximately 1-10 km2) and elevation (75-400 m). Further, all sites were underlain by sedimentary rock and had perennial flow. Each hypothesis was tested with linear regression to evaluate the correlations of each age group at each scale with stream temperature data. The researchers also used AIC value comparisons for model selection to assess the correlation of other physiographic features (elevation, basin area, aspect, slope, or geologic composition) with stream temperatures. Results of general temperature patterns showed that average daily maximum (ADM) were strongly correlated with average diurnal fluctuations ($r^2 = 0.87$, $p < 0.001$, $n = 40$), indicating that cool streams also had more stable temperatures. For basin-level harvest effects on stream temperatures. The percentage of the basin harvested explained 39% of the variation in the ADM among subbasins (r2 = 0.39, p < 0.001, n = 40) and 32% of variation in the average daily range (ADR) (r2 = 0.32, p < 0.001, n = 40). The median ADM for the unharvested subbasins was 12.8 °C (mean = 12.1 °C), which was significantly lower than 14.5 °C, the median (and average) ADM for the harvested subbasins (p < 0.001). Likewise, the median (and average) ADR for the unharvested subbasins was 0.9 °C, which was significantly lower than 1.6 °C, the median ADR (average = 1.7 °C) for the harvested subbasins (p < 0.001). Results for the correlations between the riparian network scale forest harvest and stream temperature showed that the total percentage of the riparian forest network upstream of temperature loggers harvested explained 33% of the variation in the ADM among subbasins (r^2 = 0.33, p < 0.001, n = 40) and 20% of variation in the ADR (r^2 = 0.20, p = 0.003, n = 40). However, the total percentage of upstream riparian forest harvested within the last 20 years was not significantly correlated to ADM or ADR. Results for near upstream riparian harvest and stream temperature showed either non-significant, or very weakly significant correlations. For example, there were no significant correlations between the percentage of near upstream riparian forest recently clear-cut and ADM temperature (r2 = 0.03, p = 0.79, n = 40), the ADR of stream temperatures (r2 = 0.02, p = 0.61, n = 40) or any other stream temperature parameters. The proportion of total harvested near upstream riparian forest (avg = 0.66, SD ± 0.34, range = 0.0-1.0) was weakly correlated with ADM (r2 = 0.12, p = 0.02, n = 40) and not significantly correlated with ADR (r2 = 0.07, p = 0.06, n = 40). Even when the upstream riparian corridor length was shortened to 400 m and then to 200 m, and the definition of recently harvested was narrowed to <10 year, no significant relationships between temperature and the condition of the near upstream riparian forest was found. Results for the effect of physical landscape variables on stream temperature found that the variables of elevation, slope, aspect, percent of the basin with a glacial surficial geology, upstream distance of the site to sedimentary (bedrock) geology, and the percent of sedimentary surficial geology in the basin individually explain between 5% and 14% more of the variability relative to basin harvest. Adding any one of these variables to the model increases the r^2 from 0.40 up to between 0.48 and 0.51. However, the coefficient for percent of basin harvested and its standard error stay essentially the same, thus the authors concluded that adding additional variables to the model did not change the basic finding that there is a strong relationship between ADM and total amount of harvest in a basin. Thus, for these models, the percentage of basin area harvested was the best predictor of variation in mean maximum stream temperatures. The probability of stream temperatures increasing beyond DOE standards (16 °C for seven-day average of maximum temperatures) increased with percent harvest. Nine of the 18 sites with 50-75% harvest and seven of the nine sites with >75% harvest failed to meet these standards. The authors interpret these results as evidence that the total amount of forest harvested within a basin, and within a riparian stream network are the most important predictors of changes in summer stream temperatures. They conclude that watersheds with 25-100% of their total area harvested had higher stream temperatures than watersheds with little or no harvest. Furthermore, they speculate that past basin-wide timber management can impact stream temperatures over long periods of time in a way that riparian buffer treatments cannot entirely ameliorate.

Stream Temperature

Groom et al., 2011a

Groom, J.D., Dent, L., Madsen, L.J., 2011. Stream temperature change detection for state and private forests in the Oregon Coast Range. Water Resources Research 47. https://doi.org/10.1029/2009WR009061

The purpose of this study was to evaluate the effectiveness of private and state forest buffer rules on state water quality stream temperature antidegradation standards in the Oregon Coast Range. According to the Department of Environmental Quality (DEQ), under the Protecting Cold Water (PCW) criterion, anthropogenic activities are not permitted to increase stream temperature by more than 0.3 °C above its ambient temperature. In addition, the cumulative amount of anthropogenic temperature increase allowed in streams with temperature total maximum daily loads (TMDLs) is 0.3 °C for all sources combined. Stream temperature and riparian stand conditions were measured pre- and post-harvest between 2002 and 2008 at 33 sites (18 private-owned, 15 state-managed). Treatment stands included 26 clear-cuts and 7 partial cuts (leave tree requirements not specified), all of which were harvested in adherence to FPA (private) and FMP (state) standards. Private sites followed FPA rules whereby the riparian management area (RMA)s are 15 and 21 m wide on small and medium fish-bearing streams, respectively, with a 6 m no-cut zone immediately adjacent to the stream. State sites followed the state management plan whereby a 52 m wide buffer is required for all fish-bearing streams, with an 8 m no cut buffer immediately adjacent to the stream. Stream temperature data was collected for at least 2 years prior to harvest. Reference reaches were located immediately upstream from the harvested reaches. Generalized least square regression was used to model ambient conditions while accounting for temporal autocorrelation. The authors examined prediction intervals to assess the rule exceedance (>0.3 °C increase in temperature). Results indicate that sites harvested according to FPA standards exhibited a 40.1% probability that a pre harvest to post harvest comparison of 2 years of data will detect a temperature change of > 0.3°C. Conversely, harvest to state FMP standards resulted in an 8.6% probability of exceedance that did not significantly differ from all other comparisons. The a priori and secondary post hoc multimodel comparisons did not indicate that timber harvest increased the probability of PCW exceedance at state sites. The authors point out that the 0.3°C change threshold still lies 1 or 2 orders of magnitude lower than previous findings from studies which took place prior to the enactment of the riparian protection standards. The authors recommend further research looking into the potential persistence of stream temperature change downstream after harvest. In addition, they recommend looking into the biological significance of increases in stream temperature change particularly to aquatic life.

Stream and subsurface water temperature

Guenther et al., 2014

Guenther, S.M., Gomi, T., Moore, R.D., 2014. Stream and bed temperature variability in a coastal headwater catchment: influences of surface-subsurface interactions and partial-retention forest harvesting. Hydrological Processes 28, 1238–1249. https://doi.org/10.1002/hyp.9673

This study documented changes in stream and subsurface water temperature in response to forest harvesting in two paired headwater catchments. Specifically, the researchers hypothesized that post-logging changes in bed temperatures should be greatest in locations experiencing hyporheic downwelling (DW) and least in areas with lateral inflow/groundwater discharge. This study took place in the University of British Columbia Malcolm Knapp Research Forest near Vancouver, Canada. As a part of an ongoing study into the effects of riparian buffers on stream ecology, the catchments of 3 southerly-aspect first order streams were harvested using partial retention (50% removal of basal area including riparian zone) methods resulting in approximately 14% reduction in canopy cover on average; 3 other southerly-aspect streams served as unharvested controls. Before thinning treatments, the harvested riparian forests were dominated by western hemlock, (Tsuga heterophylla), western red cedar (Thuja plicata), and Douglas-fir (Pseudotsuga menziesii). The forests were mature second growth forests with trees approximately30-40 m tall, and canopy closure than 90%. Harvest operations began in September 2004 and completed in November of 2004. Temperature data was summarized from 10-minute intervals to daily minimum, maximum, and mean temperatures for stream and bed temperatures for one-year prior to, and one year following harvest. An analysis of the post-harvesting effects was conducted using a paired-catchment analysis. Results from this study show treatment sites resulted in higher daily maximum stream and bed temperatures after harvest but smaller changes in daily minima. Daily maximum post-harvest stream temperatures averaged over July and August ranged from 1.6°C to 3°C at different locations. Post harvest changes in bed temperature at the lower reaches were smaller than changes in stream temperature, but was greater at sites with downwelling (DF) flow, and decreased with depth at upwelling (UW) and DF sites dropping to approximately 1°C at a depth of 30 cm. Changes did not vary significantly with depth at the middle reach, and averaged approximately 1°C change in daily maximum bed temperature over July and August. In summary, stream temperature responses differed at different locations within the cutblock. Bed temperatures also differed between UW and DW zones as well as between reaches with different contributions of lateral inflow. Given evidence that stream/bed temperature is shown to change spatially and with differences in hyporheic exchange and lateral inflow, the authors conclude by suggesting further research into the how these results might impact biological and ecological processes.

Stream Temperature and evaporation/wind speed

Guenther et al., 2012 (not in focal, does not separate the effects of shade reduction from wind speed/)

Guenther, S. M., Moore, R. D., & Gomi, T. (2012). Riparian microclimate and evaporation from a coastal headwater stream, and their response to partial-retention forest harvesting. Agricultural and Forest Meteorology, 164, 1-9.

The purpose of this study was to (1) develop and test an evaporimeter designed specifically to measure stream surface evaporation from headwater streams; (2) fit a wind function for computing evaporation from meteorological observations, and to compare it to previously published wind functions for evaporation from streams; and (3) quantify the influence of partial-retention forest harvesting on riparian microclimate and evaporation. This study was conducted in the University of British Columbia Malcom Knapp Research Forest (MKRF), approximately 60 miles east of Vancouver, Canada and focused on the headwater stream of Griffith Creek. The harvesting treatment involved removal of 50% of the basal area from within the cut block, including the riparian zone. Smaller stems were removed, leaving the larger stems for harvest at a later date. creek. Analysis of paired pre- and post-logging hemispherical photographs indicated that canopy closure decreased by about 14% due to the logging treatment. Air temperature and relative humidity were measured by a Campbell Scientific CS500 sensor with stated accuracies of ±0.5 ◦C for temperature and ±3–6% for relative humidity. Wind speed was measured with a Met One anemometer with a stall speed of 0.447 m s−1. Instruments were scanned every 10 s by a Campbell Scientific CR10x data logger; observations were averaged and stored every 10 minutes. Evaporation was measured using four specially designed evaporimeters comprising an evaporation pan connected to a Mariotte cylinder. Results showed that Daily mean wind speeds increased following harvest, but were still consistently lower than wind speeds at the control site, with a maximum of 1.09 m s−1. Vapor pressure was generally lower after harvesting. Vapor pressure deficit (vpd) increased following harvesting, but tended to remain lower than vpd measured at the control site. After harvesting, the relatively high wind speeds in the afternoon generally coincided with higher water temperatures, which in turn are associated with higher vpd at the water surface and a stronger vapor pressure gradient to drive evaporation. After harvest, wind speeds and vapor pressure gradients were higher and stability was weaker, consistent with the observed increase in evaporation. The authors conclude that the generally stronger relations between riparian and open microclimate variables after harvesting suggest that the riparian zone became more strongly coupled to ambient climatic conditions after harvesting as a result of increased ventilation. Further, that stream evaporation increased markedly as a result of partial retention harvest, consistent with the decrease in atmospheric vapor pressure, the increase in stream vapor pressure, the increase in wind speed and the decreased stability. In fact, prior to harvest, vapor pressure gradients often favored condensation rather than evaporation.

LW

Opperman, 2005 (Not in focal)

Opperman, J. J. (2005). Large woody debris and land management in California's hardwood-dominated watersheds. Environmental Management, 35(3), 266-277. DOI:10.1007/s00267-004-0068-z

The purpose of this paper was to evaluate the effects of stream and riparian area characteristics (bankfull width, gradient, basal area), and land ownership (public vs. private) on LW loading, and frequency, and debris jam frequency (response variables) in 21 hardwood-dominated forests of a Mediterranean climate region of northern California. The relationship between the stream and riparian area characteristics (explanatory variables: basal area of riparian trees, bankfull width, and gradient), and the response variables (woody debris loading and frequency, and debris-jam frequency) were evaluated with linear regression. The characteristics were then combined with ownership categories and their relative weight in explaining LW loading, frequency and pool frequency were assessed with a multi-variate analysis. Debris jam frequency was also analyzed by channel position with a chi-square. Results showed that debris jam frequency in the 21 reaches analyzed were strongly influenced by living standing trees rooted at the margins of the bank, especially in channel positions near the stream bank, but also spanning the channel partially, or completely. In general, LW loading was significantly higher in reaches adjacent to public lands (104 ± 13 m3/ha) than in those adjacent to private lands (46 ± 8 m3/ha; P = 0.0015). The strongest relationship for LW loading was with bankfull width ($r^2 = 0.32$; $p = 0.0006$), and riparian basal area ($r^2 = 0.22$; $p = 0.006$) riparian basal area. This is likely the cause of the difference in public vs. private, as the public lands had significantly higher basal area in the riparian areas at distances >5 m from the stream, than the private lands. Debris jam frequency was also significantly influenced by riparian area gradient ($r^2 = 0.14$; $p = 0.03$) and basal area ($r^2 = 0.11$; $p = 0.05$). The author concludes that landownership, and thus, land-management practices are driving factors in LW dynamics in this region.

LW

Nowakowski & Wohl, 2008

Nowakowski, A. L., & Wohl, E. (2008). Influences on wood load in mountain streams of the Bighorn National Forest, Wyoming, USA. Environmental Management, 42(4), 557-571. DOI:10.1007/s00267-008-9140-4

The purpose of this paper is to evaluate the relationship between riparian area characteristics, and land management practices with in-stream wood-loads in the Bighorn National Forest of northern Wyoming. The authors hypothesized that 1) valley geometry correlates with wood load, 2) stream gradient correlates with wood load, 3) wood loads are significantly lower in managed watersheds than in similar unmanaged watersheds. The study analyzed data from 19 conifer dominated, forested headwater reaches in the bighorn mountains. Study reaches were separated by two watersheds, managed and unmanaged, with similar drainages, elevation, and lithology. Unmanaged watersheds were defined as having a history of minimal anthropogenic influences. The managed watershed had a history of different harvest prescriptions from unregulated in the late 1800s, clearcutting in the mid-1900s with tie floating practices. The relationship between in-stream wood loads (m^3/ha) was analyzed with 11 valley-scale (elevation, forest type, forest stand density, etc.) and 13 channel-scale (reach gradient, channel width, etc.) variables with linear regression. Results support the first and third hypotheses. Across all streams, the highest explanatory power of all models tested produced land use (managed vs unmanaged), and basal area as a significant predictor of wood loads ($r2 = 0.8048$). For the unmanaged watershed the model produced stream valley sideslope gradient as the single best predictor of wood load ($r2 = 0.5748$) supporting the first hypothesis. Shear stress was the best predictor of wood load in the managed watersheds ($r2 = 0.2403$), These results did not directly support the second hypothesis. The authors suggest that while shear stress is a function of stream gradient (shear stress and stream gradient were significantly correlated, $r2 = 0.9392$), gradient itself did not have the highest explanatory power of wood load in any of the models tested. Valley characteristics consistently explained more of the variability in wood load (42-80%) than channel characteristics (21-33%). When land use (managed vs. Unmanaged) effect on wood loads was analyzed the number of wood pieces per 100 m of stream was marginally significant ($p = 0.0565$), and the difference in wood volume per channel was significant ($p = 0.0200$) supporting the third hypothesis. When the significant valley and channel characteristics of the managed and unmanaged watersheds were controlled for, the significant difference in wood loads between managed and unmanaged watersheds were enhanced ($p = 0.0006$). Managed watersheds (1.1 m3/100 m) had, on average, 2-3 times lower in-stream wood loads than unmanaged (3.3 m3/100 m) watersheds. These results suggest watersheds with a history of timber harvest have a decrease in stream wood loads than unmanaged watersheds, and that wood load dynamics can be driven by valley morphology, specifically, slope.

Harvesting Practices on Suspended Sediment Yields

Hatten et al., 2018

Hatten, J.A., Segura, C., Bladon, K.D., Hale, V.C., Ice, G.G., Stednick, J.D., 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. https://doi.org/10.1016/j.foreco.2017.10.049

The objectives of this study were to (1) determine the effects of contemporary harvesting practices on suspended sediment yields and concentration, and (2) determine if contemporary harvesting practices produce lower sediment yields than historic practices. This study took place in the central Oregon Coast Range and consisted of a paired watershed study whereby Flynn Creek (FC) served as a reference watershed and Needle Branch (NB) served as a treatment watershed. A third watershed, Deer Creek (DC) served as a secondary control to compare historical vs contemporary harvest practices. The upper section of the treatment watershed was clearcut harvested using contemporary harvest practices (no buffer in non-fish-bearing streams with equipment exclusion zones, and a 15 m no-cut-buffer in fish-bearing streams) adhering to BMP's. Daily precipitation, discharge, and suspended sediment were collected at all three watersheds from October 2005 to June 2016. The upper half of the treatment watershed, (35 ha; measured at the Needle Branch Upper Gage or NBUG) was harvested in 2009 (Phase I) and the lower half (NBLG) was harvested in the fall of 2014 and mid-summer 2015 (Phase II). A model was developed using step wise linear regression to compare suspended sediment concentration (SSC). Differences in SSC among downstream sites and across harvest entries were compared utilizing an analysis of covariance. Results of the stepwise multiple linear regression showed strong evidence ($p < .001$) that all covariates (hydrograph limb, cumulative area discharge within water year, day of water year, daily precipitation, previous day's precipitation) were related to SSC across all watersheds. Both the mean and maximum SSC were greater in the reference catchments (FCG and DCG) compared to the harvested catchment (NBLG) across all water years. In NBLG the mean SSC was 32 mg L^{-1} (~63%) lower after the Phase I harvest and 28.3 mg L^{-1} (~55%) lower after the Phase II harvest when compared to the pre-harvest concentrations. Compared to the reference watersheds, the mean SSC was 1.5-times greater in FCG (reference) compared to NBLG during the pre-harvest period. After the Phase I harvest the mean SSC in FCG (reference) was 3.1-times greater and after the Phase II harvest was 2.9-times greater when compared to the SSC in NBLG, the harvested watershed. Data from historical and contemporary harvests indicate contemporary practices are more effective at mitigating sedimentation. Historical data from the original study show harvesting without buffers, road building, and slash burning resulted in ~2.8 times increase in annual sediment yields and aquatic ecosystem degradation. The authors conclude that contemporary harvesting practices (i.e., stream buffers, smaller harvest units, no braodcast burning, leaving material in channels) using buffers were shown to sufficiently mitigate sediment delivery to streams, especially when compared to historic practices.

Riparian Vegetation Removal Effects on Inputs and Production.

Hetrick et al., 1998 (Removed, outside of timeline)

Hetrick, N.J., Brusven, M.A., Meehan, W.R., Bjornn, T.C., 1998. Changes in Solar Input, Water Temperature, Periphyton Accumulation, and Allochthonous Input and Storage after Canopy Removal along Two Small Salmon Streams in Southeast Alaska. Transactions of the American Fisheries Society 127, 859–875. https://doi.org/10.1577/1548-8659(1998)127<0859:CISIWT>2.0.CO;2

The purpose of this study was to assess whether or not the removal of second growth riparian vegetation would affect the production of juvenile coho salmon. In addition, this study aims to understand whether perceived effects are due to changes in habitat or food availability. This study took place in the Tongas National Forest on Prince of Wales Island, Alaska. Experimental reaches were divided into untreated and treated sections whereby treated sections had all vegetation on both sides of the streambank 6-15 m back removed. Stream discharge, water temperature, periphyton accumulation, allochthonous inputs, and storage of benthic organic matter were assessed during the summer and fall of 1988-1989. Differences in measured variables were assessed with a split-block analysis of variance. Results from this study show average light intensities reaching the water surface was significantly greater ($P < 0.01$) in the open canopy block than in the closed canopy block and was influenced significantly by weather conditions. Removal of riparian vegetation in both sections of the study significantly increased the accumulation of periphyton biomass and chlorophyll a ($P < 0.01$), and significantly decreased the amount of allochthonous organic inputs to streams ($P < 0.01$). Average daily allochthonous input rates for closed and open canopy conditions at Eleven creek were 789 and 6 mg AFDM/m2 respectively, while input rates for closed and open canopy conditions at Woodsy creek were 805 and 6 mg AFDM/m2. Average daily water temperatures in open and closed canopy blocks at Eleven Creek were similar in 1988 but were significantly higher in the open blocks than in the closed blocks in 1989 ($P < 0.01$). The authors conclude by suggesting a thorough investigation into the interactions and responses of higher trophic levels to increases in periphyton biomass production and decreases in allochthonous inputs resulting from removal of riparian vegetation. Furthermore, the authors point out that the ability of stream segments to retain organic inputs through in-stream large woody debris may be a more important factor for allochthonous input processing by stream biota than the amount of allochthonous inputs entering a stream.

Wood Recruitment and Retention

Hough-Snee et al., 2016

Hough-Snee, N., Kasprak, A., Rossi, R.K., Bouwes, N., Roper, B.B., Wheaton, J.M., 2016. Hydrogeomorphic and Biotic Drivers of Instream Wood Differ Across Sub-basins of the Columbia River Basin, USA. River Research and Applications 32, 1302–1315. https://doi.org/10.1002/rra.2968

The purpose of this study was to understand the hydrogeomorphic and ecological processes which lead to wood recruitment and retention in seven sub-basins of the interior Columbia River Basin (CRB), USA. To achieve this, in-stream wood volume and frequency are quantified across sub basins. Following this, the riparian, geomorphic, and hydrologic attributes which are most strongly correlated to in-stream wood loads were determined. Random forest models were used to identify relationships between ecological and hydrogeomorphic attributes that influence in-stream wood within each sub-basin. Non-metric multidimensional scaling was performed on a matrix of hydrogeomorphic and forest cover variables, excluding instream wood frequency and volume to visualize reaches and sub-basins' relative similarity. To determine how wood predictors differed between sub-basins, ordinary least squares regression models of wood volume and frequency were built within each sub-basin. Results from this study show that in stream wood volume and frequency were distinctly different across all seven sub-basins. Across the CRB, wood frequency ranged from 0 to 2117.0 pieces km^{-1}, while volume ranged from 0 to 539 $m^3\ km^{-1}$. Large wood volume (PERMANOVA $F= 5.1$; $p = 0.001$) and frequency (PERMANOVA $F= 5.4$; $p = 0.001$) differed significantly between sub-basins. According to random forest (RF) models, mean annual precipitation, riparian large tree cover, and individual watershed were the three most important predictors of wood volume and frequency. Watershed area was the fourth strongest predictor of wood frequency, while catchment-scale and reach-scale forest cover were the fourth and fifth strongest predictor of wood volume. In contrast, sinuosity and measures of streamflow and stream power were relatively weak predictors of wood volume and frequency. Taken together, wood volume and frequency increased with precipitation and large riparian tree cover and decreased with watershed area. Final RF models explained 43.5% of the variance in volume and 42.0% of the variance in frequency of in stream wood loads. Results for drivers of wood frequency and volume between sub-basins were highly variable either showing no relationship between candidate models and predictive power (e.g., $r^2 \leq 0.12$; Entiat sub-basin). The highest predictive models for wood volume ($r^2 > 0.55$) and wood frequency ($r^2 \leq 0.45$) were for the John Day sub basin. Depending on the sub basin wood volume and frequency was positively correlated with forest cover, watershed area, large tree cover, 25-year flood event stream power, riparian conifer cover, and precipitation. Negative correlations, depending on sub basin, of wood volume and frequency with baseflow discharge, riparian woody cover, watershed area, and large tree cover. Given the heterogeneous results across all sub-basins studied, the authors conclude by emphasizing the importance of incorporating local data and context when building wood models to inform future management decisions.

Stream Temperature

Hunter, 2010 (not in focal, treatments and results not relevant to questions)

Hunter, M.A., 2010. Water Temperature Evaluation of Hardwood Conversion Treatment Sites Data Collection Report (Data Collection Report). Cooperative Monitoring, Evaluation, and Research (CMER). Fp_cmer_05_513

The purpose of this study is to evaluate the response of stream temperature to changes in canopy cover using a before-after-control-impact design. This study took place along nine hardwood-dominated riparian stands in Western Washington. Variables measured among locations and years include riparian conditions, canopy cover, channel dimensions, substrate, flow and stream temperature. Results from this study show that hardwood conversion buffers (HCB - approximately 15 m width) intended to convert hardwood-dominated riparian areas to conifer-dominated riparian areas usually resulted in decreased canopy cover of streams. Mean Global Site Factor (GSF - the proportion of global radiation under a plant canopy relative to the amount in an open area) increased in most study sites with HCB's. However, mean GSF did not change substantially at sites with buffers closer to standard (~ 18 – 45 m) non-hardwood conversion buffers. Temperature was highly variable over time and among locations suggesting stream temperature is affected by many factors that might differ among locations and throughout time. Longitudinal patterns of warming and cooling were consistent at all sites indicating the potential importance of careful site selection to account for changes in the longitudinal distribution of temperatures.

Influence of Stream Geomorphology on Water Temperature

Hunter & Quinn, 2009

Hunter, M.A., Quinn, T., 2009. Summer Water Temperatures in Alluvial and Bedrock Channels of the Olympic Peninsula. Western Journal of Applied Forestry 24, 103–108. https://doi.org/10.1093/wjaf/24.2.103

The purpose of this study was to understand how stream geomorphology influences water temperature in managed stands on the Olympic Peninsula, Washington. Sites chosen for this included an alluvial study site and a bedrock study site whose overall characteristics were otherwise comparable apart from geomorphology. The alluvial study site was a 1.6-km reach of Thorndyke Creek. The bedrock study site was a 1.4-km reach of the South Fork Pysht River.

Both channels were located in 35–50-year-old managed forests dominated by Douglas-fir (Pseudotsuga menziesii) in the uplands and red alder (Alnus rubra) in the riparian zone. Surface substrate at the alluvial channel was composed mostly of gravel, whereas the bedrock channel was composed of mostly bedrock, boulder, and cobble. The mean solar input (GSF: global site factor) did not differ between streams. Water temperature was recorded at 75-m intervals along each channel during the summers of 2003 and 2004. Results from this study show consistent differences in stream temperature response in alluvial versus bedrock channels. Seasonal maximum and minimum average daily temperatures varied less at the alluvial site compared to the bedrock site. This, the authors suggest may be due to hyporheic exchange in alluvial channels helping to buffer surface water temperatures from gaining or losing heat. In addition, groundwater may also contribute to the increased stability at the alluvial site. Two same-day measurements at each site showed the alluvial site gaining 8% of its flow, as compared to the bedrock site whose flow decreased by approximately 15%. The bedrock site was also shown to have the highest variation in reach-scale water temperatures during low flow. The authors conclude that stream geomorphology may have profound impacts on spatial and temporal patterns of channel water temperature. The authors suggest temperature reading from a single location may not accurately represent the entire channel. Additional research involving collection of temporal and longitudinal data will be needed to tailor riparian buffers to channel type.

Stream temperature, sediment, nutrient

Murray et al., 2000

Murray, G. L. D., Edmonds, R. L., & Marra, J. L. (2000). Influence of partial harvesting on stream temperatures, chemistry, and turbidity in forests on the western Olympic Peninsula, Washington. Northwest science., 74(2), 151-164. Handle: https://hdl.handle.net/2376/1065

This study investigates the effects of partial watershed harvest (7-33%) on stream temperature, chemistry, and turbidity relative to an unharvested old-growth watershed in the western Olympic Peninsula, Washington. Both harvested watersheds (Rock and Tower creeks) originally contained old-growth forests. Rock Creek had 7% of its watershed harvested in 1981, and Tower Creek had 33% of its watershed harvested between 1985 and 1987. Logging extended to the stream edge near the in-stream monitoring sites. Data for stream daily maximum, minimum, and mean temperatures, chemistry, and turbidity was recorded and monitored from June 1996 to June 1998 (10-15 years post-harvest). Differences in variables between treatment and reference watersheds were compared with a one-way ANOVA with a posthoc Tukey HSD test. Results showed higher maximum summer stream temperatures (15.4 ºC), and lower winter maximum stream temperatures (3.7 ºC) in the two treatment watersheds compared to the unharvested reference watershed (12.1 ºC and 6.0 ºC for summer max, and winter max, respectively). Winter minimum temperatures for one of the harvested watersheds reached 1.2 °C (Rock Creek) compared to a winter minimum of 6 °C Thus, seasonal variation of stream maximum temperatures and winter minimum temperatures were more extreme in the treatment watershed than in the control. There were no seasonal patterns or significant differences between watersheds in stream chemistry except for calcium and magnesium concentrations being consistently higher in the unharvested watersheds. Turbidity was low and not significantly different between watersheds. The authors interpret these results as evidence of partial harvest having minimal impact on stream temperatures, chemistry, and turbidity long-term (after 10-15 years). The stream temperature changes were significant but did not exceed the 16 ºC threshold used as a standard for salmonid habitat. However, there was no data collection during the first decade following harvest.

Channel Habitat, Particle Size, Stream Temperature, and Woody Debris Response to Harvest

Jackson et al., 2001

Jackson, C.Rhett., Sturm, C.A., Ward, J.M., 2001. Timber Harvest Impacts on Small Headwater Stream Channels in the Coast Ranges of Washington1. JAWRA Journal of the American Water Resources Association 37, 1533–1549.

https://doi.org/10.1111/j.1752-1688.2001.tb03658.x

The purpose of this study was to evaluate changes in stream temperature, particle size distributions of bed material, and channel habitat distributions in 15 first- or second order streams located on the Coast Range of Western Washington. Four of the fifteen stream basins were not harvested and served as references; three streams were cut with unthinned riparian buffers; one with a partial buffer; one with a buffer of non-merchantable trees; and six were clearcut to the stream edge. Buffer widths varied by operation; the average buffer width varied from 15 – 21 meters. The narrowest buffer measured on one side of the stream was 2.3 meters. Data for woody debris, sediment concentrations, turbidity, and stream temperatures were recorded for one-year prior to harvest (1998). Harvest was conducted in the spring and early summer of 1999, and post-harvest data was collected for about a month after operations were complete. Thus, the results presented in this study represent changes in stream attributes and characteristics immediately following harvest. Results from this study show that logging without buffers had immediate and dramatic effects on channel morphology. Without buffers, and the relatively steep topography of the study sites logging debris tended to accumulate at the bottom of slopes thereby burying or covering many headwater streams. Covered channels were defined in this study as having flow completely obscured by organic debris, but a recognizable channel still exists below the debris. Buried channel was defined as having so much organic detritus in the flow cross-section that the channel was no longer definable. Needles, twigs, whole branches, and logs buried headwater streams with a mean depth of 0.94 meters of organic debris (range: 0.5 - 2.0 meters). Of the clearcut streams the percent of stream buried with organic matter ranged from 6 to 90%, and the percent covered by organic matter ranged from 8 to 85%. The sum of buried and covered for each stream ranged from 72 to 100%. On the other hand, most buffered streams had 0% covered or buried by organic matter post-harvest with the only exception being one stream that experienced blowdown post-harvest that covered 29% of the stream. While debris accumulation tended to protect streams from the effects of solar radiation, organic logging debris was also shown to trap fine sediment in the channels which, in the near term, greatly reduced downstream sediment movement. As a result of increased roughness and additional bank failures within the clearcut sites, sediment size shifted towards finer particles growing from 12 to 44 percent. In contrast, particle size distributions continued nearly unchanged in buffered and reference sites. In the first summer after logging, significant increases were detected in overall macroinvertebrate densities, collector densities, shredder abundance and biomass, and organic and inorganic matter accretion. However, these responses were not detected one year following logging. For stream temperature changes, because the data collection was for such a short period of time (1-year pre- and1-month post-harvest), and because the summer of 1999 was much cooler than 1998, the assessment of harvest effects on stream temperature changes was difficult. Thus, to interpret significant changes in stream temperatures from pre- to post- harvest, daily maximum temperatures were plotted against the appropriate reference stream, and a regression equation was calculated. The slopes of the regression lines were compared with a student's t-test to determine significant differences. Of the seven clearcut streams, three showed no significant changes in temperature, one became cooler (-1.1 °C), one became slightly warmer (+0.8 °C), and the other 2 became warmer or colder depending on location with decreases in temperature upstream (-2.2 and –1.7 °C) and increases in temperature downstream (+5.2 and +15.1 °C). The buffered streams had significant but less dramatic changes in temperature with one decreasing in temperature (-0.3 °C), and 2 increasing in temperature (+1.6 and +2.4 °C). The one site with the non-merchantable buffer had much higher temperature increases (+3.7 and +6.6 °C). The authors posit that sites which retained riparian buffers succeeded in keeping debris out of streams as well as served to protect streambanks from failure or erosion. Some mature trees left within buffers experienced blow down and spanned the channel. While the clearcut streams had nearly all canopy cover removed, the buildup of slash and LW in the stream also provided shade and insulation that caused reductions in stream temperatures, or slight increases with one exception (+15.1 °C) The authors point out that this study only served to point out immediate effects of logging on physical channel conditions. Although important, there are still many questions about how channel conditions will evolve over time.

LW

Meleason et al., 2003

Meleason, M. A., Gregory, S. V., & Bolte, J. P. (2003). Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecological Applications, 13(5), 1212-1221. https://doi.org/10.1890/02-5004

This study used simulation modeling to evaluate the potential effects of three different riparian and watershed harvest scenarios on the standing stock of large wood in a hypothetical stream in the Pacific Northwest. The three scenarios involved harvest 1) clearcut to the streambank, 2) riparian management buffer widths ranging from 6-75 m, and 3) riparian buffers of various widths with upland forest plantation. The effects of each scenario on wood load dynamics were simulated with OSU STREAMWOOD for four harvest rotation periods (no harvest, 60, 90, and 120 years) over the course of 720 years. Results for scenario one (clear-cut to stream) showed minimal accumulation of wood into the stream with little change over time due to the lack of a forested riparian management zone. Results for scenario two showed the maximum standing stock of in-stream wood loads required $\geq$ 30 m no-cut buffer zones for 500-year-old forests. Wood loads in streams with 6 m wide buffers showed 32% of standing wood load stocks after 240 years. Results from scenario three showed minimal amounts of wood contributed into streams from forest plantations when > 10 m wide buffers were used. The authors interpret these results as evidence that riparian buffer widths and forest age are more important for estimating changes in wood loads over time than the harvest rotation age of plantation forests.

LW

Martin & Grotefendt, 2007

Martin, D. J., & Grotefendt, R. A. (2007). Stand mortality in buffer strips and the supply of woody debris to streams in Southeast Alaska. Canadian Journal of Forest Research, 37(1), 36-49. https://doi.org/10.1139/x06-209

This study compared riparian stand mortality and in-stream LW recruitment characteristics between riparian buffer strips with upland timber harvest and riparian stands of unharvested watersheds using aerial photography. This study was conducted in the northern and southern portions of Southeast Alaska at multiple sites in nine timber harvest areas. All study sites were along moderate- and low-gradient streams with channel widths ranging from 5 m to 30 m wide. All buffer strips were conifer dominated and a minimum of 20 m wide that included selective harvest within the 20 m zone. Reference sites were along unharvested reaches in the same area. Stand mortality was estimated by the proportion of downed trees within a buffer strip. Differences in downed tree proportions relative to reference streams were assumed to be caused by timber harvest, accounting for selective in-buffer harvests. A one-tailed paired t-test or a

Wilcoxon signed rank test was used to check for statistical differences between treatment and reference sites. Results showed significantly higher mortality (based on cumulative stand mortality: downed tree counts divided by standing tree counts + downed tree counts), significantly lower stand density (269 trees/ha in buffer units and 328 trees/ha in reference units), and a significantly higher proportion of LW recruitment from the buffer zones of the treatment sites than in the reference sites. Densities within all units ranged from 0 – 1334 trees/ha depending on location. Overall, mean stand density in the buffer units was 18% lower than in the reference units. Results also showed that mortality varied with distance to the stream. Differences in mortality for the treatment sites were similar to the reference sites for the first 0-10 m from the stream (only a 22% increase in the treated sites). However, mortality in the outer half of the buffers (10-20 m) from the stream in the treatment sites was more than double (120% increase) what was observed in the reference sites. This caused a change in the LW recruitment source distance curves, with a larger proportion of LW recruitment coming from greater distances in logged watersheds. LW recruitment based on the proportion of stand recruited (PSR) was significantly higher in the buffered units compared to the reference units. However, PSR from the inner 0-20 m was only 17% greater in the buffer units than in the reference units, while PSR of the outer unit (10 – 20 m) was more than double in the buffered units than in the reference units. The researchers conclude that the increase in mortality was caused by an increased susceptibility to windthrow. They estimate that future recruitment potential from the logged sites diminished by 10% relative to the unlogged reference sites.

Stream temperatures

Macdonald et al., 2003b

Macdonald, J. S., MacIsaac, E. A., & Herunter, H. E. (2003). The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. Canadian journal of forest research, 33(8), 1371-1382. https://doi.org/10.1139/x03-015

This study investigates the impacts of forest harvest on stream temperatures under three variable retention buffer treatments in headwater streams of the interior sub-boreal forests of British Columbia. Temperature data were recorded for two years pre- and five years post-harvest from five harvested streams and two unharvested reference streams. Differences between pre- and post-harvested stream temperatures were compared with the paired reference streams using repeated measures ANOVA. Treatment riparian areas were harvested with the following prescriptions: 1) low-retention – removal of all merchantable timber >15 or >20 cm DBH for pine or spruce respectively, within 20 m of the stream 2) high-retention – removal of merchantable timber >30 cm DBH within 20-30 m of the stream, and 3) Patch-cut – high retention for the lower 60% of watershed approaching streams and removal of all vegetation in the upper 60% of the watershed. Eight first-order streams were included in this study: two in the Gluskie Creek watershed (G5, G7) and six in the Baptiste Creek watershed (B1–B6). Five of these streams were within the harvested boundaries (2 high-retention, 2 low-retention, and 1 patch cut), and 3 reaches outside of the harvest boundary served as controls. Results showed a significant increase in stream temperatures ranging from 4 – 6 ºC at five years post-harvest, and increased ranges of diurnal temperature fluctuations for all treatment streams relative to the reference streams. Streams that had summer maximum mean weekly temperatures of 8°C before harvesting had maximum temperatures near 12°C or more following harvesting. Daily ranges of 1.0–1.3°C before harvesting became 2.0–3.0°C following harvesting, Greater temperature ranges occurred in low-retention and patch treatments than the high-retention or control treatment locations. The high-retention buffer treatment mitigated temperature increases for the first three years. Still, increased mortality (windthrow) caused a reduction in the canopy that increased stream temperatures equivalent to other treatment streams by year five. The results of this study show evidence that high-retention buffers are no more effective in preserving stream temperature changes than small retention buffers when treatment areas have a high susceptibility to windthrow.

Sediment delivery pathways

Litschert & MacDonald, 2009

Litschert, S. E., & MacDonald, L. H. (2009). Frequency and characteristics of sediment delivery pathways from forest harvest units to streams. Forest Ecology and Management, 259(2), 143-150. https://doi.org/10.1016/j.foreco.2009.09.038

This study investigates the frequency of sediment delivery pathways ("features") in riparian management areas and measures the physical characteristics and connectivity of these pathways following timber harvest. The results of this study were then used to develop models for predicting the length and connectivity of pathways formed from harvest units. Data was collected from over 200 harvest units with riparian management areas in the Eldorado, Lassen, Plumas, and Tahoe National Forests in the Sierra and Cascade mountains of northern California. Riparian buffer widths for this area are 90 m and 45 m for perennial and annual streams respectively. No machinery is allowed in the riparian management areas. Data collected and analyzed for the pathways included years since harvest, mean annual precipitation, soil depth, soil erodibility, hillslope gradient, aspect, and elevation. Characteristics of pathway length, gradient, and roughness were also collected. Relationships between site variables and pathway variables were assessed using linear regression. The site variables with the most significant relationships with the pathway variables were used in a multivariate regression model to predict pathway length.

Only 19 of the 200 harvest units had sediment development pathways. Pathways ranged in age (time since harvest) from 2 to 18 years, and in length from 10 m to 220 m. Of the 19 pathways, only six were connected to streams, and five of those originated from skid trails. Pathway length was significantly related to mean annual precipitation, cosine of the aspect, elevation, and hillslope gradient. The authors conclude that timber prescription practices for these National Forests are effective in reducing sediment delivery pathways. The authors interpret these results as evidence that skid trails should be directed away from streams, maintaining surface roughness, and promptly decommissioning skid trails.

LW

Liquori, 2006

Liquori, M. K. (2006). POST-HARVEST RIPARIAN BUFFER RESPONSE: IMPLICATIONS FOR WOOD RECRUITMENT MODELING AND BUFFER DESIGN 1. JAWRA Journal of the American Water Resources Association, 42(1), 177-189. https://doi.org/10.1111/j.1752-1688.2006.tb03832.x

This study investigates the differences in treefall characteristics in riparian management areas based on ecological and physiographic variables to give insight on the variables important for wood recruitment modeling. Data were collected from 20 riparian buffer sites that had all been clearcut within three years of sampling with standard no-cut buffers 25 ft. An additional 50-100 ft buffer was applied to fish-bearing streams depending on stream type, in a managed tree farm in the Cascade Mountains of western Washington. These riparian buffers generally consisted of naturally regenerated, second-growth conifer stands about 45 to 70 years old. “Very modest” thinning was applied to some stands to meet wildlife objectives and any downed wood not affecting the channel was removed. Tree characteristic data collected included tree size (DBH and height), species, fall direction, tree fall angles, estimated cause of mortality, and distance to the stream. Site characteristics included stream gradient, valley morphology, and time since harvest. Tree recruitment probability curves were developed as a function of tree height using methods described by Beschta, (1990). Results showed that wind-caused mortality and tree fall rates were significantly higher, up to three times higher, than competition-induced mortality within buffers for three years following treatment. The median observed treefall per site was 15% of all trees in each buffer, ranging from 1 to 57%. total treefall at each site for one, two, and three years since harvest was 16 ± 10%, 28 ± 21%, and 10 ± 10%, respectively. Total treefall percentage for each site was not correlated to years since harvest (Spearman R = 0.11; p = 0.34). The mean and standard deviation of the total normalized treefall for one-year old sites was 405 ± 394 trees/km (n = 9), for two-year old sites was 264 ± 280 trees/km (n = 7), and for three-year old sites was 556 ± 316 trees/km (n = 4). Treefall varied significantly by species. Downed red alder (Alnus rubra), western red cedar (Thuja plicata), and Douglas-fir (Psuedotsuga menziesii) comprised 3 percent to 8 percent of all downed trees; these species had treefall rates ranging from 5 percent to 9 percent of the total number of trees of the same species. By contrast, treefall rates for western hemlock (Tsuga heterophylla) and Pacific silver fir (Abies amabalis) ranged from 23 percent to 26 percent. Treefall rates also varied somewhat by size, with the 31 to 41 cm (12 to 16 in) diameter class having the greatest treefall rates (All trees were grouped into size classes based on diameter at breast height: 1 to 8 in; 8 to 12 in; 12 to 16 in; 16 to 20 in; and more than 20 in). Treefall following harvest greatly exceeded the expected competition induced mortality rates (posited by Franklin, 1970) of 0.5%, and the model of average competition mortality used in Rainville et al. (1985), which ranged from 0.7 - 1.6%, and 2% per year for bank undercutting. Treefall direction was heavily biased towards the channel regardless of channel or buffer orientation and tree fall probability was highest in the outer areas of the buffers (adjacent to the harvest area). Fall direction bias increased significantly in the inner portions of the buffer. Within the 0 to 7 m zone and 7 to 15 m zone, 68% and 67% of the trees, respectively, fell toward the channel (n = 125 and 153, respectively). Only 44% of the outer zone (> 15 m) downed trees fell toward the channel (n = 403). Generally, recruitment was negatively correlated to buffer width ($r^2 = 0.40$). Treefall was generally highest at the outside edges of buffers (50+ feet), representing about 60% of the total observed treefall, while the 0–25-foot zone represented ~18%, and the 25–50-foot zone represented ~22%. The authors interpret their results as evidence that tree fall models that use a random fall direction may underrepresent the probability of LW recruitment into streams. Further, they suggest that the increase in windthrow mortality and the probability of tree fall with increasing distance from the stream should be considered.

LW

Lininger et al., 2021 (removed from focal list, this is a case study)

Lininger, K. B., Scamardo, J. E., & Guiney, M. R. (2021). Floodplain large wood and organic matter jam formation after a large flood: Investigating the influence of floodplain forest stand characteristics and river corridor morphology. Journal of Geophysical Research: Earth Surface, 126(6), e2020JF006011. https://doi.org/10.1029/2020JF006011

This study examines how river corridor morphology and forest stand density influence LW and coarse particulate matter (CPOM) deposition patterns in the flood plain resulting from a 400-year flood event in West Creek in the Colorado Front Range in 2013. The researchers tested the hypothesis that if river corridor geomorphology affects LW and CPOM deposition then there should be an inverse relationship between elevation above and distance from the stream's edge. Further, that deposition frequency would be higher in unconfined portions of the corridor. Considering forest stand structure, the researchers hypothesized that LW/CPOM jams would be pinned by trees, higher in intermediate forest densities, and decrease in size with increasing forest stand density. Field data of LW/CPOM jams were analyzed with non-parametric Spearman correlation tests to determine the strength of their relationship with channel and stand characteristics. Results showed support for most of the hypotheses. LW accumulations did decrease in size with distance from the stream, but CPOM did not. Confined channels (steeper reaches) contained fewer LW/CPOM loads per unit area. The authors speculate that these reaches had higher flow rates and thus lower deposition during the flood. CPOM jams increased in number per area with increasing stand density with most jams pinned against live trees. The authors conclude that the effect of riparian forest stand density is evidence that riparian forests in the floodplains should be preserved to increase LW and CPOM trapping probability.

Stream Temperature

Janisch et al., 2012

Janisch, J.E., Wondzell, S.M., Ehinger, W.J., 2012. Headwater stream temperature: Interpreting response after logging, with and without riparian buffers, Washington, USA. Forest Ecology and Management 270, 302–313. https://doi.org/10.1016/j.foreco.2011.12.035

The purpose of this study was to assess the stream temperature response to three different harvesting treatments in small, forested headwater catchments in western Washington. The pre-logging calibration period lasted 1–2 summers and stream temperatures were monitored for two or more summers after logging. Harvest treatments occurred between September 2003 and July 2005; catchments were clustered by harvest year for analysis. A before-after-control-impact study design was used to contrast stream temperature responses for three forest harvest treatments: clearcut logging to the stream (n=5), a continuous buffer (n=6) with widths 10-15 m on each side of the channel, and a patched buffered (n=5) where portions of the riparian forests ~50-110 m long were retained in distinct patches along some portion of the channel with the remaining riparian area clearcut. For the patch buffers there was no standard width, the buffer spanned the full width of the floodplain area and extended well away from the stream. Upland areas adjacent to buffers were clearcut. Regression relationships were developed between temperatures measured in the treatments and corresponding reference catchments. A simple ANOVA model was used that only included fixed effects for treatment, years since treatment, and day of year. Because of the unbalanced experimental design and variation in time of harvest, clustering of treatments caused the sample sizes to become too small to apply a more complex nested, repeated measures ANOVA could not be used. Correlation analysis was conducted between post-harvest stream temperatures and descriptive variables on a subset of catchments to examine possible factors that might control post-harvest thermal responses. Results from this study show significant increases in stream temperature in all treatments. Although temperature responses were highly variable within treatments, July and August daily maximum temperatures increased in clearcut catchments during the first year after logging by an average of 1.5°C (range 0.2 to 3.6°C), in patch-buffered catchments by 0.6°C (range – 0.1 to 1.2°C), and in continuously buffered catchments by 1.1°C (range 0.0 to 2.8°C). Canopy cover in all streams averaged 95% prior to harvest and did not differ between treatment and reference streams. Following treatment, canopy cover in the clearcut catchments averaged 53%, canopy cover in the patch buffer treatment averaged 76%, and canopy cover in the continuous buffer treatment averaged 86%. Following treatment, the canopy cover of the clearcut and patch buffer treatments were significantly lower than in the reference streams. The continuous buffer treatments did not differ significantly from the reference streams for canopy cover. Further analyses which attempted to identify variables responsible for controlling the extent of stream temperature responses showed the amount of cover retained in the riparian buffer was not a strong explanatory variable. Post-treatment temperature changes suggested that treatments ($p = 0.0019$), the number of years after treatment ($p = 0.0090$), and the day of the year ($p = 0.0007$) were all significant effects explaining observed changes in temperature. Wetland area ($r2 = 0.96$, $p<0.01$) and length of surface flow ($r2 = 0.67$, $p = 0.05$) were strongly correlated with post-logging temperature changes. Regression analysis of these variables showed streams with fine-textured substrates responded differently than coarse textured substrates. The authors speculate this is possibly due to groundwater interactions which can buffer thermal responses of small streams. In summary, the authors conclude that their results suggest small headwater streams may be fundamentally different than larger streams partly because factors other than canopy shade can greatly influence stream energy budgets to moderate stream temperatures despite changes and/or removal of the overstory canopy.

Large woody debris

Jones et al., 2011 (Removed from focal list, study not relevant to focal questions)

Jones, T.A., Daniels, L.D., Powell, S.R., 2011. Abundance and function of large woody debris in small, headwater streams in the Rocky Mountain foothills of Alberta, Canada. River Research and Applications 27, 297–311. https://doi.org/10.1002/rra.1353

The purpose of this study was to assess LW abundance in the upper foothills of the Rocky Mountains in Alberta, Canada. This study also sought to understand key processes that underlie changes in LW function. Finally, this study used results to develop a LW recruitment, decay and interaction model. This research was conducted in 21 headwater streams spanning two watersheds. At each site, all LW was sampled and was classified according to decay, orientation, position and function. LW frequency, total volume, and total in-stream volume were calculated and analyzed for differences using a one-way ANOVA followed by a Tukey post hoc test to differentiate among significant classes. Results show LW frequency was greater in the Alberta foothills (64.0 ±3.3 LW 100 m1) than in many small, headwater streams in mountain (46.2 ±3.6), coastal (47.6 ±3.8), mixed broad-leaf (47.0 ±4.2) and boreal (31.0 ±3.0) streams. This, the authors suggest, is likely due to the narrow bankfull width channels characteristic of the Alberta foothills which are less able to transport LW downstream. LW with ≥20 cm was more frequent in coastal streams, and overall LW volume was also greatest in coastal streams (721.0 ±99.9 m3 ha^{-1}). The authors note that large LW volumes in coastal streams are likely due to geomorphic disturbances alongside large, long-lived, decay resistant tree species. According to Harmon et al. 1986, much of the variation in LW recruitment is due to differences in species life history and forest type which together govern log size and decay rates.

Suspended Sediment

Karwan et al., 2007

Karwan, D., Gravelle, J., Hubbart, J., 2007. Effects of timber harvest on suspended sediment loads in Mica Creek, Idaho. Forest Science 53, 181–188. https://doi.org/10.1093/forestscience/53.2.181

The purpose of this study was to examine the effects of forest road construction and timber harvest on total suspended solids (TSS) in a forested watershed. This study took place at the Mica Creek Experimental Watershed in northern Idaho. The study area consisted of dense, naturally regenerated, even-aged stands ~65 years old and ~300 trees per acre. Timber harvesting and heavy road use began in 2001. Treatments in the paired-watershed experiment consisted of (1) commercial clearcut of the watershed area of 50%, and was broadcast burned and replanted by the end of May 2003, (2) partial cut in which half the canopy was removed in 50% of the watershed in 2001, with final 10% of log processing and hauling in early summer of 2002. and (3) a no-harvest control. All harvests were carried out according to best management practices and in accordance with the Idaho Forest Practices Act. At the time of the study this involved a 22.86 m (75 ft) stream protection zones (SPZs) on each side of fish-bearing (Class I) streams. The inner 50 ft is an equipment exclusion zone where no ground-based skidding machinery is allowed. Timber harvesting is allowed in Class I SPZs, but 75% percent of existing shade must be retained. Along non-fish-bearing (Class II) streams, harvesting equipment was excluded from entering within 9.14 m (30 ft) of definable stream channels and any cut trees were felled away from the stream; however, there were no tree retention requirements. In the clearcut and partial cut units, line skidding was used on slopes in the watershed exceeding approximately 20%, while tractor skidding was used on the lower gradient slopes. On all skid trails, drainage features, such as water bars, were installed for erosion control at the end of the harvest period. Time series data were compiled for all measured TSS values from1991 through 2004. Data was collected via seven stream monitoring flumes located within the Mica Creek Watershed. Monthly TSS loads were compared across watersheds for five time intervals: (1) pretreatment: ~6 years, (2) immediate post-road construction: ~1 year, (3) recovery post-road construction: ~3 years, (4) immediate post-harvest: ~1 year, and (5) recovery post-harvest: ~3 years. Trends in the relationship between treatment and control watersheds were statistically examined for each of the time intervals. Treatments in the paired-watershed experiment consisted of (1) commercial clearcut of the watershed area of 50%, and was broadcast burned and replanted, (2) partial cut in which half the canopy was removed in 50% of the watershed (3) a no-harvest control. All harvests were done according to best management practices and the Idaho Forest Practices Act. This included equipment exclusion zones of 50- and 30-feet for fish- and non-fish-bearing streams, respectively. On all skid trails, drainage features, such as water bars, were installed for erosion control at the end of the harvest period. Analysis of covariance was used for each treatment-control watershed pair. Results show monthly TSS loads from watersheds 1(clearcut), 2 (partial cut), and 3 (no-harvest) ranged from 0.4 kg km^{-2} to above 10,000 kg km^{-2}, with a maximum in the spring months and minimum in the winter and late summer months similar to intra-annual trends in water yield. Road construction in both watersheds did not result in statistically significant impacts on monthly sediment loads in either treated watershed during the immediate or recovery time intervals. A significant and immediate impact of harvest on monthly sediment loads in the clear-cut watershed ($p = 0.00011$), and a marginally significant impact of harvest on monthly sediment loads in the partial-cut ($p = 0.081$) were observed. Total sediment load from the clearcut over the immediate harvest interval exceeded predicted load by 152% (6,791 kg km^{-2}); however, individual monthly loads varied around this amount. The largest increases in percentage and magnitude occurred during snowmelt months, namely April 2002 (560%, 2,958 kg km^{-2}) and May 2002 (171%, 3,394 kg km^{-2}). Neither treatment showed a statistical difference in TSS during the recovery time (clearcut: p = 0.2336; partial-cut: p = 0,1739) compared to calibration loads (pre-treatments). The authors conclude that best management practices for road construction, including improvement of existing roads, did not produce significant changes in TSS. Significant changes in TSS only occurred immediately after harvest. However, after one year, the TS load became statistically indistinguishable from the control.

Harvest effects on Instream light

Kaylor et al., 2017

Kaylor, M.J., Warren, D.R., Kiffney, P.M., 2017. Long-term effects of riparian forest harvest on light in Pacific Northwest (USA) streams. Freshwater Science 36, 1–13. https://doi.org/10.1086/690624

The purpose of this study was to evaluate relationships between riparian forest stand age and stream light availability. The specific goals dealt with evaluating characteristics of late-successional forest light regimes, and whether canopy openness and light differed between streams flowing through harvested units and late-successional forest units. This study took place at the HJ Andrews Experimental Forest in the Cascade Mountain, Oregon. Approximately 11.5 km of stream length were sampled in the McCrae Basin which consists mostly of old-growth forests Douglas-fir forests with small patch clear cuts. All treatment sites were harvested within 50 to 60 years before the study. Clearing up to both stream banks occurred at two of seven treated sites and clearing up to one bank occurred on all other treated sites. Stream bank-full width, wetted width, canopy openness, % red alder, and estimated photosynthetically active radiation (PAR) were quantified at 25-m intervals to evaluate relationships between channel and riparian characteristics and stream light. Results from this study show mean estimated PAR reaching the streams was lower in the recovering harvested units (50-yeasr post-treatment) than in up and downstream reaches bordered by old growth for all comparisons (n=14), while only 6 were significant ($p<0.05$). All in all, old growth reaches averaged 1.7 times greater PAR values than in nearby harvested units with the greatest differences occurring when harvest was implemented on both banks. Mean canopy openness was higher in late-successional forests (> 300 years old) than in young second growth forests (30–100-year-old forests), 18% and 8.7% respectively. Results also indicate the relationship between canopy openness and PAR was stronger at the reach scale than at individual locations with mean canopy openness explaining 78% of the variance in mean PAR estimates. The researchers also conducted a review of available literature of studies that contained information on the effects of Northwest Douglas-fir forest growth dynamics on canopy cover and light availability. The researchers concluded from this review that canopy closure, and thus lower light availability, occurs approximately 30 years after growth and maintained until after 100 years of growth when the canopy structure begins to open and produce gaps. Altogether, this study suggests stream light regimes are affected by initial canopy removal and subsequent recovery. Depending on forest type, dominant species and the age of the stand, different stages of stand development may reflect complex overstory structures allowing variable levels of light to the stream.

Stream Temperatures

Kibler et al., 2013

Kibler, K.M., Skaugset, A., Ganio, L.M., Huso, M.M., 2013. Effect of contemporary forest harvesting practices on headwater stream temperatures: Initial response of the Hinkle Creek catchment, Pacific Northwest, USA. Forest Ecology and Management 310, 680–691. https://doi.org/10.1016/j.foreco.2013.09.009

The purpose of this study was to investigate the effects of contemporary forest harvesting practices on headwater stream temperatures using a BACI design. This study was conducted as part of the Hinkle Creek paired Watershed Study (HCPWS). This study consisted of a nested, paired watershed study in which harvesting treatments in accordance with the Oregon Forest Practices Act (FPA) were applied to four headwater catchments in southern Oregon. Oregon FPA does not require retention of fixed-width buffer strips adjacent to non-fish-bearing streams. Thus, as a part of the harvest activities, fixed-width buffer strips containing merchantable overstory conifers were not left adjacent to the non-fish-bearing streams. Clearcut harvest took place between August 2005 and May 2006. Streamflow and temperature were measured at 8 locations within the basin from autumn 2002 until autumn of 2006 giving 3 years of pre-harvest data and <1 year of post-harvest data. Treatment and reference catchments were paired based on similarity in catchment area, aspect, stream orientation, stream length, and discharge. Significant differences between pre- and post-harvest daily max temperature measurements were detected across all sites, however, magnitude and direction of changes were inconsistent. Results for daily mean maximum stream temperatures show a variable response across all four harvested streams ranging from 1.5°C cooler to 1.1°C warmer relative to pre-harvest years. No statistically significant changes in max, mean, or minimum daily stream temperatures to timber harvest were observed. The authors suggest possible explanations for lack of consistent temperature increases to shading provided by logging slash. Interestingly, statistically significant changes to relationship between treatment and reference site pairs with respect to minimum and mean stream temperatures resulted in decreased minimum daily stream temperatures on days where high temperatures were observed in reference streams. At one treatment site, mean minimum temperatures across the warm season decreased 1.9°C relative to pre-harvest years, and the minimum temperature on the warmest day decreased by 2.8°C relative to pre-harvest years. Except for one treatment-reference pair, highly significant changes to slope and intercept parameters of minimum daily stream temperatures were detected for each stream pair ($p<0.001$). The authors suggest decreases in daily minimum stream temperature is a likely consequence of timber harvest.

Shade and Stream temperature

Cupp & Lofgren, 2014

Cupp, C.E. & Lofgren, T.J. (2014). Effectiveness of riparian management zone prescriptions in protecting and maintaining shade and water temperature in forested streams of Eastern Washington. Cooperative Monitoring Evaluation and Research Report CMER 02-212. Washington State Forest Practices Adaptive Management Program. Washington Department of Natural Resources, Olympia, WA.

The purpose of this study was to assess the percent reduction in canopy cover, and the response in stream temperatures following riparian timber harvest under the "all available shade" rule (ASR), and the standard rule (SR) in eastern Washington. The ASR is applied to areas in the Bull Trout Habitat Overlay (BTO; map of bull trout habitat) that requires retention of all available shade within 75 feet of the stream. Under the standard shade rule (SR) some harvest is allowed within the 75-foot buffer depending on elevation and pre-harvest canopy cover. The primary objectives of this study were to (1) Quantify and compare differences in post-harvest canopy closure between the SR and the ASR riparian prescriptions of eastern Washington; and (2) Quantify and compare differences in stream temperature effects of the two riparian prescriptions: the SR and the ASR. This study was conducted at 30 sites in eastern Washington. Sites were between 65-100 years old and were situated along second to fourth order streams with harvest-regenerated or fire-regenerated forests. Reference reaches were located upstream from treatment reaches where harvest was applied. Eighteen sites were located on state owned and managed forests and 12 sites were located on private industrial forests. Prior to harvest treatments, canopy closure measurements ranged from 89% to 97%, with a mean of 93%. The riparian management zone (RMZ) consists of three zones: The core zone is nearest to the edge of the stream and extends out 30 feet horizontally from the bankfull edge or outer edge of the channel migration zone (CMZ), whichever is greater. The inner zone is situated immediately outside of the core zone. For streams with a bankfull width of less than or equal to 15 feet wide, the inner zone width is 45 feet wide. All streams assessed in this study were less than or equal to 15 feet wide. The outer zone of the RMZ is the zone furthest from the water and its width varies according to stream width and site class for the land. The specific site class (a measure of site productivity) at each treatment site would vary the outer zone width from 0 to 55 feet wide. Seven sites had up to four years pre-harvest temperature data with only two years post-harvest data. Nine sites had three years pre-harvest data and one site had only one year pre-harvest data. The remaining 13 sites had two years pre-harvest data. Following harvest treatments, all 30 sites had at least two years post-harvest temperature data collection, although 21 of the 30 sites had at least three years post-harvest monitoring. Data collection included twice hourly stream and air temperature data during each sample period. Canopy, shade, riparian, and channel data were collected during the first-year pre-harvest and the first year post-harvest. Stream temperature data were collected at 30-minute intervals between 1 July and 15 September for a total of 77 days each year a site was investigated. Stream canopy closure and shade were quantified at 75-ft intervals within each reach using a hand-held densiometer (for canopy closure measurements) and a self-leveling fisheye lens digital camera (for shade measurements). A t-test was used to evaluate differences in pre-harvest canopy cover between reference and treatment reaches, and between ASR and SR sites. A correlation analysis between post-harvest change in shade and the descriptive riparian and channel values (e.g., trees per acre, basal area, channel gradient, etc.) was also used to examine possible factors that may control post-harvest changes in shade. A linear mixed effects model was used to quantify and compare differences in daily max stream temperatures (DMAX) between no harvest, ASR and SR prescriptions. Results showed post-harvest shade values decreased in SR sites (mean effect of -2.8%, $p = 0.002$), as did the canopy closure values (mean effect of -4.5%, $p < 0.001$). Shade and canopy closure values did not significantly change in the treatment reaches of the ASR sites. Mean shade reduction in the SR treatment sites exceeded the mean shade reduction in the ASR sites by 3%. Canopy closure reduction was also greater in the SR sites than in the ASR sites by a mean of 4%. Specifically, the mean shade reduction in ASR sites was 1% with a maximum reduction of 4%. The mean reduction of shade in the SR sites was 4% with a maximum reduction of 10%. Mean shade contribution of upland trees (trees outside of the RMZ) per study site was calculated as < 1 %. Shade reduction levels did not differ between the sites receiving RMZ-harvest only and the sites receiving standard operational upland harvest. Site seasonal means of daily maximum stream temperature treatment responses in the first two years following harvest ranged from - 0.7 °C to 0.5 °C in the ASR reaches and from -0.3 to 0.6 in the SR reaches. Site seasonal mean post-harvest background responses in reference reaches ranged from - 0.5 °C to 0.6 °C in the first two years following harvest. Mean daily maximum stream temperature increased 0.16 °C in the SR harvest reaches, whereas stream temperatures in both the ASR sites and in the no-harvest reference reaches increased on average by 0.02 °C. Seasonal mean stream temperature responses of up to 0.5 °C in the no-harvest references were common during the post-harvest test period. Sample period means of daily maximum temperature responses varied from –1.1 °C to 0.7 °C in the first two years post-harvest for the ASR sites, from –0.5 to 0.8 °C, in the SR sites, and –0.5 to 0.9 °C in the reference sites. The authors interpret these results as evidence that temperature effects of the SR, and ASR were similar to reference conditions along sampled reaches for small streams in the mixed fir zone mid-successional forests of eastern Washington. Further, that processes not directly related to canopy cover alteration over streams may be primarily responsible for the small variations observed in stream temperatures following harvest.

Ehinger et al., 2021 (results are only descriptive)

Ehinger, W.J., W.D. Bretherton, S.M. Estrella, G. Stewart, D.E. Schuett-Hames, and S.A. Nelson. 2021. Effectiveness of Forest Practices Buffer Prescriptions on Perennial Non-fish-bearing Streams on Marine Sedimentary Lithologies in Western Washington. Cooperative Monitoring, Evaluation, and Research Committee Report CMER 2021.08.24, Washington State Forest Practices Adaptive Management Program, Washington Department of Natural Resources, Olympia, WA.

The purpose of this study was to assess the effectiveness of riparian management zone prescriptions in maintaining functions and processes in headwater perennial, non-fish-bearing streams in incompetent (easily eroded) marine sedimentary lithologies in western Washington. Specifically, this study used a multiple before after control impact (MBACI) design to compare unharvested reference sites to sites harvested under the western Washington Forest Practices for non-fish-bearing streams to assess the effects of these rules on riparian vegetation and wood recruitment, canopy closure and stream temperature, stream discharge and downstream transport of suspended sediment and nitrogen, and benthic macroinvertebrates. The Forest Practices rules for non-fish-bearing streams in the study area includes clearcut harvest with a two-sided 50-foot-wide riparian buffer along at least 50% of the riparian management zone, including buffers prescribed for sensitive sites and unstable slopes. Ten study sites were chosen with first-, second-, and third-order non-fish-bearing streams. Data was collected for 1-2 years of pre-harvest, during the harvest period (2012 – 2014), and at least 2 years post-harvest at all sites. Because of unstable slopes, total buffer area was 18 to 163% greater than the 50-foot-buffer. This resulted in 4 different buffer types 1) Buffers encompassing the full width (50 feet), 2) <50ft buffers, 3) Unbuffered, harvested to the edge of the channel, and 4) Reference sites in unharvested forests. Because of the separation into multiple treatments, sample sizes became small and unbalanced. Thus, no statistical analyses were conducted, and only descriptive statistics were applied for changes in stand structure and wood loading. Density decreased by 33 and 51% and basal area by 26 and 49% in the full and <50ft buffers, respectively, with high variability among sites. Nearly all trees were removed from Unbuffered sites during harvest (>99% of basal area). In the reference plots, cumulative post-harvest mortality during the 3-year post-harvest interval was only 6.5% of live density. In contrast, mean post-harvest mortality in the full buffer sites and the <50 ft buffer sites were 31 and 25% of density, respectively. However, there was considerable variation in mortality among sites exceeding 65% in two full buffer treatment sites. Windthrow and physical damage from falling trees accounted for ~75% of mortality in the full and <50 ft buffers. In contrast to the treated sites, <10% of trees died due to wind or physical damage in the reference sites. There was little post-harvest large wood input in reference sites: an average of 4.3 pieces and 0.34 m3 of combined in- and over-channel volume per 100 m of channel. In contrast, the full buffer sites and <50 ft buffer sites received an average of 23 and 10 pieces/100 m and 2.3 and 0.7 m3/100 m of large wood, respectively. The majority of recruited large wood pieces had stems with roots attached (SWRW); 60, 70, and 100% in the reference, full buffer, and <50 ft buffer types, respectively. Pre-harvest channel large wood loading ranged from 55.8 to 111 pieces/100 m and from 9.8 to 25.2 m3/100 m among buffer types. Piece counts remained stable in the reference sites through year 3 post-harvest, increased in the full buffer and unbuffered sites (8 and 13%, respectively), and decreased in the <50 ft buffers (15%). For effects of treatment on shade, data was analyzed with generalized linear mixed-effects models. For effects of treatment on stream temperature, data was analyzed for the seven-day average in a linear-mixed-effects model analysis of variance. Mean canopy closure decreased in the treatment sites from 97% in the pre-harvest period to 75%, 68%, and 69% in the first, second, and third post-harvest years, respectively, and was related to the proportion of stream buffered and to post-harvest windthrow within the buffer. The seven-day average temperature response increased by 0.6°C, 0.6°C, and 0.3°C in the first, second, and third post-harvest years, respectively. During and after harvest, mean monthly water temperatures were higher, but equaled or exceeded 15.0°C only in 2 treatment sites by up to 1.8°C at one site and by 0.1°C at another. None of the three REF sites exceeded 15°C during the study. Predictive models could not be fitted to the temperature data for statistical analysis. Results for changes in nutrient concentrations post-harvest were highly variable. Harvest treatment effects on nutrient concentrations, discharge, and suspended sediment export could not be calculated because prediction equations could not be developed.

McIntyre et al., 2018

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

The purpose of the study was to evaluate the effectiveness of forest management prescriptions in maintaining aquatic conditions and processes for small non-fish-bearing (Type N) headwater stream basins underlain by competent "hard rock" lithologies (i.e., volcanic or igneous rock) in western Washington. Specifically, this study quantified and compared the effects of timber harvest adjacent to Type N streams on riparian stand structure and tree mortality, in stream wood loading and recruitment, stream temperature and canopy cover, stream discharge, turbidity, and suspended sediment export, nitrogen export, and response of stream associated amphibians. This study used a before-after control-impact (BACI) study design. This involved evaluation of four experimental treatments: (1) unharvested reference (n = 6), (2) 100% treatment (n = 4), a two-sided 50-ft riparian buffer along the entire Riparian Management Zone (RMZ), (2) FP treatment (n = 3), a two-sided 50-ft riparian buffer along at least 50% of the RMZ, consistent with the current Forest Practices buffer prescription for Type N streams, This treatment also included a circular buffer protecting the uppermost points of perennial flow (PIP), (3) 0% treatment (n = 4), clearcut to stream edge (no-buffer). The upland forests of all treatments were clearcut harvested. The study design included data collection for at least two years pre-harvest (2006 –2008), and three years of post-harvest data (2009 – 2011). Results for stand structure and tree mortality showed that in the RMZs, the proportional changes in stem count (dstems) and basal area (dBA) were similar for the reference (mean dstems: -11.8, SE 5.3; dBA: -6.9, SE 5.4) and 100% (mean dstems: -3.8, SE 5.9; dBA –6.7, SE 6.0) treatment. In contrast, the magnitude of decrease was significantly greater in the FPB (portion of FP containing trees; mean dstems: -29.6, SE 6.5; dBA 124.4, SE 6.7) treatment than in either the reference or 100% treatment. The pattern was similar in the PIPs. 2 years post-harvest tree mortality was mostly (70%) attributed to wind/mechanical agents (pre-harvest wind/mechanical agent caused mortality was 70%). In the reference sites, trees that died post-harvest had smaller diameters (mean 10.3 in) and fewer came from the overstory crown class (59.0%) than the other treatments. In contrast, in the 100% and FPB treatments, ~70% of trees that died were from the overstory crown class and their mean diameters were 1 (11.2 in) and 2 (12.2 in) in greater than those in the reference sites, respectively. Results for wood recruitment and loading showed that tree fall rates were highly variable during the pre-harvest period between sites ranging from 0 to 239.9 trees/ha/yr. Large wood (LW) recruitment rates in the pre-harvest period were also highly variable ranging from 0 to 121.6 pieces/ha/yr, along with recruitment volume (0-16.2 m^3/ha/yr). 2 years post-harvest recruitment rates in the reference riparian management zones (RMZs) were lower and less variable (5.9 to 37.3 trees/ha/yr) than in buffer treatments. Tree fall rates for the 100% treatment ranged from 7.7 to 76.4 trees/ha/yr, and for the FPB treatments tree fall rates ranged from 4.2 to 152.2 trees/ha/yr. Post-harvest LW recruitment volumes in reference RMZs were relatively low, ranging from 0.7 to 2.2 m3/ha/yr. Post-harvest LW recruitment volumes were generally higher and more variable in the 100% and FPB RMZs, ranging from 0.3 to 14.0 m3/ha/yr in the 100% treatment and 0 to 7.6 m3/ha/yr in the FPB. Because of the high variability between sites in all treatments the p values for comparisons between treatments were generally high ($p \geq 0.35$), except for the FPB vs. reference comparison for piece count which was nearly significant ($p = 0.13$). The only significant differences were for the 0% treatments which had significantly lower LW recruitment by volume than the Reference RMZ ($P = 0.02$). For PIPs, LW recruitment in the 100% treatment was over 12 times the reference rate by piece count ($P = 0.03$) and 30 times the reference rate by volume ($P = 0.04$). Recruitment in the FPB PIPs was also high, over nine times the reference rate by piece count ($P = 0.08$) and 18 times the reference rate by volume ($P = 0.11$). The amount of change in the number of LW pieces per meter from pre-harvest to post-harvest depended on treatment ($P <0.01$). Analysis estimated the changes in 100%, FP and 0% treatments to be different from the change in the reference (P <0.001, 0.03 and <0.01, respectively). The percentage of the stream channel length covered by newly recruited wood in the second post-harvest year ranged from 0 to 11% in the reference, 1 to 15% in the 100% treatment and 0 to 10% in the FP treatment and was 0% in all four of the 0% treatments. The percent of stream channel covered by new wood differed between the 0% treatment and the reference ($P = 0.03$), 100% ($P <0.01$), and FP treatments ($P = 0.03$). Overall, the authors estimated a mean between-treatment increase of 60% (95% CI: 0−150%), 70% (95% CI: 0−190%) and 170% (95% CI: 80−330%) in the number of SW pieces per stream meter in the 100%, FP and 0% treatments compared with the reference, respectively. Also, a between-treatment increase of 60% (95% CI: 30−110%), 40% (95% CI: 0−100%) and 50% (95% CI: 10−90%) in the number of LW pieces per stream meter in the 100%, FP and 0% treatments compared with the reference, respectively. The authors conclude that windthrow was responsible for much of the increase in LW. However, they also posit that the timing and magnitude of wood inputs was inconsistent, resulting in considerable variability between and within sites, especially in the FP treatment. Results for shade response to treatments post-harvest was greatest in the 0% treatment than in either the 100% or the FP treatment. Effective shade decreased to 77, 52, and 14% 2 years post-treatment, in the 100%, FP, and 0% buffer treatments, respectively. Canopy and Topographic Density (CTD), defined as the percentage of the photograph obscured by vegetation or topography decreased from an average of 95% pre-harvest to 86, 71, and 43% 2 years post-harvest in the 100%, FP, and 0% buffer treatments, respectively. All were significantly lower than the reference (92% 2 years post-treatment). Results for stream temperature showed maximum daily water temperatures increased post-harvest in all but one of the harvested sites and was elevated over much of the year at most of the sites. Daily temperature response (TR) increased in late winter or early spring, reached a maximum in July–August and was still elevated well into the fall. This pattern was observed at most of the sites. For the Buffer Treatment locations, 94 of the 131 calculated mean monthly temperature responses (MMTRs) were significant and 91 of these significant responses were positive. In comparison, only 52 of 156 MMTR values calculated for the reference sites were significant and these were nearly evenly split with 25 positive and 27 negative responses. This strongly suggests that the pattern of post-harvest increases in daily maximum water temperature is real even though the magnitude of some of the individual MMTRs is relatively small (<0.5°C). Warming tended to be greatest in July or August with MMTR ranging from 0.5°C to 2.3°C in the 100%, −0.4°C to 1.8°C in the FP, and 1.0°C to 3.5°C in the 0% treatments. Post-harvest, Max7D (seven-day-average maximum stream temperature) was higher at 36 of the 40 locations within the harvest units across all 11 buffer treatment sites regardless of presence or absence of a buffer, buffer width, and longitudinal location along the stream. Relative to the unharvested sites, there were summertime temperature increases throughout the stream length and across all buffer treatment sites. The authors conclude that none of the buffer treatments were successful in preventing significant increases in maximum stream temperature. The generalizable conclusions made by the authors from this portion of the study are that 1) Buffer widths greater than 50 ft (15.2 m) are needed to prevent shade loss and (2) Maximum water temperature decreased below the harvest unit after flowing through approximately 100 m of intact forest but was still elevated compared to pre-harvest conditions. Results for nitrogen and phosphorus concentrations showed that post-harvest changes for total-N or total-P were not significant for any of the treatments relative to the Reference. The only significant difference detected within 2 years post-harvest was for nitrate-N concentration between the 0% buffer treatment and all other treatments. However, for annual export, total-N and nitrate-N export increased post-harvest at all sites, with the smallest increase in the 100% treatment and the largest in the 0% treatment. Compared to the reference sites, the GLMM analysis showed a relative increase in total-N export post-harvest of 5.52 (P = 0.051), 11.52 (P = 0.0007), and 17.16 (P <0.0001) kg ha-1 yr-1 in the 100%, FP, and 0% treatments. The GLMM analysis showed a relative increase in nitrate-N export post-harvest of 4.83 (P = 0.048), 10.24 (P = 0.001), and 15.35 (P <0.0001) kg ha-1 yr-1 in the 100%, FP, and 0% treatments, respectively, only slightly less than the changes in total-N. Total-P export increased post-harvest by a similar magnitude in all treatments: 0.10 (P = 0.006), 0.13 (P = 0.001), and 0.09 (P = 0.010) kg ha-1 yr-1 in the 100%, FP, and 0% treatments, respectively. The increase in N, total-N and nitrate-N, from the treatment watersheds post-harvest was strongly correlated with the increase in annual runoff (R2 = 0.970 and 0.971; P = 0.001 and 0.001, respectively) and with the proportion of the basin harvested (R2 = 0.854 and 0.852; P = 0.031 and 0.031, respectively). The correlation with the proportion of stream length buffered was weaker (R2 = 0.761 and 0.772; P <0.079 and 0.072, respectively). In contrast, total-P export was uncorrelated with all three variables. Overall, the authors concluded that mean flow-weighted concentration of total-N and nitrate-N increased at all buffer treatment sites post-harvest, however the magnitude was variable and significant only for the 0% treatment. However, the export of total-N increased in the FP and 0% treatments and nitrate-N increased in all buffer treatments. Increases in N export was correlated with increased stream discharge and the proportion of the site that was harvested. Pre-harvest total-P concentration was low and remained so post- harvest, although P export increased slightly post-harvest in all treatments due to the increase in discharge. Results for changes in water turbidity and suspended sediment concentrations (SSC) showed both turbidity and SSC increased with increasing discharge during storm events but then rapidly fell off. Analysis of treatment effects revealed no significant effects of harvest and no clear pattern regarding the relative effectiveness of buffer treatments at mitigating the effects of clearcut harvests on suspended sediment export (SSE). The general conclusions made by the authors were that all sites appeared to be supply limited both pre- and post-harvest. Results for litterfall input showed a decrease in TOTAL litterfall input in the FP ($P = 0.0034$) and 0% ($P = 0.0001$) treatments between pre- and post-treatment periods. LEAF litterfall (deciduous and conifer leaves combined) input decreased in the FP ($P = 0.0114$) and 0% ($P <0.0001$) treatments in the post-treatment period. In addition, CONIF (conifer needles and scales) litterfall input decreased in the FP ($P = 0.0437$) and 0% ($P <0.0001$) treatments, DECID (deciduous leaves) in the 0% ($P <0.0001$) treatment, WOOD (twigs and cones) in the FP ($P = 0.0044$) and 0% ($P = 0.0153$) treatments, and MISC (e.g., moss and flowers) in the 0% ($P = 0.0422$) treatment. Results for comparison of the post-harvest effects between treatments showed LEAF litterfall input decreased in the 0% treatment relative to the reference ($P = 0.0040$), 100% ($P = 0.0008$), and FP ($P = 0.0267$) treatments. Likewise, there was a decrease in DECID litterfall input in the 0% treatment relative to the Reference ($P = 0.0001$), 100% ($P <0.0001$), and FP ($P = 0.0015$) treatments. Results for detritus with comparisons between the pre- and post-treatment periods showed an increase in TOTAL detritus export in the 100% treatment ($P = 0.0051$) and a decrease in the 0% treatment ($P = 0.0046$; Table 12-9). Likewise, there was an increase in CPOM, WOOD, MISC, and FPOM detritus export in the 100% treatment ($P <0.05$), but a decrease in the 0% treatment ($P <0.05$) The authors for this portion of the study conclude that overall, total litterfall input was slightly higher after harvest in the 100% treatment, lower in the FP treatment and lowest in the 0% treatment; however, statistical differences were only detected for deciduous inputs between the 0% treatment and the other treatments. Total detritus export decreased in the 0% treatment relative to the reference, and in the FP and 0% treatments relative to the 100% treatment.

McIntyre et al., 2021

McIntyre, A.P., M.P. Hayes, W.J. Ehinger, S.M. Estrella, D.E. Schuett-Hames, R. Ojala-Barbour, G. Stewart and T. Quinn (technical coordinators). 2021. Effectiveness of experimental riparian buffers on perennial non-fish-bearing streams on competent lithologies in western Washington – Phase 2 (9 years after harvest). Cooperative Monitoring, Evaluation and Research Report CMER 2021.07.27, Washington State Forest Practices Adaptive Management Program, Washington Department of Natural Resources, Olympia, WA.

This study was a follow-up study to the hard-rock Phase 1 study (McIntyre et al., 2018) to assess changes over longer time periods (up to 9 years post-harvest).The purpose of the study was to evaluate the effectiveness of forest management prescriptions in maintaining aquatic conditions and processes for small non-fish-bearing (Type N) headwater stream basins underlain by competent “hard rock” lithologies (i.e., volcanic or igneous rock) in western Washington. Specifically, this study quantified and compared the effects of timber harvest adjacent to Type N streams on riparian stand structure and tree mortality, in stream wood loading and recruitment, stream temperature and canopy cover, stream discharge, turbidity, and suspended sediment export, nitrogen export, and response of stream associated amphibians. This study used a before-after control-impact (BACI) study design. This involved evaluation of four experimental treatments: (1) unharvested reference (n = 6), (2) 100% treatment (n = 4), a two-sided 50-ft riparian buffer along the entire Riparian Management Zone (RMZ), (2) FP treatment (n = 3), a two-sided 50-ft riparian buffer along at least 50% of the RMZ, consistent with the current Forest Practices buffer prescription for Type N streams, (3) 0% treatment (n = 4), clearcut to stream edge (no-buffer). The upland forests of all treatments were clearcut harvested. The study design included data collection for at least two years pre-harvest (2006 –2008), and up to nine years post-harvest from 2009 (harvest began in 2008) until 2016 or 2017 depending on the variable (e.g., wood loading, shade, etc.). Results for stand structure showed that in the buffered portions of the FP treatments (FPB) density, basal area and relative density (RD) decreased by 59%, 55% and 54%, respectively, 8 years after harvest. For the same variables, reductions in the 100% RMZs were 30%, 14%, and 17%, respectively. In contrast, stand structure in the reference RMZs was more stable, with a 17% decrease in density and little change in basal area or RD. Change in live basal area did not differ statistically between 100% and REF RMZs for any time interval although the differences increased over time. The FPB–REF contrast was not significant in the first interval (years 1 and 2 post-harvest), but it was in subsequent intervals (5- and 8-years post-harvest) as the magnitude of change in FPB RMZs increased over time. The FPB–100% contrast was not significant until the last interval when basal area stabilized in the 100% treatment but continued to decline in FPB. Between treatment comparison of cumulative change in live basal area (m2/ha) between the 100% treatment and the Reference was –2.9 (CI: -16.9, 11.0), -6.0 (CI: -20.0, 8.0), and -6.8 (CI -20.8, 7.1) for the first-, second-, and third-time intervals respectively (none were significant). Comparison between the FPB and Reference were -10.2 (CI: -25.5, 5.2), -16.1 (CI: -31.4, -0.8), and -21.1 (CI: -36.4, -5.8) for the first-, second-, and third-time intervals respectively (differences for intervals 2 and 3 were significant). For tree mortality, results showed that by year 8 post-harvest mortality as a percentage of pre-harvest basal area was lower in the reference (16.1%) than in the 100% (24.3%) and FPB (50.8%). The FPB–Reference contrast was not significant 2 years post-harvest, but it was at 5- and 8-years post-harvest as mortality in FPB increased relative to the reference. The contrast between the 100% and Ref were not significant for any time interval 8 years post-harvest. The contrasts 100% vs. REF and FPB vs. 100%—were not significant for any time interval. This may have been because of the high variability in the data. There was a temporal pattern to mortality in 100% and FPB RMZs. Annual rates of mortality as percentage of live basal area and density were highest in the first two years after harvest, then decreased. Wind/physical damage was the primary cause of mortality. In the 100% treatment it accounted for 78% and 90% of the loss of basal area and density, respectively; in FPB it accounted for 78% and 65% of the loss. Wind accounted for a smaller proportion of mortality in reference RMZ (52%). Large wood recruitment to the channel was greater in the 100% and FPB RMZs than in the reference for each pre- to post-harvest time interval. Eight years post-harvest mean recruitment of large wood volume was two to nearly three times greater in 100% and FPB RMZs than in the references. Large wood recruitment rates were greatest during the first two years, then decreased. However, these differences were not significant between any treatment comparisons, again, likely due to the high variability in the data. Mean large wood loading differed significantly between treatments in the magnitude of change overtime. Results showed a 66% ($P < 0.001$), 44% ($P = 0.05$) and 47% ($P = 0.01$) increase in mean large wood density in the 100%, FP and 0% treatments, respectively, in the first 2 years post-harvest compared with the pre-harvest period and after controlling for temporal changes in the references. Five years post-treatment the mean LW density in the FP continued to increase 42% ($P = 0.08$), and again 8 years post-treatment (41%; $P = 0.09$). Results for canopy cover showed that riparian cover declined after harvest in all buffer treatments reaching a minimum around 4 years post-harvest. The treatments, ranked from least to most change, were REF, 100%, FP, and 0% for all metrics and across all years. Effective shade results showed decreases of 11, 36, and 74 percent in the 100%, FP, and 0% treatments, respectively. Significant post-harvest decreases were noted for all treatments and all years. Results for stream temperature showed that within treatment mean post–pre-harvest difference in the REF treatment never exceeded 1.0°C. In contrast, the mean within treatment difference in the 100% treatment was 2.4°C in 2009 (Post-harvest year 1) but never exceeded 1.0°C in later years. The mean difference in the FP treatment exceeded 1.0°C immediately after harvest then again in 2014–2016 (post-harvest years 6–9) while in the 0% treatment the mean difference was 5.3°C initially, then decreased over time to near, but never below, 0.9°C. Stream temperature increased post-harvest at most locations within all 12 harvested sites and remained elevated in the FP and 0% treatments over much of the nine years post-harvest. Temperature responses varied by treatment, by season, and over the years. In three out of the first four post-harvest years there was, at least, a weak ($r < -0.48$) negative correlation between July monthly mean temperature response (MMTR) and the change in riparian cover based on each of the four shade metrics. The correlation was generally weaker ($-0.4 < r$ and $P > 0.10$) after post-harvest year 4, except for post-harvest year 9 ($-0.6 < r < -0.4$). However, there were only eight data pairs available for Post 9, compared to ten to twelve for the other years, which affected the correlation coefficient and p-value. However, there was a great deal of variability in the correlation coefficient of July MMTR with shade across post-harvest years among sites and treatments with some sites showing negative correlations and others positive for some treatments in some years. Considering site characteristics, aspect showed an influence on stream temperature response. In the first five post-harvest years and in Post 7 the highest MMTR in each treatment was nearly always the site with a southern (SE or SW) aspect. No significant correlation between July MMTR and either mean July discharge or the post-harvest difference in discharge was observed. For the effects of harvest on stream discharge, cumulative results of regression analysis (forward and reverse regression approaches) indicated that discharge did increase following harvest. In relative terms, discharge increased by 5-7% on average in the 100% treatments while increasing between 26-66% in the FP and 0% treatments. The change in discharge following harvest was also affected by climate, weather, and physical hydrology of the watershed. In all basins, discharge varied with precipitation, but this was a complex relationship showing lag time between precipitation events and discharge rate response in some watersheds. This indicated a potential relationship with physical hydrology at some watersheds. Results for water turbidity and suspended sediment export (SSE) were stochastic in nature and the relationships between SSE export and treatment effects were not strong enough to confidently draw conclusions. Results for harvest effects on total nitrogen export following a generalized linear mixed effects model, however, showed significant (P <0.05) treatment effects were present in the FP treatment post-harvest and in the 0% treatment in the post-harvest (2-years immediately following harvest) and extended periods (2015 – 2017; 7 and 8 years post-harvest) relative to the reference sites, but there were no significant differences in total-N export between the treatments. Analysis showed an increase in total-N export of 5.73 (P = 0.121), 10.85 (P = 0.006), and 15.94 (P = 0.000) kg/ha/yr post-harvest in the 100%, FP, and 0% treatments, respectively, and of 6.20 (P = 0.095), 5.34 (P = 0.147), and 8.49 (P = 0.026) kg/ha/yr in the extended period. Results for nitrate-N export showed changes similar to but slightly less than those seen in the total-N analysis with a relative increase in nitrate-N export of 4.79 (P = 0.123), 9.63 (P = 0.004), and 14.41 (P <0.001) kg/ha/yr post-harvest in the 100%, FP, and 0% treatments, respectively. None of the changes in the extended period were significant. However, the authors note that there was high variability in the data for the extended period and nitrate-N export only returned to pre-harvest levels in one watershed. The increase in total-N and nitrate-N export tended to be highest during the high flow months in the fall and early winter. The authors conclude that the 100% treatment was generally the most effective in minimizing changes from pre-harvest conditions, the FP was intermediate, and the 0% treatment was least effective. The collective effects of timber harvest were most apparent in the 0% treatment in the two years immediately post-harvest.

LW

Johnston et al., 2011

Johnston, N. T., Bird, S. A., Hogan, D. L., & MacIsaac, E. A. (2011). Mechanisms and source distances for the input of large woody debris to forested streams in British Columbia, Canada. Canadian journal of forest research, 41(11), 2231-2246. https://doi.org/10.1139/x11-110

The purpose of this study was to determine whether the processes and source distances from which LW entered streams differed among channel types and sizes, to describe LW source distance curves for a wide range of undisturbed stream and forest types, and to characterize the relationships between LW input mechanism, source distance, and piece size. Input processes, source distances, and physical characteristics of approximately 2100 pieces of LW at 51 anthropogenically undisturbed stream reaches throughout south and central British Columbia were determined. Large wood (LW) was defined in this study as pieces within or suspended above the active channel, with a minimum length of 1 m. and capable of inducing sediment scour or deposition. A delivery mechanism was assigned to each LW piece, when it could be determined, as bank erosion, landslide, windthrow of live trees, stem snap, or standing dead tree fall. Differences in the frequencies of count data among LW delivery mechanisms, LW positions, or LWD functions were assessed using chi-square tests. The effects of channel (type, width) and forest (maximum tree height) characteristics on the proportions of LWD pieces entering the channel by a given input mechanism were examined using ANCOVA. Channel type for this study was grouped into 3 categories; riffle-pool (RP), cascade-pool (CP), and step-pool (SP). Results showed that tree mortality was the most common entry mechanism at all channel types and width categories and accounted for 65% of all LW pieces sampled. Both channel and riparian forest characteristics influenced the proportion of LW pieces that entered streams by tree mortality ($P < 0.05$) but did not vary significantly among channel types ($P = 0.13$). The proportion of LW pieces recruited by tree mortality decreased with increasing channel width and with increasing maximum tree height. Bank erosion inputs accounted for 20%–25% of all LW pieces at the lower-gradient RP and CP sites but were much less important at the SP channels. Erosion inputs increased with increasing stream size within all channel types ($P = 0.0004$). Wind-induced inputs (windthrow and stem snap) accounted for 13%–20% of inputs over the channel types and generally increased in importance in the smaller channels. The proportion of LW recruited to the stream by stem breakage increased with increasing tree height ($P < 0.0001$) and varied among channel types ($P = 0.040$), being about twice as prevalent at SP channels as elsewhere. Landslide inputs of LWD were a minor delivery mechanism. There was considerable variability in distances from which LW entered the stream. However, based on the cumulative distributions over sites, 90% of the LW pieces or volume entering the channels originated within 18 m of the stream in 90% of all cases (between 2 and 23 m in all cases). The distances from which LW entered the streams differed significantly among the various input mechanisms ($P < 0.001$), the rank ordering of the mean source distances being bank erosion $<$ tree mortality $<$ stem breakage $<$ windthrow $<$ landslides. Bank erosion and landslides delivered the largest LW pieces and tree mortality and stem breakage the smallest. In general, source distances increased with increasing tree height, with the effect being stronger in the steeper channel types and weaker in the wider channels for LW pieces and volume. However, all two-way interactions among variables were significant implying that the mechanisms through which vegetation and stream geomorphology influenced LW source distance were complex. Maximum tree height in the adjacent forest accounted for the greatest variance in in-stream LW source distance for all models.

Nutrient

Deval et al., 2021

Deval, C., Brooks, E. S., Gravelle, J. A., Link, T. E., Dobre, M., & Elliot, W. J. (2021). Long-term response in nutrient load from commercial forest management operations in a mountainous watershed. *Forest Ecology and Management*, *494*, 119312. https://doi.org/10.1016/j.geomorph.2013.11.028

The purpose of this study was to quantify and compare the differences in nitrogen and phosphorus concentrations and loads between pre-disturbance, post road construction (post-road), post experimental harvest (PH-I), and post operational harvest (PH-II) from both a hydrological yield and nutrient concentration perspective. This study was carried out in the Mica Creek Experimental Watershed in Northern Idaho. For this analysis time periods have been broken into four distinct phases: Pre-disturbance (1992–1997), Post-road (1997–2001), experimental-harvest Phase I (PH-I) (2001–2007), and operational sequential harvest Phase II (PH-II) when the extent and frequency of harvests increased (2007–2016). PH-I represents an experimental treatment phase during which harvest activities were experimentally controlled (only upstream headwater watersheds were harvested and mature vegetation removal ranged between 24% and 47%) followed by site management operations including broadcast burning and replanting. PH-II represents the post-experimental phase where the study area transitioned to operational treatments that consisted of additional road construction and timber harvest, with site management operations including pile burning and competition release herbicide application. During this operational phase, the mature vegetation removal in the upstream and cumulative downstream watersheds ranged between 36% and 50% and 17–28%, respectively. Monthly annual grab samples of stream water were collected from seven flumes over the course of 25 years (from pre- to post-treatments). The samples were analyzed for six parameters, specifically nitrate + nitrite (NO3 + NO2), total Kjeldhal nitrogen (TKN), total ammonia nitrogen (TAN) containing un-ionized (NH3) and ionized (NH4+) ammonia, total nitrogen (TN), total phosphorus (TP), and orthophosphate (OP). This study used a before-after, control-impact paired series design (BACIPS) to evaluate direct and cumulative effects of forest management practices on stream nutrient concentrations in paired and nested watersheds. Results for long-term trends in stream flow showed a statistically significant increasing trend in all the watersheds during the fall and winter seasons. Significant increases in summer streamflow only occurred in the control watersheds. There were minimal changes in TKN concentration with a slight observed reduction in long-term TKN loads. Overall, the cumulative mean TAN loads from all watersheds did not show large variations with sequential varying treatments over time. In contrast to TAN, there was a significant response in NO3 + NO2 following timber harvest. The response in NO3 + NO2 concentrations was negligible at all treatment sites following the road construction activities. However, NO3 + NO2 concentrations during the PH-I period increased significantly ($p < 0.001$) at all treatment sites. Similar to the PH-I period, all watersheds experienced significant increases in NO3 + NO2 concentration during the PH-II treatment period. Overall, the cumulative mean NO3 + NO2 load from all watersheds followed an increasing trend with initial signs of recovery in one treatment watershed after 2014. Mean monthly TP concentrations showed no significant changes in the concentrations during the post-road and PH-I treatment periods. However, a statistically significant increase in TP concentrations ($p < 0.001$) occurred at all sites, including the downstream cumulative sites, during PH-II. Generally, OP concentrations throughout the study remained near the minimum detectable concentrations. A statistically significant increase in mean monthly OP concentrations occurred only at the cumulative downstream treatment site during both Post-road (p-value = 0.021) and PH-I (p-value < 0.001) treatment periods, respectively. The largest cumulative increase in mean annual loads was largely attributed to increased flow. The authors conclude that only relatively small increases in nutrient loads were detected suggesting that Idaho Forest Practices Act regulations and BMPs are effective in minimizing the delivery of particulate-bound pollutants. Forest management activities increased stream NO3 + NO2 concentrations and loads following timber harvest activities, but these effects were also attenuated in downstream reaches and reduced through time as vegetation regrowth occurred.