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MEMORANDUM

July 30, 2020

To: Forest Practices Board

Form: Mark Hicks, Adaptive Management Program Administrator

Subject: Bull Trout Add-On Report

At their February 7, 2020 meeting, TFW Policy (Policy) formally accepted the findings report and associated materials for the Bull Trout Add-On study, formally titled ***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***. The purpose of this memo is to transmit the final study report to the Board along with a summary of the report's findings and Policy's recommendations.

The Cooperative Monitoring, Evaluation, and Research Committee (CMER) conducted the Bull Trout Add-On study to better understand how riparian forests within Type F (fish-bearing) stream buffers change after stands are harvested under the existing forest practices rules.

The study uses an After, Control, Impact (ACI) study design to examine changes in stand structure, tree mortality, ingrowth, and wood recruitment from tree fall over a five-year post-harvest period at 17 sites. The current study documents the differences for 8 sites harvested under the standard eastside rules, and for 9 sites harvested under the leave all available shade within 75 feet of the stream restrictions that apply to sites inside the eastside bull trout protection overlay.

The 17 study sites are a subset of sites included in the 2014 CMER Eastside Riparian Shade/Temperature study (Cupp and Lofgren 2014). Sites were non-randomly selected with the majority located in northeastern Washington. Study sites were adjacent to Type F streams with continuous flowing water that were less than 15 feet in bankfull width. Post-harvest surveys were completed at each site one to two years and five years post-harvest.

The report compares changes in riparian stands, tree fall, and wood input in riparian management zone (RMZ) buffers following harvest under the two variations of the eastern Washington riparian prescriptions for fish-bearing streams in the Mixed Conifer Timber Habitat Type (2500-5000 feet elevation). Both prescriptions have an unharvested core zone within 30 feet of the stream, but differ in leave tree requirements within the inner zone, 30–75 feet from the stream, due to differences in shade requirements. The All Available Shade (AAS) rule requires retention of all inner zone trees that provide shade, while standard rule (SR) prescriptions have a lower shade requirement that typically allows greater inner zone harvest.

The SR treatment resulted in the greatest change in stand structure, tree mortality, and wood recruitment from fallen trees compared to the unharvested reference (REF) sites. The responses to the AAS treatment were intermediate, but more similar to the REF than to the SR treatment. The SR responses, including change in stand structure, tree mortality, and wood recruitment from tree fall were significantly different from both the AAS and REF treatments; but there were no significant differences in the AAS and REF responses.

Thinning within the inner zone under the SR and AAS treatments reduced live density, basal area and relative density compared to unharvested reference sites. Inner zone thinning guided by the preferred species list (WAC 222-26-010) appeared to increase the proportion of preferred species and reduce the proportion of shade tolerant species relative to the core zones; however the effects were limited and SR and AAS RMZs continued to be dominated by shade tolerant species. Post-harvest tree mortality was significantly higher in SR buffers compared to AAS and REF sites. Damage from wind was the most frequent cause of mortality at SR and AAS sites in contrast to the reference sites.

The pattern of wood recruitment from fallen trees followed the pattern of tree mortality. Wood input from tree fall in SR RMZs was significantly greater than in AAS or REF RMZs. The cumulative density of fallen trees that provided wood input in SR RMZs was nearly double that in AAS RMZs, primarily due to extensive wind throw at two of eight SR sites. While the SR and AAS prescriptions increased wood input during the first five years after harvest, inner zone thinning and post-harvest mortality reduced the standing stock of trees available for future wood recruitment. The density of standing trees in SR inner zones was only half that of the unharvest REF sites, while AAS stocking was more similar to REF stocking.

The results of this study, combined with the results from the associated Eastside Bull Trout Overlay Temperature and Solar Radiation/Effective Shade studies, enhance our scientific understanding of the response in stand structure, buffer tree mortality, wood recruitment, shade, and stream temperature response to the tested Eastern Washington Type F prescriptions. This information reduces scientific uncertainty about attaining resource objectives for Heat/water temperature and LWD/Organic inputs, and have increased our understanding of buffer tree mortality and post-harvest stand trajectory following harvest. This study is limited, however, by the relatively small number of sites (17), the limited geographic distribution of the sites, and the five-year post-harvest timeframe.

The authors recommend: 1) additional long-term monitoring of a larger sample of sites to address uncertainty about the effect of the prescriptions on episodic mortality due to wind throw, insects, fire, and disease, and 2) intensive in-channel research to document the effects of the prescriptions on water quality, wood loading, and fish habitat.

Policy-makers are advised to consider these findings in association with other studies that directly measure aquatic resource effects, while additionally beginning a conversation on potential long-term chronic implications of RMZ management.

This study, similar to the Westside Type N BCIF study, does not provide direct evidence on the level of water quality or other aquatic resource protection provided.

After reviewing the study findings, Policy agreed by consensus not to recommend the Board take any formal action in response to this study.

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

By: Dave Schuett-Hames and Greg Stewart

August 2019

CMER #

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Washington State Forest Practices Adaptive Management Program

The Washington State Forest Practices Board (FPB) has established an Adaptive Management Program (AMP) by rule in accordance with the Forests & Fish Report (FFR) and subsequent legislation. The purpose of this program is to:

> *Provide science-based recommendations and technical information to assist the FPB in determining if and when it is necessary or advisable to adjust rules and guidance for aquatic resources to achieve resource goals and objectives. The board may also use this program to adjust other rules and guidance.* (Forest Practices Rules, WAC 222-12-045(1)).

To provide the science needed to support adaptive management, the FPB established the Cooperative Monitoring, Evaluation and Research (CMER) committee as a participant in the program. The FPB empowered CMER to conduct research, effectiveness monitoring, and validation monitoring in accordance with WAC 222-12-045 and Board Manual Section 22.

Report Type and Disclaimer

This technical report contains scientific information from research or monitoring studies that are designed to evaluate the effectiveness of the forest practices rules in achieving one or more of the Forest and Fish performance goals, resource objectives, and/or performance targets. The document was prepared for the Cooperative Monitoring, Evaluation and Research Committee (CMER) and was intended to inform and support the Forest and Fish Adaptive Management program. The project is part of the Eastside Type F Riparian Effectiveness Program, and was conducted under the oversight of the Riparian Scientific Advisory Group.

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

Proprietary Statement

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

Full Reference

Schuett-Hames, Dave and Stewart, Greg. 2019. 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.

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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

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Acknowledgements

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EXECUTIVE SUMMARY

This report compares the response of riparian stands, tree fall and wood input in riparian management zone (RMZ) buffers following harvest under two variations of the eastern Washington riparian prescriptions for fish-bearing streams in the Mixed Conifer Timber Habitat Type (2500-5000 feet elevation). Both prescriptions have an unharvested core zone within 30 feet of the stream, but differ in leave tree requirements within the inner zone, 30–75 feet from the stream, due to differences in shade requirements. The All Available Shade (AAS) rule requires retention of all inner zone trees that provide shade, while standard rule (SR) prescription has a lower shade requirement that typically allows greater inner zone harvest. We documented changes in stand structure, tree mortality, ingrowth, and wood recruitment from tree fall over a five-year post-harvest period and compared responses to the AAS and SR prescriptions with unharvested reference (REF) sites using a general linear mixed model. The eight SR and nine AAS sites were originally selected for a study of shade and stream temperature response (Cupp and Lofgren 2014).

The SR treatment resulted in the greatest change in stand structure, tree mortality, and wood recruitment from fallen trees compared to the unharvested REF sites. The responses to the AAS treatment were intermediate, but more similar to the REF than to the SR treatment. The SR responses, including change in stand structure, tree mortality, and wood recruitment from tree fall were significantly different from both the AAS and REF treatments; but there were no significant differences in the AAS and REF responses.

Thinning within the inner zone under the SR and AAS treatments reduced live density, basal area and relative density compared to unharvested reference sites. Inner zone thinning guided by the preferred species list appeared to increase the proportion of preferred species and reduce the proportion of shade tolerant species relative to the core zones; however the effects were limited and SR and AAS RMZs continued to be dominated by shade tolerant species not on the preferred species list. Post-harvest tree mortality was significantly higher in SR buffers compared to AAS and REF sites. Damage from wind was the most frequent cause of mortality at SR and AAS sites. Mortality rates were classified as chronic (<5%/year) at all AAS sites and seven of eight SR sites, but reached the partial stand replacement level (7.5%/year) at one SR site with extensive windthrow. We did not observe episodic mortality from fire, insects, or disease during the five-year post-harvest period.

The pattern of wood recruitment from fallen trees followed the pattern of tree mortality. Wood input from tree fall in SR RMZs was significantly greater than in AAS or REF RMZs. The cumulative density of fallen trees that provided wood input in SR RMZs was nearly double that in AAS RMZs, primarily due to extensive windthrow at two SR sites. About 60% of recruiting fallen tree pieces at SR and AAS sites were uprooted trees with attached roots, which are likely to remain stable and persist through time. Most recruiting fallen tree pieces initially came to rest over the channel where they provide shade and cover but do not to influence channel morphology or create in-channel habitat. While the SR and AAS prescriptions increased wood input during the first five years after harvest, inner zone thinning and post-harvest mortality reduced the standing stock of trees available for future wood recruitment. The density of standing trees in SR inner zones was only half that of the unharvest REF sites, while AAS stocking was more similar to REF stocking.

This study is limited by the relatively small number of sites, the limited geographic distribution of the sites, and the five-year post-harvest timeframe. The scope of inference is strongest for well-stocked conifer-dominated stands adjacent to fish-bearing streams <15 feet wide in mixed conifer forests at 2500-5000 feet in elevation in the northeast part of Washington State. We recommend 1) additional long-term monitoring of a larger sample of sites to address uncertainty about the effect of the prescriptions on episodic mortality due to insects, fire, and disease, and 2) intensive in-channel research to document the effects of the prescriptions on water quality, wood loading, and fish habitat.

INTRODUCTION

The purpose of this study was to reduce uncertainty about the effects of the eastern Washington riparian prescriptions for fish-bearing (Type F and S) streams on post-harvest stand structure, mortality, tree fall and wood input to streams. Washington State regulates forest practices on state and private forest land in order to protect public resources, including water quality and aquatic life in streams. Changes were made to the Washington Forest Practices Rules in 2000 to increase protection for aquatic species and habitat. These changes were incorporated into Washington's Forest Practice Habitat Conservation Plan (FPHCP). The riparian protection strategy is a key element of the FPHCP because riparian forests provide functions that create and maintain productive habitat for aquatic species and water quality (WDNR 2005). Many species of native salmonids require cool (e.g. 10–14 °C) summer stream temperatures (Bjornn and Reiser 1991). The canopy provided by streamside forests reduces the solar radiation reaching the stream and provides thermal buffering from warm air above the canopy, helping to moderate stream temperature increases during warm weather (Naiman et al. 1992, Poole and Berman 2001). Wood plays a critical role in the creation and maintenance of productive salmonid habitat and provides nutrients and energy to support the aquatic food chain (Gregory et al. 1987). Geomorphic functions of wood include formation of pool habitat, cover, sediment and nutrient retention, and energy dissipation (Bilby and Ward 1991, Beechie and Sibley 1997, Montgomery et al. 2003). Wood input comes from a variety of sources, including stream-adjacent stands, debris flows from headwater streams, mass wasting of upslope areas and tree mortality; but mortality of streamside trees is an important source of wood input for many streams (May and Gresswell 2003, Burton et al. 2016).

Harvest of riparian forests results in changes in riparian stand structure and riparian functions; and ultimately to aquatic habitat, water quality, and aquatic organisms (Gregory and Bisson 1997). Clear-cut harvest of streamside forests decreases canopy cover and allows more solar energy to reach the stream; increasing stream temperature until vegetation is re-established (Poole and Berman 2001, Moore et al. 2005). Clear-cut harvest also reduces potential future wood input, resulting in long-term reduction in the size and amount of wood input (Beechie et al. 2000, Bragg 2000, Burrows et al. 2012, Pollock and Beechie 2014, Burton et al. 2016). Riparian buffers reduce the effects of timber harvest on shade and wood input (Naiman et al. 2000); but the response varies depending on stand structure, buffer width, level of retention (thinning), and channel characteristics (Groom et al. 2011, Cole and Newton 2013, Burton et al. 2016).

The riparian prescriptions for fish-bearing streams on state and private land in eastern Washington retain trees within stream-adjacent riparian management zones (RMZs) to provide shade, wood recruitment, litter fall, and nutrient cycling and to maintain stocking within a range that promotes forest health (WDNR 2005). RMZ widths and leave tree requirements vary depending on Timber Habitat Type (THT), stream width, and shade requirements. For the standard forest practices rules, RMZs consist of a 30-foot wide core zone adjacent to the stream where all trees are retained and an inner zone that is either 45 or 70 feet in width, depending on whether the stream is under or over 15 feet in width, respectively. Inner zone stand structure is managed to retain basal area within a range that varies by THT to address differences in forest composition (Daubenmire and Daubenmire 1968, Franklin and Dyrness 1973, Cassidy et al. 1997, Van Pelt 2008). The three timber habitat types are delineated by elevation, including Ponderosa Pine (<2500 feet), Mixed Conifer (2500-5000 feet), and High Elevation (>5000 feet). Harvest within the inner zone is constrained by shade requirements to meet stream temperature objectives. The shade requirement under the standard forest practice rules varies by elevation. However in areas designated as potential bull trout habitat (i.e. the Bull Trout Overlay), all available shade must be retained to avoid increases in stream temperature. Typically, more trees can be harvested within the inner zone under the standard rule.

This study focuses on specific prescriptions developed for the Mixed Conifer THT. Mixed-conifer forests cover large areas of eastern Washington. Of approximately 3.2 million acres of state and private forestland in eastern Washington covered by the FPHCP, approximately 2 million acres (63%) is within the Douglas-fir and Grand fir zones (WDNR 2005); approximating the coverage of the FPHCP mixed conifer timber habitat type. Mixed conifer forests occur in mesic settings; intermediate between warm, dry conditions in the Ponderosa pine zone and cold, wet conditions typical of high elevation forests (Stine et al. 2014). The dry mixed conifer forests typical of the Douglas-fir zone typically occur in lower montane, ridgetop or south-facing settings with <40 inches of prescriptions and fire return intervals of 10–25 years. They are dominated by fire tolerant species such as Douglas-fir (*Pseudotsuga menziesii*), Ponderosa pine (Pinus ponderosa) and western larch (*Larix occidentalis*). The moist mixed conifer forests of the Grand fir zone typically occur in mid to upper montane settings with 40–60 inches of precipitation and mixed severity fire regimes with return intervals of <20–50 years (Stine et al. 2014). These conditions produce forests of diverse composition, including Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), western white pine (*Pinus monticola*), lodgepole pine (*Pinus contorta, var. contorta*), western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*).

The composition, structure and seral stage distribution of eastern Washington mixed-conifer forests is strongly influenced by natural and human disturbance; e.g. timber harvest, fire, and outbreaks of insects and disease (Agee 1993, Robbins and Wolf 1994, Quigley and Arbelbide 1997, Hessburg et al. 1999, Edmonds et al. 2000, Everett et al. 2000). Disturbance processes, especially fire, had a strong influence on the composition of the forests of eastern Washington prior to widespread timber harvest in the twentieth century (Agee 1993, Robbins and Wolf 1994, Van Pelt 2008). Selective harvest of large Ponderosa pine and Douglas-fir, combined with increasingly effective fire suppression, increased density and shifted composition to shade-tolerant, fire-intolerant species over the last 100 years (Agee 1993, Everett et al. 2000, Hemstrom 2001, Van Pelt 2008, Merschel et al. 2014). These changes increased the vulnerability of many mixed-conifer forests to increased disturbance and mortality from fire, insect outbreaks, and disease (Hemstrom 2001, Perry et al. 2011). This has heightened concerns about the health of eastern Washington forests, as well as potential increases in the frequency of drought and conditions favorable to fire and insect outbreaks (Littell et al. 2010, WDNR 2014, Stine et al. 2014).

The riparian prescriptions for the eastern Washington Mixed Conifer THT allow thinning in the inner zone to reduce stand density while retaining fire and disease-resistant species. It is uncertain how stands will respond due to the diversity in stand structures and composition, legacy effects from past management, and vulnerability to fire, insects, and disease. Most existing research focuses on upland forests, so there is greater uncertainty about riparian forests in eastern Washington and their response to management; however riparian forests may be subject to similar changes in composition and structure as upland forests, putting them at increasing risk of catastrophic disturbance (CH2MHill 2000, WDNR 2014, Haugo et al. 2015).

CMER undertook two studies to evaluate the effect of the eastern Washington riparian prescriptions for fish-bearing streams in the Mixed Conifer THT on shade and stream temperature. These studies compared sites harvested according to the SR and AAS treatments with unharvested reference reaches and concluded that changes in shade and differences in stream temperature response were minor among the two treatments and reference reaches in the first two summers after harvest (McGreer et al. 2011, Cupp and Lofgren 2014). This report presents results of a follow-up study to reduce uncertainty about changes in stand structure, tree mortality, tree fall and wood input at a sub-set of sites used in the previous studies.

OBJECTIVE AND RESEARCH QUESTIONS

The study objective was to compare changes in stand structure, tree mortality, ingrowth, and wood recruitment from fallen trees during the first five years after harvest in response to the standard rule and all available shade riparian prescriptions for fish-bearing streams on state and private forest land in eastern Washington.

The research questions were:

1. What is the structure and composition of stands in the core and inner zones of riparian management zones (RMZs) harvested under the standard rule (SR) and all available shade (AAS) prescriptions for eastern Washington, both immediately and five years after harvest.
2. Are there differences in the direction and magnitude of change in stand structure between the SR and AAS prescriptions in comparison to unharvested reference sites?
3. What are the rates of tree mortality and wood recruitment from fallen trees during the first five years after harvest?
4. Are there differences in rates of tree mortality and wood recruitment from fallen trees between the SR and AAS prescriptions in comparison to unharvested reference sites?

STUDY SITES

This study used 17 sites from the Eastside Riparian Shade/Temperature study (Cupp and Lofgren 2014). Potential sites were not randomly selected but were located using remote sensing imagery and outreach to forest landowners due to the extensive site selection criteria, the requirement for an unharvested reference reach, and the need for landowner cooperation on harvest timing. Site selection criteria and screening procedures are described in Cupp and Lofgren (2014). The majority of the sites were located in northeastern Washington State (Figure 1). The characteristics of the study sites are shown in Appendix A, Table 1. Elevations ranged from 1852–4134 feet, bankfull width from 4.3–19.9 feet, and gradient from 1.7−18.7%.

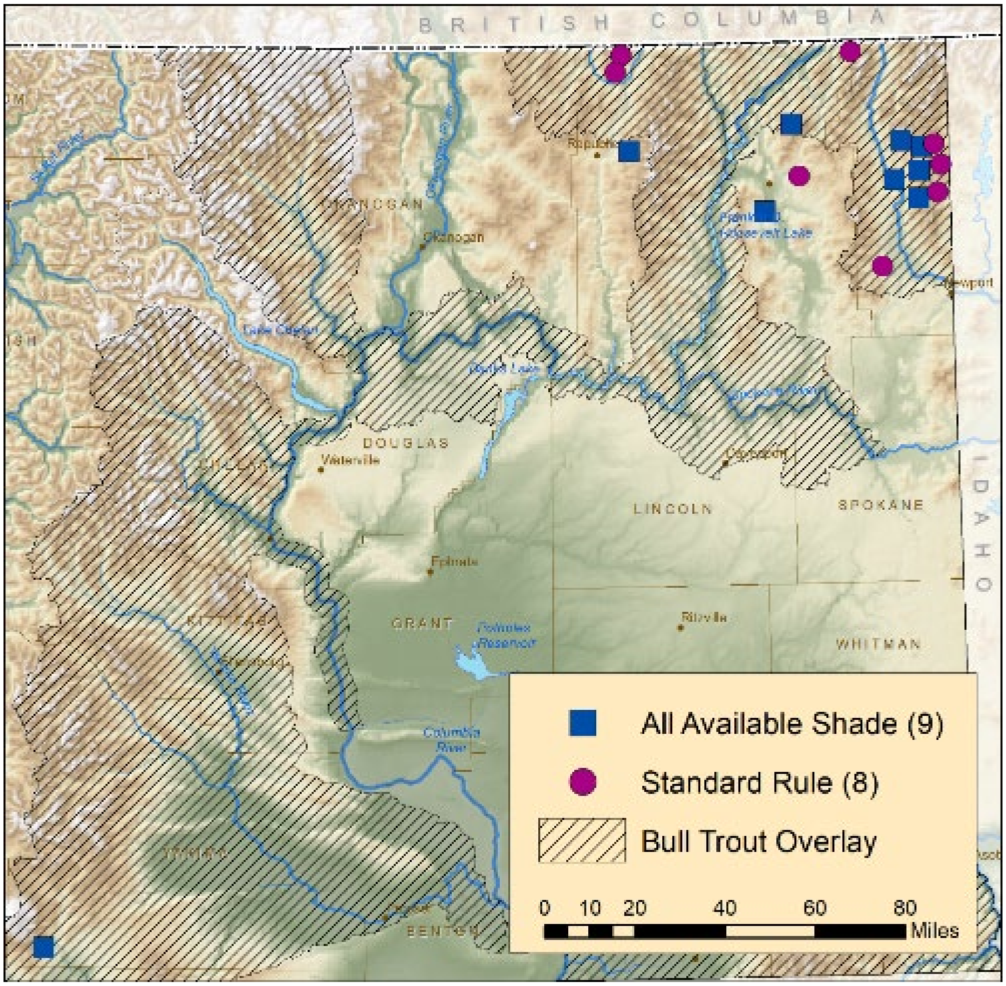

Figure 1. Study site locations.

Study sites were adjacent to Type F (fish-bearing) streams with continuous flowing water less than 15 feet in width. The stream-adjacent stands had >50% canopy closure and sufficient conifer basal area to meet the minimum requirements for timber harvest (WDNR 2016). Each site had an unharvested reference reach immediately upstream of the treatment reach with no harvest within 175 feet of the stream. Sites with road crossings or stream-adjacent roads in the core or inner zone of the RMZ of the treatment or reference reaches were eliminated because openings could cause impacts such as tree mortality from wind not directly associated with the riparian prescriptions.

METHODS

DATA COLLECTION

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, and DBH were recorded for each tree. The canopy class for live trees was designated as overstory (dominant or co-dominant), understory (intermediate or suppressed), or no competition (open-growing trees). Dead trees were assigned a decay class code (Table 1) from Hennon et al. (2002). Dead or fallen trees with a decay class of 1 or 2 were classified as post-harvest mortality (Martin and Benda 2001, Hennon et al. 2002, Bahuguna et al. 2010) and a mortality agent was recorded (e.g. wind, erosion, suppression, fire, insects, disease, and physical damage).

Table 1. Decay class codes for snags and fallen trees.

Decay class	Description
1	Foliage (dead leaves and needles) present
2	Twigs present
3	Secondary branches present
4	Primary branches present
5	No branches remaining (nubs may be present)

Data were collected on post-harvest fallen trees that originated within 75 feet of the channel. Fallen trees were classified as uprooted trees that toppled over with the roots still attached or broken stems that were sheared off above the ground if the broken portion had a diameter ≥4 inches at the large end. If the base of the tree remained standing and was ≥4.5 feet high, it was treated as a dead standing tree and the upper portion was treated as a fallen top. Fallen tree data included condition (live/dead), species, DBH, fall azimuth, horizontal distance to the channel (from where the tree was rooted), number of pieces, and tree fall process. We recorded the number of fallen trees pieces that crossed the edge of the bankfull channel (recruited to the channel) and the diameter at the bankfull channel edge. Recruitment class was determined by location of the fallen tree relative to the channel. Bankfull trees have a portion that protrudes into the bankfull channel, while suspended and spanning pieces rest above the bankfull channel but do not intrude into it. Spanning pieces cross over the channel and touch the ground on both sides, while suspended pieces are in contact with the ground on only one side. If a portion of a fallen tree piece crossed the plane of the bankfull channel, was greater than four inches in diameter and extended a minimum of 1.6 feet into or over the channel, we recorded the length and mid-point diameters of the in- or over-channel portions to estimate post-harvest wood recruitment frequency and volume. The 1.6 foot criterion for intrusion into the channel was used by Gomi et al. (2001) for wood in small streams. We noted if the portion of the fallen tree that recruited was a stem with roots attached.

DATA ANALYSIS

Stand structural metrics including live density (trees/acre), basal area (ft^2/acre), quadratic mean diameter (Curtis and Marshall 2000), and relative density (Curtis 1982). Metrics were calculated separately for regulatory zones defined by horizontal distance from the channel (WFPB 2001); including the core zone (0–30 feet) and inner zone (30–75 feet) and the combined core and inner zone (the RMZ). Means for the REF, AAS and SR treatment groups were obtained by averaging the values for sites in each group. Stand structure metrics were calculated at two points in time: immediately post-harvest (IPH) and five years post-harvest (Yr5post). Since there was no immediately post-harvest survey, IPH stand conditions were reconstructed using decay class data from standing and post-harvest fallen trees collected during the initial post-harvest survey (Martin and Benda 2001, Hennon et al. 2002, Schuett-Hames et al. 2012). Live tree density and basal area were summed by species for each site and regulatory zone, and used to calculate the dominant species with the greatest basal area, the proportion of live trees on the regulatory preferred species list for Mixed Conifer Timber Habitat Type in eastern Washington (WFPB 2016), and the proportion by shade tolerance category (Burns and Honkala 1990). Proportional change in live stem count and basal area over the five-year post-harvest interval were computed by subtracting the Yr5post value from the initial IPH value and dividing by the initial value. Cumulative ingrowth in trees/acre was the total count of new trees that reached the four inch DBH threshold during the five-year period divided by the area in acres for each regulatory zone in each reach. Cumulative mortality, the percentage of initial live tree count and live basal area that died over the five-year period, was calculated by regulatory zone for each site and averaging site values by treatment group. Since there was no survey immediately post-harvest, the reconstructed IPH live tree data were used as the initial values for calculating mortality. Mortality rates were expressed on an annual basis using the compounding formula of Sheil et al. (1995). The proportion of recruiting fallen trees attributable to wind versus other causes was calculated by grouping trees by mortality agent and dividing by the total number of trees in each treatment group. Recruited fallen trees pieces were sorted by recruitment class to determine the proportion that intruded into the channel. Cumulative tree fall/acre was calculated separately for all fallen trees and for the subset of fallen trees that fell into or over the channel (recruiting fallen trees). The count over the five-year period was summed by regulatory zone for each site, divided by the area in acres, and the site values were averaged by treatment group. Annual tree fall rates were calculated by dividing the cumulative totals by five.

To create a source distance curve, recruiting fallen trees were grouped according to their original rooting location in five-foot intervals from the stream (0–5 feet, 5–10 feet, etc.) and the count for each interval was divided by the total count to calculate the proportion from each interval. The proportion of recruiting fallen trees that were uprooted versus broken above the ground was estimated by sorting by fall type, and dividing the tally by the total count. The number of pieces of fallen trees that that came to rest in or over the bankfull channel was tallied and the volume for the in- or over-channel portion of each recruited portion was estimated using the formula:

Volume in ft^3*:* $\pi * midpoint\,radius^2 * piece\ length$

Cumulative recruited count and volume per 100 feet of reach length was calculated for each reach by summing the recruited piece counts and volume, dividing by the reach length in feet and multiplying by 100. Fallen tree stems with roots attached have greater stability and are more likely to persist over time and provide functions than wood without attached roots (Fox and Bolton 2007), so we performed separate calculations on the sub-set of recruiting fallen tree stems with attached roots (SWAR).

Data were processed using queries in an MS Access database. JMP 13 software was used to generate descriptive statistics (e.g. means and standard errors) for data grouped by treatment and regulatory zone, and to create box plots showing the distribution of the data. We selected a subset of metrics for statistical analysis in order to reduce the overall number of comparisons and used mixed models to calculate treatment contrasts between AAS and SR using population means estimated for each treatment within a single model (Table 2). Mixed model analyses were performed in R 3.3.2 (Core Team 2016) using the lme4 package (Bates et al. 2015) and SAS/STAT software version 9.3 copyright © 2002-2012 by SAS Institute Inc., Cary, NC, USA. Linear Mixed Models (LMM) were fit by Restricted Maximum Likelihood (REML). Generalized Linear Mixed Models (GLMM) were fit by Maximum Likelihood (ML) with Adaptive Gauss-Hermite Quadrature and 10 nodes to ensure fitting consistency between R and SAS. GLMM distributions included binomial and Poisson with the default links (Table 2). If the overall ANOVA p-value was less than 0.05, pairwise comparisons were conducted for all treatment contrasts. None of the reported p-values were corrected for the large number of tests, and therefore do not control for the family-wise error rate**.** Alpha = 0.1 was used for statistical significance. Contrast Denominator Degrees of Freedom (DDF) were calculated using the Kenward-Roger (KR) method. KR DDF were implemented in R using the lmerTest package (Kuznetsova et al. 2016). Quadrature methods do not allow for estimates of the KR DDF, so SAS's default containment method was used to calculate DDF for the GLMM contrasts. The containment method produces 15 DDF on 17 sites and may be slightly conservative compared with KR DDF. In each model, treatment (i.e. REF, AAS, SR) was treated as a fixed effect and the site identifier was treated as a random effect or subject. GLMM generated means and standard errors are shown in Appendix B.

Table 2. Mixed model properties.

Response Variable	Model Type	Distribution/Link	Core Zone Contrast DDF*	Inner Zone Contrast DDF*
Live basal area/acre, IPH	LMM	Gaussian/Identity	N/A	18.4 – 24.4
Live basal area/acre, Yr5post	LMM	Gaussian/Identity	N/A	18.6 – 24.8
Cumulative % change in live basal area	LMM	Gaussian/Identity	119.2 – 27.1	18.8 – 25.8
Cumulative % mortality in basal area	GLMM	Binomial/Logit	15	15
Cumulative wood recruitment piece count (total, SWRA)	GLMM	Poisson/Log	Channel contrast DDF = 15	

*Pairwise contrasts were performed on basal area, but not density in order to reduce the overall number of comparisons.

RESULTS

STAND STRUCTURE

There was little difference in core zone stand structure among treatments immediately post-harvest (IPH). Mean core zone live tree density and basal area were similar in the reference (REF) and standard rule (SR) groups, and slightly lower in the all available shade (AAS) group (Appendix A, Table 2; Figure 2, left panel). There was no harvest in the core zone, so stand structure immediately after harvest is indicative of pre-harvest conditions.

The IPH differences in inner zone stand structure reflect the intensity of inner zone harvest. Mean live density, basal area and relative density were greatest in unharvested REF inner zones, intermediate in lightly thinned AAS inner zones, and lowest in more heavily thinned SR inner zones (Appendix A, Table 2). Mean SR inner zone live density and basal area were about half that of the REF group. The IPH inner zone quadratic mean diameter (QMD) was largest in the SR group, lower in the AAS group and smallest in the REF group, apparently in response to the rule requirements to retain the largest trees when thinning the inner zone. IPH diameter distributions are shown in Appendix C. Mean IPH inner zone relative density (RD) was lower in the SR group compared to the AAS and REF groups (36, 51 and 58, respectively) and mean RD in the SR and AAS inner zones was lower than core zone values, consistent with the reduction in density and basal area due to thinning. The contrast between the core and inner zone was most pronounced in the SR group, where core zone RD was double that of the inner zone. Core zone stand structure at year five post-harvest (Yr5post) was similar to the IPH values. There was substantial variation in live basal area in the core zones for all treatments (Figure 2, right panel). The decrease in live density and basal area in the inner zone from REF to AAS to SR at Yr5post was similar to the IPH pattern.

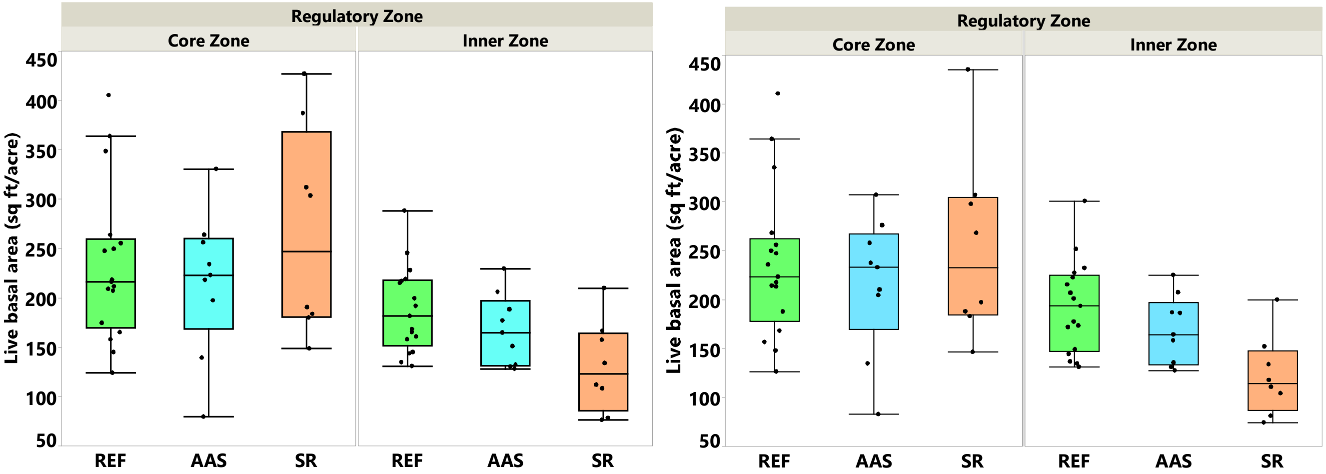

Figure 2. Live basal area (ft^2/acre) immediate post-harvest (left) and five years post-harvest (right) by treatment and regulatory zone.

There were significant differences in inner zone basal area/acre among treatment groups in mixed model comparisons, but no significant differences between core zones. The pairwise comparisons for the inner zone indicated that SR group live basal area/acre was significantly lower compared to both the REF and AAS groups ($p < 0.001$ and $p = 0.015$, respectively. The difference between REF and AAS inner zones was not significant. The Yr5post results were similar (Appendix A, Table 3).

Over 95% of live trees were conifers by count and basal area in all treatment groups. Western redcedar and western hemlock were the most frequently occurring dominant species by live basal area, followed by Douglas-fir and Engelmann spruce. Between 40–60% of mean live basal area in the core and inner zones of all treatment groups was made up of two species classified as very shade tolerant, western hemlock and western redcedar. Four shade tolerant species (grand fir, subalpine fir, Engelmann spruce and Douglas maple) made up an additional 20–30% of live basal area. In combination, shade tolerant and very shade tolerant species provided 65–90% of Yr5post live basal area in the core and inner zones of all treatment groups (Table 3).

Table 3. Proportion of basal area from shade tolerant species (very tolerant and tolerant categories combined) for live trees by treatment and regulatory zone.

Treatment	Regulatory Zone	% by count		% by basal area	
		IPH	Yr5post	IPH	Yr5post
REF	Core	83.0	83.1	79.9	80.4
	Inner	76.9	77.7	69.3	69.9
AAS	Core	80.4	80.6	76.6	76.5
	Inner	73.8	73.9	63.7	62.8
SR	Core	83.8	83.8	82.3	82.2
	Inner	76.4	78.0	68.9	69.6

The preferred species list for inner zone leave trees in the Mixed Conifer THT includes (in priority order) all hardwoods (broadleaf species), western larch, ponderosa pine, western redcedar, western white pine, Douglas-fir, and lodgepole pine (WFPB 2016, WAC 222-16-010). The percentage of live basal area provided by species on the preferred species list ranged from 45–66%. The proportion of trees on the preferred species list was greater in the inner zones than the core zones of the AAS and SR group sites (Table 4).

Table 4. Proportion of IPH live trees on the preferred species list.

Treatment	Regulatory Zone	% count		% basal area	
		IPH	Yr5post	IPH	Yr5post
REF	**Core**	48.9	49.0	56.2	55.8
	Inner	46.2	45.9	53.9	53.9
AAS	**Core**	36.6	36.4	44.9	45.1
	Inner	42.8	42.7	54.7	55.9
SR	**Core**	53.5	54.0	57.9	58.8
	Inner	57.3	57.3	65.6	66.4

Change in Stand Structure

There were differences in the direction and magnitude of change in inner zone stand structure among treatment groups. Live density and basal area increased in the REF and AAS inner zones while decreasing in the SR inner zones (Appendix Table 2, Figure 3). There was little change in live density and basal area in core zones among all treatments over the first five years following harvest. Relative density increased slightly over the first five years following harvest in the core and inner zones of both the REF and AAS groups; but decreased in the SR group; consistent with the changes observed in density and basal area. Consequently, the ordering of the groups by mean live density, basal area and RD persisted five years after harvest, and differences between the REF and SR groups increased (Appendix Table 2).

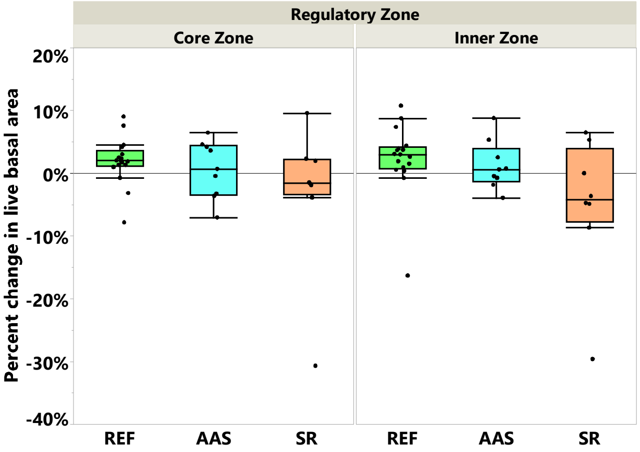

Figure 3. Cumulative percent change in live basal area during the first five years after harvest by treatment and regulatory zone.

There were significant differences among treatment groups in mixed model comparisons of percent change in live basal area/acre for both the core and inner zones (Appendix Table 3). The pairwise comparisons for the core zone indicated that change in live basal area was significantly greater in SR core zones compared to the REF group ($p = 0.042$), while the AAS−SR and REF−AAS differences were not significant. The inner zone comparisons indicated the change was significantly greater in the SR treatment compared to both the REF and AAS groups ($p = 0.005$ and 0.036, respectively), while the difference between REF and AAS inner zones was not significant. The direction of change differed among groups, with a tendency towards a reduction in mean live density and basal area in the core and inner zones of SR sites over time in contrast to a tendency for live density and basal area to increase in the AAS and SR sites.

Post-harvest changes in stand structure resulted from the interplay of growth and mortality. Mean ingrowth (recruitment of new trees to the stand) exceeded mortality in the core and inner zones of the REF and AAS groups during the first five years post-harvest, resulting in an increase in density. In contrast, mortality exceeded ingrowth in the core and inner zones of the SR group by about 12 and seven trees/acre respectively, causing a reduction in density (Table 5). Mean basal area increased at AAS and REF sites because new ingrowth and diameter growth of existing trees was greater than mortality, while greater mortality resulted in a net loss of basal area at the SR sites.

Table 5. Mean cumulative ingrowth and mortality during the five years after harvest by treatment and regulatory zone (standard error in parenthesis).

Regulatory Zone	**Treatment**	**Cumulative trees/acre**	
		Ingrowth	**Mortality**
Core	**REF**	13.0 (2.6)	7.7 (1.5)
	AAS	11.0 (2.8)	10.1 (2.2)
	SR	8.6 (2.5)	21.0 (10.6)
Inner	**REF**	14.7 (3.5)	8.4 (1.5)
	AAS	11.9 (3.4)	9.5 (1.8)
	SR	6.5 (1.6)	13.7 (5.3)

Ingrowth during the first five years after harvest added an average of 8.6–13 trees/acre to the core zones and 6.5–14.7 trees/acre to the inner zones. Despite heavier thinning and lower relative density, the inner zones of the SR group had the least ingrowth, less than half that of unthinned REF group inner zones.

Mean mortality rates, as an annual percentage of live stem count and basal area during the first five years after harvest, was lowest in the REF group, higher in the AAS group and highest in the SR group for both the core and inner zones (Table 6). Mortality rates in the SR group core and inner zones were nearly three times the respective REF rates. One SR site with mortality in excess of 7% of basal area per year raised the mean mortality rate for both the core and inner zones of the SR group and contributed to greater variability in the SR values (Figure 4). The mean diameter of REF group trees that died was smaller than for the AAS or SR groups.

Table 6. Mean cumulative mortality and annual mortality rates as a percentage of initial live density and basal area by treatment and regulatory zone during the five-year post-harvest period (standard error in parenthesis).

Zone	**Treatment**	**Cumulative Mortality**		**Mortality Rate**		**Diameter**
		% density	**% basal area**	**% density/year**	**% basal area/year**	**(inches)**
Core	**REF**	2.3 (0.4)	3.0 (0.7)	0.5 (0.3)	0.6 (0.6)	10.8 (1.1)
	AAS	3.4 (0.7)	4.5 (1.1)	0.7 (0.4)	0.9 (0.7)	12.1 (1.4)
	SR	6.3 (3.0)	6.9 (3.7)	1.3 (2.0)	1.5 (2.5)	11.6 (1.3)
Inner	**REF**	2.8 (0.6)	3.2 (1.0)	0.6 (0.6)	0.7 (0.9)	10.0 (0.8)
	AAS	3.6 (0.5)	3.7 (0.6)	0.7 (0.3)	0.8 (0.4)	10.5 (1.1)
	SR	7.9 (2.7)	9.3 (3.7)	1.7 (1.7)	2.0 (2.4)	12.0 (1.4)
Combined core/inner	**REF**	2.5 (0.5)	3.0 (0.8)	0.5 (0.1)	0.6 (0.2)	10.4 (0.8)
	AAS	3.6 (0.5)	4.1 (0.8)	0.7 (0.1)	0.8 (0.2)	11.0 (1.1)
	SR	7.0 (2.9)	8.0 (3.7)	1.5 (0.6)	1.7 (0.9)	12.1 (1.1)

Pair-wise comparisons of mixed model estimates of cumulative mortality as a percentage of live basal area indicated that mortality was significantly greater in both the core and inner zones of the SR group compared to the REF and AAS groups ($p < 0.001$), while differences between REF and AAS groups were not significant (Appendix Table 3).

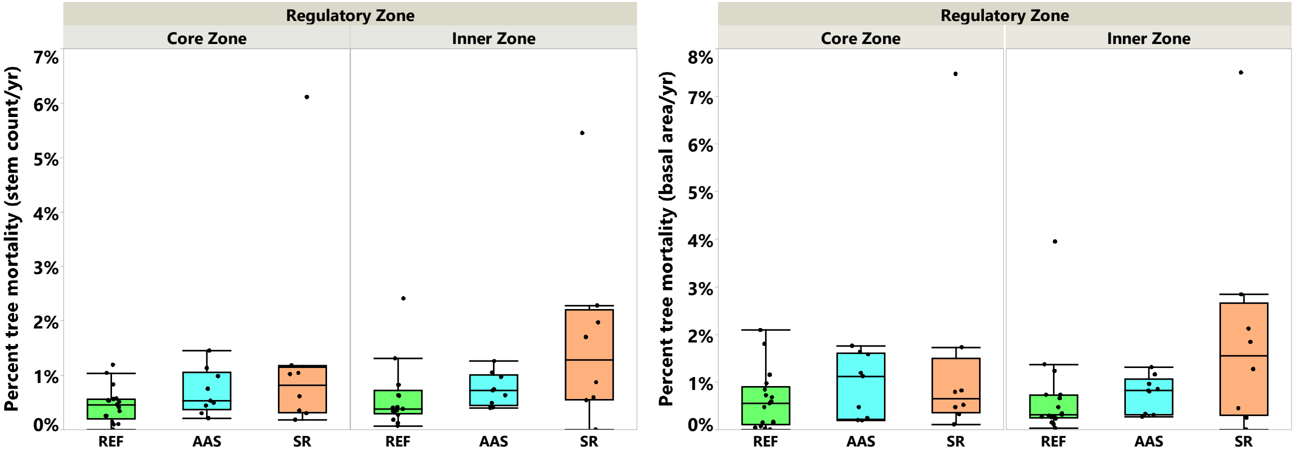

Figure 4. Mortality rates as the percentage of live stem count/year (left) and live basal area/year (right) during the first five years after harvest by treatment and regulatory zone.

The percentage of trees that died during the first five post-harvest years differed among species. Cumulative mortality was greatest (10–15%) for western white pine, lodgepole pine, and black cottonwood; lower (5–10%) for grand fir, ponderosa pine, and subalpine fir; and <5% for all other species. Wind was the most frequent cause of mortality in AAS and SR RMZs; 63.8% and 76.1% of the total, respectively (Table 7). In contrast, undefined mortality agents (e.g. suppression, disease, insect damage) were dominant in REF group RMZs. Mortality from fire occurred at only one SR site where a post-harvest site preparation burn penetrated into the RMZ.

Table 7. Proportion of mortality by mortality agent and treatment.

	Percent by Stem Count			Percent by Basal Area		
Treatment	**Wind/physical damage**	**Fire**	**Other**	**Wind/physical damage**	**Fire**	**Other**
REF	37.6	0.0	62.4	40.1	0.0	59.9
AAS	63.8	0.0	36.2	74.8	0.0	25.2
SR	76.1	0.6	23.2	81.3	0.1	18.6

TREE FALL AND WOOD RECRUITMENT

There was a consistent pattern in mean tree fall rates among treatment groups during the five-year post-harvest interval; rates were highest for the SR group, lower for the AAS group, and the lowest for the REF group. This pattern held for both total and recruited fallen trees (those that reached the bankfull channel). The rate for tree fall that recruited to the channel in the SR group was nearly double the REF rate in the core zone and over four times the REF rate in the inner zone. The AAS rate for tree fall that recruited was only slightly higher than the REF rate in the core zone and 2–3 times the REF rate in the inner zone (Table 8).

Table 8. Mean cumulative tree fall/acre and annual tree fall rates for total and recruited fallen trees by regulatory zone and treatment during the five-year post-harvest period (standard error in parenthesis).

Zone	**Treat-ment**	**Cumulative (fallen trees/acre)**		**Rate (trees/acre/year)**		**Mean DBH (inches)**	
		Total	**Recruiting**	**Total**	**Recruiting**	**Total**	**Recruiting**
Core	**REF**	9.5 (2.2)	4.4 (1.1)	1.9 (0.4)	0.9 (0.2)	10.5 (0.7)	11.8 (0.8)
	AAS	11.8 (3.0)	5.6 (2.0)	2.4 (0.6)	1.1 (0.4)	11.8 (1.1)	11.3 (0.9)
	SR	21.7 (11.4)	9.5 (5.1)	4.5 (2.4)	1.9 (1.0)	11.0 (1.1)	11.4 (1.5)
Inner	**REF**	9.0 (1.7)	1.1 (0.3)	1.8 (0.3)	0.2 (0.1)	9.9 (0.9)	13.8 (1.3)
	AAS	14.0 (2.7)	1.9 (0.8)	2.8 (0.6)	0.4 (0.2)	10.6 (1.1)	16.1 (2.4)
	SR	14.7 (6.4)	4.3 (2.1)	3.0 (1.3)	0.9 (0.4)	10.8 (1.1)	13.9 (1.1)
Combined Core/Inner	**REF**	9.2 (1.7)	3.4 (1.2)	1.8 (0.3)	0.7 (0.2)	10.5 (0.9)	12.7 (1.3)
	AAS	13.1 (2.7)	2.4 (0.5)	2.6 (0.5)	0.5 (0.1)	11.0 (1.0)	13.0 (1.0)
	SR	17.6 (8.3)	6.4 (3.1)	3.5 (1.7)	1.3 (0.6)	11.1 (0.8)	11.8 (1.3)

There were differences among treatment groups in source distance curves for fallen trees that recruited wood to the channel from within the 75-foot wide RMZ (Figure 5). 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.

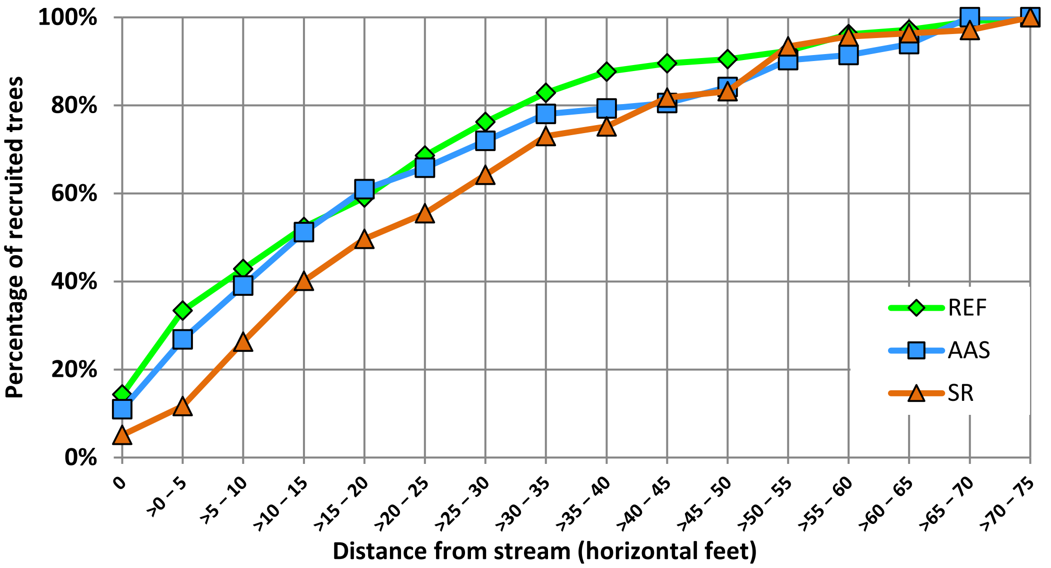

Figure 5. Percentage of recruited fallen trees originating within the 75-foot wide RMZ by source distance (horizontal feet from stream) and treatment.

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 (Table 9). 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 (Appendix Table 3).

Table 9. Mean cumulative wood recruitment from fallen trees and annual rates for all pieces and the subset of stems with roots attached, by count and volume per 100 feet of RMZ length (standard error in parenthesis).

Treatment	All pieces	Stems w/attached rootwads	All pieces	Stems w/ attached rootwads
	Cumulative pieces/100 feet		*Cumulative volume (ft^3)/100 feet*	
REF	0.9 (0.2)	0.3 (0.1)	5.4 (2.2)	1.5 (0.5)
AAS	1.2 (0.4)	0.7 (0.3)	7.5 (2.5)	3.9 (1.6)
SR	2.2 (1.1)	1.4 (0.9)	13.6 (8.8)	10.7 (7.7)
	Annual rate in pieces/100 feet/year		*Annual rate in volume (ft^3)/100 feet/year*	
REF	0.18 (0.04)	0.05 (0.01)	1.1 (0.4)	0.3 (0.1)
AAS	0.24 (0.08)	0.15 (0.06)	1.5 (0.5)	0.8 (0.3)
SR	0.45 (0.22)	0.27 (0.18)	2.7 (1.8)	2.1 (1.5)

The majority of AAS and SR fallen trees were uprooted. Consequently, 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 ($p < 0.001$; Appendix Table 3). The mean diameter of SWAR pieces where they crossed the edge bankfull channel was greater than for pieces without attached rootwads (11.0 and 10.3 inches, respectively). In combination, the larger size and attached rootwad should increase the stability of the SWAR pieces contributed by uprooted trees (Fox and Bolton 2007).

Most newly recruited wood pieces from fallen trees initially came to rest either spanning or suspended over the bankfull channel. On average, only about 20% of recruited pieces intruded into the bankfull channel and only 16–18% of the recruited volume was located below bankfull channel height (Table 10). Both in- and over-channel fallen tree pieces provide shade and cover, however only in-channel pieces can interact with flowing water and perform in-channel functions; including sediment storage and pool, step, and debris-jam formation.

Table 10. Mean in-channel versus over-channel wood recruitment from fallen trees by treatment.

Treatment	Total	In-channel	Over-channel	% In-channel
		Count (pieces 100 feet/year)		
REF	0.18	0.03	0.14	21.6
AAS	0.24	0.03	0.21	18.9
SR	0.45	0.03	0.41	20.8
		Volume (ft^3/100 feet/year)		
REF	1.08	0.19	0.79	18.1
AAS	1.50	0.18	1.18	16.3
SR	2.73	0.07	2.65	17.6

Change in Wood Recruitment Potential

The live and dead trees standing immediately post-harvest (IPH) comprise a pool of wood potentially available for recruitment to the channel following harvest. Harvest decreased the number of standing trees available for post-harvest recruitment in SR and AAS inner zones. The processes of growth, mortality and tree fall during the post-harvest period caused additional changes in the number and size of standing trees available for recruitment. Ingrowth added new trees to the live tree count, while height and diameter growth add volume to the live trees. Tree fall reduced the number available for future wood recruitment while increasing in-channel, over-channel and upland down wood.

The pool of standing trees potentially available for wood recruitment at Yr5post consists primarily of live and dead trees that were standing IPH (green and brown in Figure 6). Few trees were added by ingrowth (blue) during the post-harvest period. The number of live and dead standing trees in the core zone, ~50 trees/100 feet of RMZ length, was similar among treatments five years post-harvest (Figure 6, bright green and bright brown). However, the number of standing trees potentially available for harvest in the inner zone was greatest in the REF group, less in the AAS group, and least in the SR group; due to inner zone harvest allowed by the prescriptions as well as post-harvest tree fall. Consequently, at year five post-harvest the mean number of trees/100 feet of RMZ length available for potential wood recruitment in the REF RMZs was 134, compared to 115 in AAS RMZs and 89 in SR RMZs.

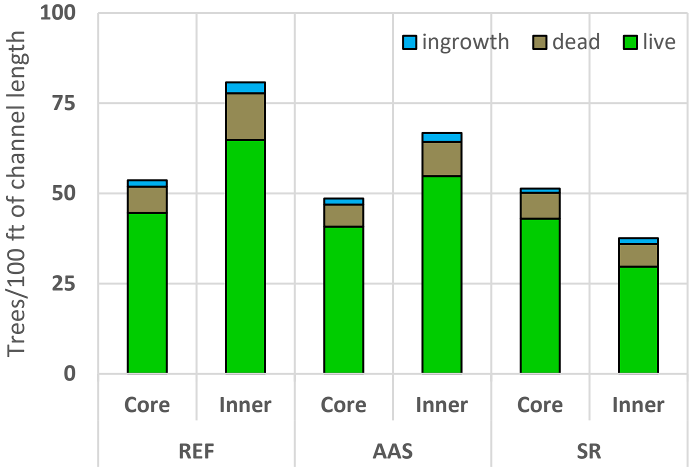

Figure 6. Standing trees potentially available for recruitment within 75 feet of the stream at five years post-harvest by treatment in mean trees/100 feet of stream length.

DISCUSSION

As expected, implementation of the SR and AAS prescriptions resulted in substantial differences in immediate post-harvest inner zone stand structure. The requirement to retain all inner zone trees that provide shade to the stream in AAS RMZs resulted in a post-harvest stand structure more similar to unharvested REF stands than to the more heavily thinned SR stands, which had significantly lower basal area than either the AAS or REF RMZs. Structure of the AAS and SR stands differed from a random sample of stands adjacent to Type F streams from the Eastern Washington Riparian Assessment Project (EWRAP) study (Bonoff et al. 2008, Schuett-Hames 2015). In contrast to comparable EWRAP sites (Mixed Conifer Timber Habitat Type, >30 years of age), mean live density was greater by 60 trees/acre in AAS inner zones and 20 trees/acre in SR inner zones, and basal area was greater in AAS inner zones by 85 ft^2/acre and lower in SR inner zones by 5 ft^2/acre. AAS and SR core zones were also denser (60–90 trees/acre) and had more basal area (80–100 ft^2/acre) than core zones of comparable EWRAP sites. This was not surprising since the EWRAP sites were a random sample with a diversity of ages and management histories, while our sites had sufficient basal area to allow inner zone harvest (Cupp and Lofgren 2014). There was evidence that inner zone tree retention guided by the preferred species list had limited success in increasing the proportion of preferred species, however shade tolerant species still comprised 60-70% of live basal area in SR and AAS inner zones after thinning.

The overall distribution of post-harvest tree mortality rates from our SR and AAS sites was similar to rates for mixed-conifer stands on USFS lands in eastern Washington and Oregon in the mid-1990s to mid-2000s (Reilly and Spies 2016). They classified mortality rates as chronic (<5%/year), partial stand replacement (5-25%/year) and stand replacement (>25%/year). Approximately 90% of their sites had chronic mortality rates associated with suppression, pathogens or insect damage, while mortality at the remaining sites was greater, primarily due to fire and associated insect damage. The distribution was similar for our sites; 16 of 17 combined SR and AAS RMZs were within the chronic mortality range, while one site fell into the partial stand replacement category. Tree mortality was the primary driver of change in stand structure in SR RMZs during the first five years after harvest. Higher mean mortality over the five-year post-harvest interval in the SR RMZs resulted in a decrease in density, basal area and relative density, magnifying the initial differences in stand structure with AAS RMZs that had slight increases in mean density and basal area. Consequently, year five stand structure in AAS RMZs was more similar to REF RMZs than to SR RMZs.

Elevated mortality in SR RMZs was not expected, since inner zone thinning was intended to increase the health and resiliency to disturbance from insects, disease and fire. However, wind was the most frequently occurring mortality agent at the AAS and SR sites, reaching partial stand replacement levels at one SR site, indicating that windthrow can be a significant mortality agent in a subset of eastern Washington riparian buffers. This observation is consistent with Reilly and Spies (2016), who documented mortality rates from wind of 10-25%/year at a small proportion of mixed-conifer zone plots in eastern Washington and Oregon. Mortality from wind in riparian buffers is well-documented in coastal areas of the Pacific Northwest, but our mortality rates were much lower than the rates of 23.8% and 19.0% reported for western Washington buffers on fish-bearing streams by Grizzel et al. (2000) and Liquori (2006), respectively. The role and significance of wind at our buffered sites is consistent with observations from young stands in the Oregon Coast range, where patchy mortality of larger trees due to mechanical damage from wind had a greater effect on stand structure than mortality of small trees due to suppression (Lutz and Halpern 2006).

Mortality and tree fall in SR and AAS RMZs resulted in increased wood input to streams compared to unharvested reference sites, contributing to the FPHCP resource objective to provide wood input to streams. Mean tree fall and associated wood recruitment was greatest in the more heavily thinned SR RMZs, consistent with Burton et al. (2016) who observed greater wood input in RMZs with narrow no-harvest buffers with adjacent thinned stands compared to sites with larger unthinned RMZs.

During the five-year post-harvest interval, wood recruitment at most SR and AAS RMZs fit the stable, individualistic wood recruitment scenario described by Bragg (2000), while input at a sub-set of sites with elevated mortality from windthrow were characteristic of the episodic wood recruitment regime associated with elevated disturbance. Mean cumulative wood recruitment from fallen trees in SR RMZs was over three times greater than in REF and AAS RMZs due to elevated input at two sites with substantial wind-associated mortality. Channels adjacent to wind-affected SR RMZs received pulses of wood input similar to those reported in newly established buffers in coastal areas of the Pacific Northwest *(*Grizzel et al. 2000, Liquori 2006, Bahuguna et al. 2010, Schuett-Hames et al. 2012, Martin and Shelly 2017). The majority (~60%) of wood input from fallen trees in AAS and SR RMZs consisted of uprooted tree stems with attached rootwads, due to the prevalence of uprooted trees associated with wind mortality at the SR and AAS sites. The combination of large size and attached roots make these pieces more likely to persist and provide functions over time (Fox and Bolton 2007). In contrast, ~76% of recruiting fallen tree pieces at REF sites were broken stems or tops of trees without attached roots. Many fallen trees came to rest spanning or suspended over the channel where they provide shade and cover but will not immediately provide in-stream habitat or functions (Martin and Shelly 2017).

The effect of harvesting streamside trees on future wood recruitment and loading depends on the stand characteristics; the frequency, intensity and method of harvest; and the presence and width of riparian buffers (Beechie et al. 2000, Meleason et al. 2003). Thinning reduces the number of trees potentially available to provide wood input, with implications for future wood recruitment (Pollock and Beechie 2014). Analysis of a similar buffer strategy proposed by the Idaho Forestry Program (75-foot wide RMZ with inner zone thinning to within 25 feet of the stream) predicted a reduction in potential wood recruitment by an average of 25% compared to a no-harvest scenario (Pollock 2013). Our data indicate that the number of standing trees available for wood recruitment within 75 feet of the stream at year five post-harvest is largely determined by the number trees remaining immediately after harvest, since changes due to ingrowth and tree fall were small compared to the initial IPH standing stock. Heavier thinning under the SR prescription resulted in a 50% reduction in inner zone basal area, compared to a 15% reduction in the more lightly thinned AAS treatment. The effects of inner zone thinning on wood recruitment potential is constrained by the requirement to leave all trees that provide shade (AAS only); and minimum basal area requirements that vary by site class including the requirement to retain the largest 21 trees/acre (both SR and AAS). Thinning reduced the relative density of inner zone stands, which should increase diameter growth in the remaining trees resulting in larger stems available for future recruitment (Pollock and Beechie 2014). 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 (Liquori 2006, Martin and Grotefendt 2007, Rollerson et al. 2009. Burton et al. 2016).

The eastside Type F riparian prescriptions are intended to promote development of healthy, riparian forests with reduced susceptibility to disease, insect outbreaks, and wildfire; while providing riparian functions (e.g., shade, wood input, and nutrients) that support the FPHCP resource objectives (WDNR 2005). Wildfire, disease, and insects are important episodic mortality processes in the forests of eastern Washington (Agee 1993, Hessburg et al. 1994, Campbell and Leigel 1996, Reilly and Spies 2016), however we did not observe substantial mortality from these causes during the five-year timeframe of this study. If thinning of the inner zone is successful in reducing the vulnerability of stands to episodic disturbances from fire, insects, and disease damage, it will result in a more stable wood input regime associated with chronic mortality of individual trees over time (Spies et al. 1988, Bragg 2000) unless sites are affected by wind. Simulation modeling indicates that both chronic and episodic disturbance regimes can provide substantial inputs of wood that increase wood loading over time if initial stocking is adequate (Hedman et al. 1996, Bragg 2000, Meleason et al. 2003); but the magnitude and timing of wood inputs vary depending on existing stand structure and the frequency and severity of disturbance (Bragg 2000, Benda and Sias 2003).

SUMMARY OF CONCLUSIONS

The SR treatment resulted in the largest change in stand structure, the greatest difference in tree mortality and wood recruitment from fallen trees compared to the unharvested REF sites. The responses to the AAS treatment were intermediate, but more similar to the REF than to the SR treatment. There were statistically significant differences in live basal area, change in stand structure, tree mortality and wood recruitment from tree fall between the SR treatment and both the AAS and REF treatments, while the only significant differences in the AAS and REF contrasts was for wood recruitment from stems with attached rootwads.

Thinning within the inner zone of the SR and AAS RMZs reduced immediate post-harvest density, basal area and relative density compared to unharvested reference sites. The reduction in inner zone basal area was greatest in the SR RMZs, which were significant different from the AAS or REF RMZs. Inner zone thinning guided by the preferred species list appeared to increase the proportion of preferred species and reduced the proportion of shade tolerant species relative to the core zones, but the reduction was only about 10% and SR and AAS RMZs continued to be dominated by shade tolerant species.

Buffer tree mortality during the first five years post-harvest was significantly higher in the SR RMZs compared to the AAS and SR RMZs. Mechanical damage from wind was the most frequent cause of mortality in SR and AAS RMZs. Mortality rates were at chronic levels (<5%/year) at all AAS sites and seven of eight SR sites; but mortality at one SR site with extensive windthrow reached the partial stand replacement level (7.5/year). We did not observe episodic mortality from fire, insects or disease during the five-year post-harvest interval.

The pattern of wood recruitment from fallen trees was similar to mortality. Input was significantly greater from SR RMZs compared to the AAS or REF RMZs. The cumulative total of recruiting fallen trees from SR RMZs was nearly double that of AAS RMZs, primarily due to episodic input from windthrow at two SR sites. Over half of the recruiting fallen tree pieces at the SR and AAS sites consisted of uprooted tree stems with attached roots, which are most likely to remain stable and persist through time. Most fallen trees initially came to rest above the channel where they provide shade and cover but are currently unable to interact with flowing water and provide in-channel habitat. Thinning and post-harvest mortality reduced the standing stock of trees available for wood recruitment in the SR and AAS RMZs compared to unharvested REF RMZs.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

All sites consisted of conifer-dominated stands in mixed conifer forests on fish-bearing streams in eastern Washington, with adequate live basal area to qualify for harvest under the eastern Washington riparian prescriptions. All but one site was located in northeast Washington; with one site in the Eastern Cascades and no sites in the Blue Mountains. Consequently, the scope of inference is strongest for well-stocked conifer-dominated stands adjacent to fish-bearing streams <15 feet in width in mixed conifer forests at 2500-5000 feet in elevation in the northeast part of Washington State. Study sites were not randomly selected but were obtained by contacting landowners who were willing to implement the prescriptions and provide unharvested reference reaches, so our results do not represent a random sample of all sites where the prescriptions are applied. Consequently, results should be extrapolated with caution.

This study provides a short-term examination of post-harvest response. It was not well suited to document long-term effects of episodic mortality events and tree recruitment processes due to the limited timeframe and sample size. A longer-term perspective is necessary to address uncertainty concerning the effectiveness of the prescriptions in reducing vulnerability to episodic disturbance from fire, disease, and insects and in providing wood to maintain aquatic habitat, because stand development, tree mortality and wood recruitment processes operate over decades to centuries. The riparian status and trend monitoring program under development by the Cooperative Monitoring, Evaluation and Research Committee (CMER) would provide an unbiased sample of riparian stands with repeated measurements over time. This data would be better suited to estimate the frequency and magnitude of episodic disturbance events, providing insights into interaction between FPHCP RMZs and fire, insects and disease over time across eastern Washington riparian forests. In the absence of long-term monitoring data, stand growth and yield modeling could provide predictions of stand development and changes in vulnerability to fire, insect and disease over time, but would not address uncertainty about episodic mortality from wind or other complex responses due to the linear pattern of RMZ buffers with adjacent harvested uplands.

The eastern Washington riparian prescriptions are intended to achieve the FPHCP resource objectives for stream temperature and aquatic habitat formation by wood. The scope of this study was limited to short-term changes in buffer stand structure, tree mortality and wood recruitment from tree fall; and did not address changes in wood loading, fish habitat or water quality over time. To address this uncertainty, we recommend an intensive, long-term study to examine the effects of the prescriptions on the amount and characteristics of in-channel wood and fish habitat over a timeframe adequate to document channel response to changes in wood recruitment.

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APPENDIX A. TABLES

Appendix A, Table 1. Study site characteristics.

Site	Reach[1]	Length (feet)	Width (feet)	Basin Area (ac)	Gradient (%)	Base Flow (ft^3/sec)	Elevation (feet)	Azimuth	Dominant Species[2]
Bacon	REF	700	14.3	2499	16.4	1.7	3304	001	TSHE
	AAS	500	12.7	2614	10.8	1.5	3163	001	TSHE
Cole	REF	850	17.6	11793	3.4	1.5	1892	081	THPL
	AAS	800	14.5	11814	4.1	1.6	1852	081	PSME
Dry Canyon	REF	800	5.6	1622	4.5	0.4	2159	037	TSHE
	AAS	800	6.5	1641	3.6	0.5	2132	037	TSHE
Loetz	REF	800	11.9	1730	4.1	1.0	3449	090	THPL
	AAS	800	14.4	1809	6.5	0.9	3379	090	THPL
Mill Tributary	REF	800	4.7	212	14.3	0.2	3511	044	TSHE
	AAS	900	5.8	273	12.5	0.2	3430	044	TSHE
M.F. Sanpoil	REF	800	4.8	2237	5.6	0.1	3359	020	PSME
	AAS	800	6.1	2387	5.2	0.1	3307	020	PSME
Seco	REF	750	8.0	1203	6.0	0.5	3488	080	TSHE
	AAS	750	7.9	1318	5.3	0.4	3444	080	TSHE
Sema 1	REF	450	4.3	210	6.3	0.1	3505	009	PIEN
	AAS	450	5.2	234	6.7	0.1	3441	009	PIEN
Sema 2	REF	800	5.9	310	9.0	0.1	3530	055	TSHE
	AAS	850	6.7	333	9.0	0.1	3450	055	TSHE
Big Goosmus	REF	700	7.0	1026	10.2	0.1	3191	010	THPL
	SR	700	9.5	1129	9.3	0.1	3105	010	THPL
Dorchester	REF	552	9.7	2056	4.3	0.6	2201	009	THPL
	SR	700	10.2	2082	5.6	0.6	2145	009	THPL
EF Cedar	REF	750	19.9	3611	9.0	2.1	3236	005	THPL
	SR	900	16.7	3686	7.4	2.4	3164	005	THPL
Little Goosmus	REF	850	5.1	896	9.3	0.0	3339	036	PSME
	SR	850	6.0	933	10.5	0.0	3221	036	PSME
Prouty	REF	800	7.9	275	18.7	0.1	4134	004	THPL
	SR	900	9.7	349	16.1	0.1	3962	004	THPL
Sema 3	REF	700	7.8	890	3.2	0.4	3471	063	PIEN
	SR	800	8.0	922	1.7	0.4	3443	063	PIEN
Sema 4	REF	750	5.5	410	8.3	0.1	3471	075	TSHE
	SR	750	5.0	429	6.8	0.1	3418	075	PIEN
Sylvus	REF	850	8.5	1759	5.6	0.7	3344	057	THPL
	SR	800	8.7	1789	5.2	0.6	3279	057	THPL

[1] REF = Reference, AAS = All Available Shade, SR = Standard Rule

[2] TSHE= western hemlock, THPL = western redcedar, PSME = Douglas-fir, PIEN = Engelmann spruce

Appendix A, Table 2. Stand structure immediately post-harvest and five years post-harvest (standard error in parenthesis).

Timing	Regulatory Zone	Treatment	Density (trees/acre)	Basal area (ft^2/acre)	QMD (inches)	Relative Density
IPH	Core	REF	333.7 (33.8)	233.1 (18.9)	11.8 (0.6)	68 (4.8)
		AAS	306.4 (47.4)	215.8 (24.2)	11.8 (0.8)	63 (6.5)
		SR	328.0 (42.5)	266.5(37.3)	12.5 (1.0)	75 (8.4)
	Inner	REF	324.4 (36.0)	187.7 (10.5)	10.9 (0.5)	58 (3.4)
		AAS	274.7 (49.5)	167.4 (12.0)	11.3 (0.7)	51 (4.3)
		SR	155.2 (21.8)	130.2 (16.3)	12.8 (1.0)	36 (3.7)
Yr5post	Core	REF	338.8 (34.1)	236.7 (18.5)	11.7 (0.6)	69 (4.7)
		AAS	307.2 (47.2)	216.0 (23.3)	11.7 (0.8)	63 (6.5)
		SR	315.4 (43.8)	252.9 (33.3)	12.5 (1.0)	71 (7.6)
	Inner	REF	330.6 (38.0)	192.4 (11.4)	11.0 (0.5)	59 (3.7)
		AAS	277.2 (50.8)	169.2 (11.6)	11.3 (0.7)	51 (4.4)
		SR	147.9 (20.3)	121.8 (14.3)	12.7 (1.0)	34 (3.2)
Cumulative Change (IPH-Yr5post)	Core	REF	1.9% (3.1)	1.9% (2.5)	-0.02 (0.06)	1.1 (0.7)
		AAS	1.0% (4.1)	0.6% (3.8)	-0.02 (0.09)	0.2 (1.0)
		SR	-3.9% (10.4)	-3.2% (15.3)	-0.01 (0.10)	-3.5 (3.8)
	Inner	REF	1.1% (3.4)	2.3% (2.4)	0.04 (0.05)	1.4 (0.6)
		AAS	0.3% (2.9)	1.2% (2.1)	0.04 (0.04)	0.5 (0.6)
		SR	-3.8% (4.4)	-5.0% (6.0)	-0.12 (0.13)	-2.2 (1.5)

Appendix A, Table 3. Mixed model treatment contrasts. Significant values are bolded.

Regulatory Zone	Treatment Contrast	Mean treatment difference	Standard Error	DF	t-value	p-value
IPH Live Basal Area/ha						
Inner	**REF – AAS**	14.9	13.5	18.4	1.10	0.284
	REF – SR	63.6	14.2	19.0	4.47	**<0.001**
	AAS – SR	48.7	18.7	24.4	2.61	**0.015**
Yr5Post Live Basal Area/ha						
Inner	**REF – AAS**	17.2	13.9	18.6	1.24	0.232
	REF – SR	77.5	14.7	19.1	5.28	**<0.001**
	AAS – SR	60.2	19.2	24.8	3.14	**0.004**
Cumulative change in live basal area, IPH–Yr5Post						
Core	**REF – AAS**	1.1	2.4	19.2	0.48	0.636
	REF – SR	5.4	2.5	19.9	2.17	**0.042**
	AAS – SR	4.3	3.2	27.1	1.34	0.193
Inner	**REF – AAS**	0.6	2.3	18.8	0.27	0.788
	REF – SR	7.8	2.5	19.5	3.13	**0.005**
	AAS – SR	7.2	3.2	25.8	2.22	**0.036**
Cumulative tree mortality as a percentage of live basal area						
Core Zone	**REF – AAS**	-0.15	0.16	15	-0.93	0.368
	REF – SR	-1.38	0.18	15	-7.62	**<0.001**
	AAS – SR	-1.23	0.24	15	-5.17	**<0.001**
Inner Zone	**REF – AAS**	0.005	0.19	15	0.02	0.981
	REF – SR	-1.61	0.19	15	-8.33	**<0.001**
	AAS – SR	-1.62	0.27	15	-6.09	**<0.001**
Cumulative total wood pieces recruited from fallen trees						
Combined Core/Inner	**REF – AAS**	-0.19	0.16	15	-1.19	0.251
	REF – SR	-1.23	0.17	15	-7.11	**<0.001**
	AAS – SR	-1.04	0.23	15	-4.49	**<0.001**
Cumulative stem with attached rootwad (SWAR) pieces recruited from fallen trees						
Combined Core/Inner	**REF – AAS**	-1.20	0.27	15	-4.45	**<0.001**
	REF – SR	-1.50	0.24	15	-6.18	**<0.001**
	AAS – SR	-0.29	0.34	15	-0.85	0.407

APPENDIX B. MIXED MODEL OUTPUTS FOR METRICS USED IN THE STATISTICAL ANALYSES

Regulatory Zone	Treatment	Mean	Standard error	95% CI	
				Lower	Upper
Live basal area in ft^2/acre, immediately post-harvest					
Inner	**REF**	187.8	10.3	167	209
	AAS	172.9	13.5	145	200
	SR	124.2	14.2	95	153
Live basal area in ft^2/acre, year 5 post-harvest					
Inner	**REF**	192.4	10.4	171	214
	AAS	175.2	13.7	147	203
	SR	115.0	14.5	85	145
Cumulative % change in live basal area, IPH–IPH–Yr5post					
Core	**REF**	1.93	1.6	-1.4	5.2
	AAS	0.80	2.2	-3.7	5.3
	SR	-3.46	2.3	-8.2	1.3
Inner	**REF**	**2.32**	**1.7**	**-1.2**	**5.8**
	AAS	1.68	2.3	-3.0	6.3
	SR	-5.48	2.4	-10.4	-0.6
Cumulative tree mortality as a percentage of live basal area, IPH–IPH–Yr5post					
Core	**REF**	0.018	0.005	0.010	0.034
	AAS	0.021	0.006	0.011	0.040
	SR	0.069	0.019	0.037	0.124
Inner	**REF**	0.022	0.005	0.013	0.036
	AAS	0.022	0.006	0.012	0.039
	SR	0.101	0.024	0.060	0.165
Total wood recruited from fallen trees (pieces/ft)					
Combined Core/Inner	**REF**	0.58	0.14	0.35	0.98
	AAS	0.71	0.19	0.40	1.25
	SR	2.00	0.51	1.16	3.47
Stems with attached rootwad (SWAR) pieces recruited from fallen trees (pieces/ft)					
Combined Core/Inner	**REF**	0.13	0.05	0.06	0.28
	AAS	0.45	0.16	0.20	0.97
	SR	0.60	0.22	0.27	1.30