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MEMORANDUM

July 30, 2020

To: Forest Practices Board

Form: Mark Hicks, Adaptive Management Program Administrator

Subject: Buffer, Characteristics, Integrity and Function (BCIF) Report

At their February 7, 2020 meeting, TFW Policy (Policy) formally accepted the findings report and associated materials for the Westside BCIF study, formally titled**:** ***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***. 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 BCIF study to evaluate changes post-harvest in select riparian functions within forested buffers along Type Np (non-fish bearing) streams.

The BCIF study used an After, Control, Impact (ACI) study design. This design uses post-harvest data from a randomly selected sample of 15 treatment sites across western Washington. Data from the treatment sites was compared with data from unharvested reference sites to estimate the magnitude and duration of treatment effects. The fifteen treatment sites contained a mixture of treatments allowed under the Westside Type Np Riparian Prescriptions, but harvest units did not typically include entire Np streams from the Type F break to the Perennial Initiation Point. Data collection occurred at three, five and 10 years post-harvest. However, the authors could not sample all sites at each date because five reference sites were harvested prior to the year-10 post-harvest survey and access was denied for one treatment and reference site in year three and another treatment site in year ten.

Three components (treatments) of the Westside Type Np Riparian Prescriptions were evaluated: unbuffered clear-cut harvest to the channel edge (CC treatment), 50-foot wide no-cut buffers (BUF treatment), and 56-foot radius no-cut buffers around the perennial initiation points (PIP treatment). Unharvested second-growth reference (REF) reaches were located in proximity of the treatment sites. The study documents the magnitude of change in stand structure, tree mortality, wood recruitment, shade, wood cover and soil disturbance when the riparian prescriptions for Westside Type Np (perennial non-fish-bearing) streams were applied in an operational setting. This extended 10-year post-harvest report augments earlier findings presented in the Westside Type N BCIF Study 5-year post-harvest report (Schuett-Hames et al. 2012).

Summary Technical Findings:

Change in Stand Structure. During the first five years after harvest, density and basal area decreased in BUF, PIP and REF stands because tree mortality exceeded ingrowth of young trees. Mean cumulative mortality as a percentage of live basal area was 48.1% in PIP stands, 27.2% in BUF stands and 9.4% in REF stands. Over the entire 10-year post-harvest period, cumulative change in live basal area (trees >4" DBH) was positive in REF stands (+2.7%) and negative in BUF (-14.1%) and PIP (-38.9%) stands, however the BUF-REF contrast was not statistically significant.

Tree fall and Wood Input to Streams. Tree fall and wood recruitment was driven by mortality with rates highest during the first five years post-harvest. Cumulative recruited wood volume in the (BUF) and (PIP) reaches was double and four times the REF volume, respectively. Wood recruitment was minimal in CC reaches during the 10 year period due to lack of trees, following slash input (primarily branches and tops) during harvest.

Shade/Cover. One year after harvest, canopy closure, an indicator of shade from trees and tall shrubs, was lower in the BUF (76%) and PIP (52%) reaches compared to the REF reaches (89%). By year 10, canopy closure in the BUF and PIP reaches increased to over 85%. Mean canopy closure in the CC reaches was only 12% one year after harvest of trees, but increased to 37% by year 5 and 72% by year 10.

Soil Disturbance. All BUF and PIP reaches met the performance target (<10% of the ELZ area with soil disturbance) but one of eight CC reaches exceeded the target. The average distance to the stream for erosion features that delivered sediment was 1.0 foot and a maximum of 7.7 feet.

Possible Implications:

The Westside Type N BCIF Study was not designed to address some important aspects of Type N riparian prescription effectiveness, including aquatic resource effects (e.g. amphibians and macro-invertebrates), water quality (e.g. stream temperature and turbidity) or downstream effects on fish-bearing streams.

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

Though the study did not warrant action by the Board, the BCIF study has increased our understanding of the short-term effects of applying the Type Np rule prescriptions along Western Washington headwater streams. As such Policy has directed the study be provided as an additional source of information to the Type Np Workgroup.

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.

By:
Dave Schuett-Hames and Greg Stewart
CMER Science Staff
Northwest Indian Fisheries Commission (NWIFC)

October 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 Type N Riparian Effectiveness Program, and was conducted under the oversight of the Riparian Scientific Advisory Group (RSAG).

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

Full Reference

Schuett-Hames, Dave and Stewart, Greg. 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.

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.

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Northwest Indian Fisheries Commission

October 2019

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EXECUTIVE SUMMARY

This report presents the 10-year post-harvest results from the Westside Type N Buffer Characteristics, Integrity and Function study conducted by Washington's Cooperative Monitoring, Evaluation and Research Committee (CMER). The purpose was to determine the magnitude of change in stand structure, tree mortality, wood recruitment, shade, wood cover and soil disturbance when the riparian prescriptions for Westside Type Np (perennial non-fish-bearing) streams were applied in an operational setting.

Treatment sites were randomly selected from approved forest practice applications. Three components (treatments) of the Westside Type Np Riparian Prescriptions were evaluated: unbuffered clear-cut harvest to the channel edge (CC treatment), 50-foot wide no-cut buffers (BUF treatment), and 56-foot radius no-cut buffers around the perennial initiation points (PIP treatment). Unharvested second-growth reference (REF) reaches were located in proximity of the treatment sites. Statistical tests were done to compare the CC, BUF and REF results.

Change in Stand Structure. During the first five years after harvest, density and basal area decreased in BUF, PIP and REF stands because tree mortality exceeded ingrowth of young trees. Mean mortality and associated change in stand structure were greatest in PIP stands, less in BUF stands and least in REF stands. Cumulative mortality as a percentage of live basal area was 48.1% in PIP stands, 27.2% in BUF stands and 9.4% in REF stands. Between years five and ten, stand structure stabilized in PIP and BUF stands due to a marked reduction in mortality rates. Over the entire 10-year post-harvest period, cumulative change in live basal area was positive in REF stands (+2.7%) and negative in BUF (-14.1%) and PIP (-38.9%) stands, however the BUF-REF contrast was not statistically significant. Wind was the dominant mortality agent in PIP and BUF stands. Mortality in REF stands was dominated by other factors (e.g. suppression); however there was an increase in wind mortality in REF stands during year 4–5 due to a storm with hurricane-force winds. Substantial conifer regeneration (seedling and saplings) was observed in BUF and PIP stands, including buffers with high mortality. Almost no trees remained in the CC reaches after harvest, but regeneration with planted trees appeared to be successful.

Tree fall and Wood Input to Streams. Tree fall and wood recruitment was driven by mortality; consequently rates were highest during the first five years post-harvest. Cumulative recruited wood pieces/100 feet in the PIP reaches (11.2) was nearly double that in the REF (6.2) and BUF (7.0) reaches over the entire IPH-YR10 period. Cumulative recruited wood volume in the (BUF) and (PIP) reaches was double and four times the REF volume, respectively. Most recruiting fallen trees came to rest above the channel where they provided cover but did not interact with flowing water. Consequently, few newly recruited pieces provided sediment storage or formed pools, steps or debris jams. Wood recruitment was minimal in CC reaches during the IPH-YR10 period due to lack of trees, following slash input (primarily branches and tops) during harvest.

Shade/Cover. One year after harvest, canopy closure, an indicator of shade from trees and tall shrubs, was lower in the BUF (76%) and PIP (52%) reaches compared to the REF reaches (89%). By year 10, canopy closure in the BUF and PIP reaches increased to over 85%, similar to the REF reaches, apparently due to growth of shrubs and sapling adjacent to the stream. Mean canopy closure in the CC reaches was only 12% one year after harvest of trees, but increased to 37% by year 5 and 72% by year 10 in response to growth of shrubs and saplings. Buffers in the BUF and PIP reaches prevented slash input from the adjacent harvest unit. Consequently, wood cover was higher in CC reaches due to logging debris input, but decreased over the post-harvest period.

Soil Disturbance. On average, harvest-related soil disturbance occurred on 6.2% of the area within the 30-foot wide equipment limitation zones (ELZ) in the CC reaches. All BUF and PIP reaches met the performance target (<10% of the ELZ area with soil disturbance) but one of eight CC reaches exceeded the target. The average distance to the stream for erosion features that delivered sediment was 1.0 foot and the maximum was 7.7 feet. Soil disturbance from uprooted trees was twice as frequent in BUF reaches as REF reaches, but the percentage of root-pits with evidence of sediment delivery was greater in the REF reaches (26%) than the BUF reaches (19.8%). Mean horizontal distance to the stream for root-pits that delivered sediment was 8.2 feet compared to 28.0 feet for those that did not deliver.

Effectiveness in Meeting Forest Practices Habitat Conservation Plan Resource Objectives. The unbuffered clear-cut treatment was least effective in meeting the FPHCP resource objectives for shade/temperature and large woody debris/organic inputs, but did meet the soil disturbance performance targets in most cases. Harvest of streamside trees resulted in a large reductions in canopy shade to the stream and substantial input of logging slash. Shade in unbuffered reaches increased over the 10-year post harvest period due to growth of streamside herbs, shrubs and saplings, however research indicates that stream temperatures increase from pre-harvest levels following harvest in unbuffered reaches, and changes persist over time (Ehinger 2017, Klos and Link 2018). There was input of logging slash in unbuffered reaches, but almost no additional post-harvest wood input occurred and cover from woody debris decreased over the ten-year post-harvest period. Modeling studies indicate that clear-cut harvest on typical rotation schedule of 40–50 years will result in a continuous cycle of disturbance and rapid changes in stand structure and shade and long-term reductions in large wood loading due to lack of input from large trees.

The RMZ and PIP buffers were more effective than unbuffered reaches in meeting FPHCP resource objectives, but were not as effective as unharvested reference sites in providing canopy shade and future wood recruitment potential due to removal of trees outside of the buffers. Over the 10-year post-harvest period, there was a substantial reduction in stand density and basal area in RMZ and PIP buffers. On average, canopy shade returned to levels similar to unharvested reference sites by year-10 post-harvest in the RMZ buffers, but not in the PIP buffers. Large wood input during the 10-year post-harvest period was greater in the RMZ and PIP buffers compared to reference sites, but future wood recruitment potential at year 10-post-harvest was lower.

The primary agent of mortality in RMZ and PIP buffers was wind, which affected trees of all sizes. Mortality from wind was a complicating factor in assessing buffer effectiveness. Mortality rates varied in RMZ and PIP buffers, but on average were greater than in reference sites. About one quarter of RMZ buffers and two thirds of PIP buffers had substantial mortality (>5%/year). Wind damage at this level reduced density, canopy shade and future wood recruitment potential, but wind-associated tree fall provided a pulse of large wood input consistent with the large wood resource objective. Over half the fallen trees were uprooted stems with attached rootwads, providing stable pieces that will persist over time (Fox and Bolton 2007). Most fallen trees came to rest suspended or spanning above the channel where they provide cover but will not immediate influence channel conditions and processes. Although the majority of fallen trees were uprooted, sediment input from soil disturbance was limited to trees in close proximity to the channel. Conifer regeneration was observed in sites with elevated mortality, so development of multi-age conifer stands is likely to occur at sites with elevated mortality over time.

Our findings raise several key policy questions for the adaptive management program:

Clear-cut harvest: Is the magnitude of disturbance from clear-cut harvest adjacent to the stream (logging debris input, reduction in and large wood recruitment) consistent with the resource objectives of the FPHCP? Does the proportion of the Type Np stream network subject to clear-cut harvest (≤50%) an appropriate balance between protection of aquatic resources and water quality and economic and operational considerations for forest landowners?

RMZ and PIP buffers. Are the incremental reductions in wood recruitment potential and shade associated with harvest of tree outside the RMZ and PIP buffers consistent with the resource objectives of the FPHCP?

Wind mortality. Is the level of wind damage to RMZ and PIP buffers and the associated wood input and loss of shade consistent with the resource objectives of the FPHCP? Do small patch buffers that are prone to wind damage provide the desired protection for sensitive sites (e.g. PIPs)?

INTRODUCTION

Background

In 2001, new regulations were adopted for timber harvest on Type Np (perennial non-fish-bearing) streams on some state and all private forest lands in Washington State based on recommendations contained in the Forest and Fish Report (USFWS et al. 1999). The Westside Type Np Riparian Prescriptions consist of a suite of treatments that are applied to forest stands adjacent to the Np stream network. A 50-foot no-harvest buffer strip must be left on each side of the stream for at least 50% of the stream length in each Type Np basin, including a minimum of 300 feet immediately upstream of the point where a Type Np stream enters a Type F (fish-bearing) stream. In addition, no-harvest buffers are required around "sensitive sites", including Type Np stream confluences, perennial initiation points (PIPs), seeps and springs. Trees may be harvested to the edge of the stream along the remaining portions of the Type Np stream network as long as soil disturbance is minimized and trees with large root systems embedded in the stream banks are retained (Washington Forest Practices Board 2016, WAC 222-30-030).

The Westside Type Np Riparian Prescriptions are part of the riparian strategy in the Forest Practices Habitat Conservation Plan (FPHCP). The FPHCP was adopted in 2006 to provide protection for aquatic resources including salmonid fish, stream-associated amphibians and water quality while providing opportunities for timber harvest and flexibility in harvest unit design. The measures in the FPHCP riparian strategy are intended to restore and maintain riparian and instream processes that create aquatic habitat, with emphasis on large wood recruitment and shade retention (WDNR 2005).

In mountainous areas of the Pacific Northwest, headwater streams typically consist of steep, narrow channels tightly constrained by adjacent hillslopes and coupled to the terrestrial environment by physical and biological processes (Gomi et al. 2002, Hassan et al. 2005, Richardson and Danehy 2007). Riparian (stream adjacent) forests are the interface between the terrestrial and aquatic ecosystems, and have an important influence on channel morphology and aquatic productivity through input of light, sediment, wood and other organic matter (Gregory et al. 1991, MacDonald and Coe 2007). The closed forest canopy above these narrow channels creates an environment with limited input of solar radiation, strong microclimatic gradients, large inputs of organic matter and low primary productivity (Richardson and Danehy 2007). Shade from riparian forests reduces solar energy input to water and modulates heat exchange, creating a cooler, more stable temperature regime (Dent et al. 2008). However shade limits primary productivity, so the aquatic food web is driven by inputs of organic matter from the riparian forest, including wood, leaf litter and terrestrial insects (Richardson and Danehy 2007). In the absence of debris flows, small channels lack the power to transport large wood so wood accumulates and is retained for long periods, increasing channel roughness and creating structure that provides cover and stores sediment and organic matter (Bilby and Ward 1989, Gomi et al. 2002, Hassan et al. 2005). Wood creates habitat in headwater streams that supports a diverse aquatic community including macroinvertebrates and stream-associated amphibians (Wilkins and Peterson 2000, Meyer et al. 2007), influencing the abundance and composition of invertebrate communities (Bilby and Bisson 1998). Organic matter and nutrients exported from headwater streams contribute to the productivity of downstream habitat (Fisher and Likens 1973, Gomi et al. 2002, Wipfli et al. 2007).

Harvest of trees adjacent to streams can affect input of solar radiation (Gomi et al. 2006a), litter and nutrients (Richardson et al. 2005), and large wood (Gomi et al. 2006b, Pollock and Beechie 2014, Burton et al. 2016). The nature and magnitude of these changes depends on the type and intensity of harvest, site conditions, and weather. Riparian buffers consisting of strips of leave trees adjacent to the stream have been used to reduce the effects of timber harvest by retaining shade, providing a source of wood and organic matter input, and creating a barrier to sediment and slash from adjacent timber harvest uplands (Jackson et al. 2001, Litschert and MacDonald 2009). However, tree mortality can be extensive when buffers are exposed to the wind, resulting in a reduction in shade and trees available for future wood recruitment (Grizzel and Wolff 1998; Grizzel et al. 2000, Liquori 2006, Schuett-Hames et al. 2012).

The Cooperative Monitoring, Evaluation and Research Committee (CMER) determined research was needed to reduce uncertainty about the effectiveness of the FPHCP Type Np riparian strategy. In 2003 CMER initiated the Westside Type N Buffer Characteristics, Integrity and Function (BCIF) study. The purpose of the BCIF study was to reduce scientific uncertainty about the magnitude and duration of changes in stand structure, tree mortality and tree fall, shade, wood recruitment, and soil disturbance following application of the Westside Type Np Riparian Prescriptions under operational conditions. The first phase of the study examined the response over the first five years after harvest (Schuett-Hames et al. 2012). Additional data were collected through year-10 post-harvest. This report summarizes the results of the entire 10 years of post-harvest data collection.

Goals and Critical Questions

The goal of the Westside Type N BCIF study is to evaluate the magnitude and duration of the response of buffer leave trees and riparian functions to harvest under the Westside Type N Riparian Prescriptions, including: change in stand structure and mortality rates in buffer leave trees, ingrowth and regeneration, shade and cover, wood recruitment, and soil disturbance.

Research questions addressed by this study include:

1) What is the magnitude and duration of change in stand structure during the 10-year post-harvest period?
2) What are the magnitudes and rates of tree mortality, ingrowth and regeneration during the 10-year post-harvest period?
3) What are the dominant mortality agents and characteristics of trees that died?
4) What is the magnitude and duration of change in shade (canopy closure) during the 10-year post-harvest period?
5) What are the magnitudes and rates of tree fall and wood recruitment during the 10-year post-harvest period?
6) What is the magnitude of post-harvest soil disturbance associated with timber harvest and were the FPHCP soil disturbance performance standards met?
7) What is the magnitude of post-harvest soil disturbance associated with uprooting of trees during the 10-year post-harvest period?

Experimental Design

This study uses an after-control impact experimental design. This design uses post-harvest data from a randomly selected sample of treatment sites where the Westside Type Np Riparian Prescriptions were applied. These data are compared with data from unharvested reference sites to estimate the magnitude and duration of treatment effects. Data collection occurred at three, five and 10 years post-harvest.

STUDY DESIGN

Treatments

We evaluated three components (treatments) specified in the Washington Forest Practices Rules for Westside Type Np waters (Washington Forest Practices Board 2016, WAC 222-30-021). The rules specify two riparian management zone (RMZ) treatments applied to areas adjacent to Type Np streams. A 50-foot no-harvest buffer (BUF treatment) is required on a minimum of 50% of the Type Np stream network, including a minimum of 300 feet immediately upstream of the outlet to fish-bearing waters. Clear-cut harvest to the edge of the channel (CC treatment) is allowed on the remainder of the Type Np stream network, with a 30-foot wide equipment limitation zone (ELZ) to minimize soil disturbance. Buffers are also required on designated sensitive sites. The most commonly occurring sensitive site buffer is a 56-foot radius no-harvest buffer centered on each perennial initiation point (PIP), referred to as the uppermost point of perennial flow (PIP treatment). These three treatments (BUF, CC, and PIP) were compared against reference sites (REF).

Study Sites

Treatment sites were randomly selected from Forest Practice Applications (FPAs) approved by the Washington Department of Natural Resources (WDNR) for timber harvest on non-fish-bearing, perennial (Type Np) streams in western Washington. Potential sites were identified by querying the WDNR Forest Practice Application Review System (FPARS) database to produce a list of FPAs approved between November 2002 (the inception date of the system) and May 15, 2003. The FPAs were sorted to select FPAs with activity within 200 feet of a stream. FPAs meeting these criteria were assigned a random number used to determine the order in which they were screened for inclusion in the study. To be selected, harvest units had to include both sides of the Type Np stream for a minimum of 300 feet without a stream adjacent road. FPAs meeting these criteria were screened to determine whether they were in the western hemlock forest zone using a GIS layer of forest zones based on Cassidy et al. (1997). When an FPA had more than one suitable Type Np stream, one was randomly selected. Landowners were contacted to determine if harvest would be completed prior to the first post-harvest sampling event (fall 2003), and sites were visited to verify that the stream existed, the prescriptions were applied according to the rules, and the site selection criteria were met. After each treatment site was accepted for inclusion in the study, a search was conducted to find an unharvested reference site in close proximity with similar stand and stream characteristics to the treatment site and a similar length. Reference sites were at least 100 feet from adjacent harvest units and roads, and were not scheduled for harvest for at least five years. We assumed the minimum buffer between the reference stands and adjacent harvest areas would minimize impacts from factors such as wind. It was difficult to find reference sites with harvest-age timber not scheduled for harvest in the next five years. Three treatment sites were paired with reference sites located on the same stream; in other cases the reference site was located as close to the treatment site as possible.

The fifteen treatment sites contained a mixture of treatments allowed under the Westside Type Np Riparian Prescriptions (Table 1), but harvest units did not typically include entire Np streams from the Type F break to the PIP. Thirteen sites included RMZs with 50-foot buffers, eight included clear-cut RMZs and three had PIP buffers.

Table 1. Distribution of prescription treatments among sites.

Site	Treatment				Notes
	50-foot Buffer (BUF)	PIP	Clear-cut (CC)	Reference (REF)	
13	✓			✓	2
23	✓			✓	2
24	✓	✓	✓	✓	2
27	✓		✓	✓	2
29	✓			✓	
31		✓	✓	✓	
36	✓			✓	
37	✓			✓	2
38	✓		✓	✓	
40	✓			✓	1
47	✓		✓		5
50	✓		✓	✓	1
56	✓		✓	✓	3
62		✓	✓	✓	
64	✓			✓	1,4
Total	13	3	8	14	

[1] Sites where the reference and treatment patches were located on the same stream.
[2] Reference site harvested prior to year 10 survey
[3] No access to treatment or reference sites for year 3 survey
[4] No access to treatment site for year 10 survey
[5] Reference site harvested prior to year 3 survey

Seven sites were located in the Willapa Hills, two in the southern Cascade Mountains, two in the southern Olympic Mountains, and one each in the Black Hills, Puget Lowlands, north Cascades and eastern Olympics (Figure 1). Appendix Table 1 shows characteristics of the study sites.

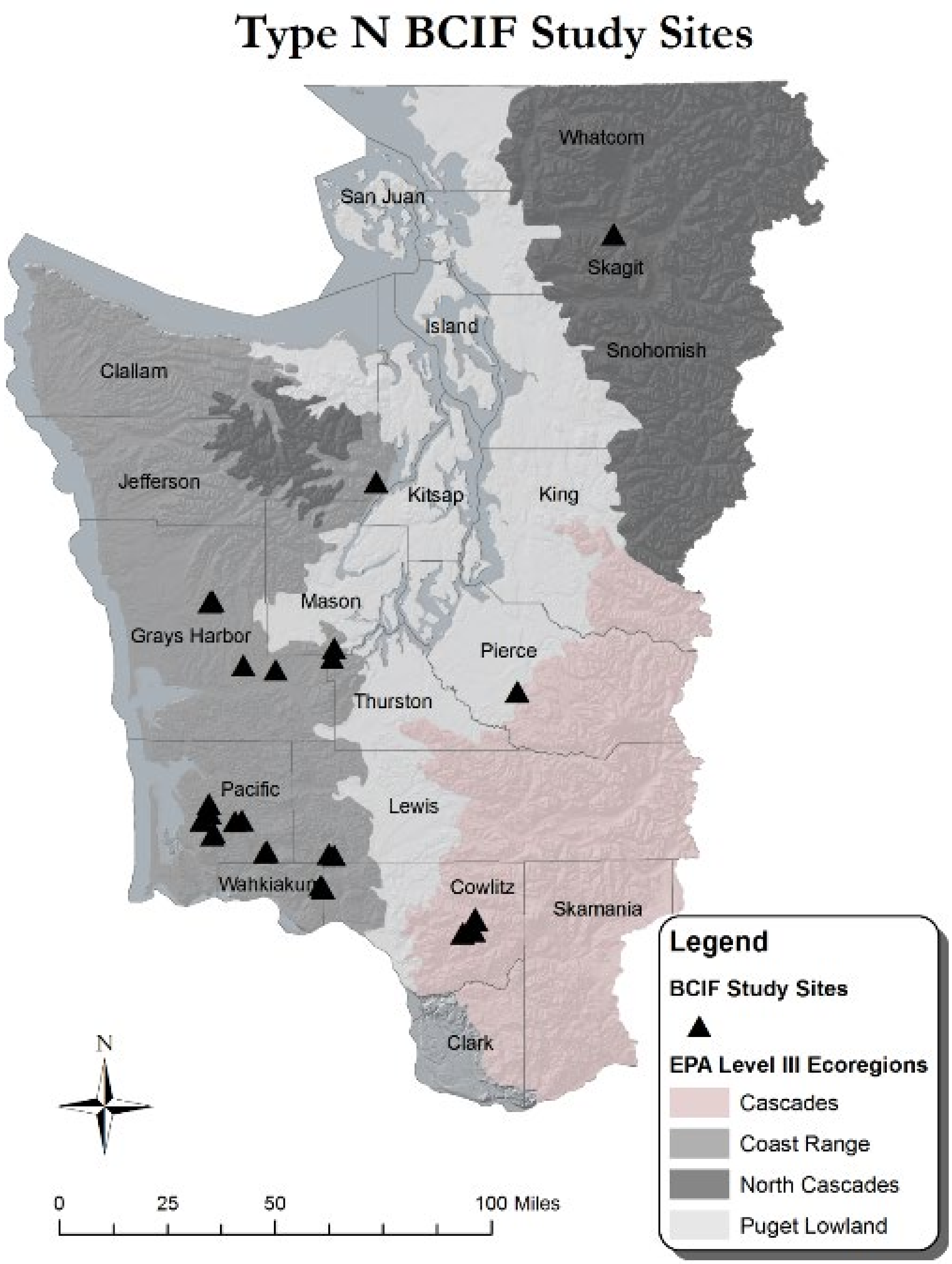

Figure 1. Westside Type N BCIF study site locations in western Washington.

Sites were randomly selected to provide an unbiased estimate of variability associated with the prescriptions applied in an operational setting. Selection of treatment sites in this manner precluded collection of pre-harvest data because in many cases the harvest operation began shortly after approval of the FPA.

Climate

The maritime climate of western Washington is affected by its position on the windward coast of the neighboring North Pacific Ocean. The prevailing westerly mid-latitude jet stream results in predominately onshore airflow which moderates summer and winter air temperatures. The prevailing high pressure system in the northern Pacific during the summer months produces a northwesterly airflow, resulting in predominately cool, dry weather. During the fall and winter months, the Aleutian low pressure center moves south, producing a southwesterly airflow that brings a series of cyclonic low pressure storm systems from the northern Pacific into western Washington. These cool, wet storm systems interact with the Olympic Mountains and Willapa Hills near the coast and the Cascade Mountains farther inland to produce heavy rainfall in the lower elevations and extensive snowfall at the higher elevations during the winter months (Western Regional Climate Center 2017). Annual precipitation for western Washington was within +/-30% of normal values during the study period. Drier conditions (70−90% of normal) prevailed in western Washington during 2004−5, 2008, and 2013, while wetter condition (110−130% of normal) were widespread in 2006 and 2012 (PRISM Climate Group 2017). Maximum temperatures tended to be higher than normal (+1−3 °F) during the early years of the study (2003−2006). This was followed by a cooler than normal (-1−3 °F) period in 2007−2008, a neutral period in 2009−2010, and another cooler than normal period from 2011−2012 (PRISM Climate Group 2017). The periods with cooler temperatures coincided with occurrence of ENSO La Niña events in the eastern Pacific (NOAA Earth Systems Research Laboratory 2017).

Cyclonic weather systems arriving from the North Pacific Ocean during the winter months often produce strong winds, particularly in exposed areas adjacent to the coast or in mountainous terrain. The frequency and magnitude of wind storms during the study were evaluated by examining records from four weather stations located near the study sites (Table 2). Peak wind-speed records from these weather stations provide an indication of the frequency and magnitude of major wind storms with storm-force or hurricane-force winds that passed through the area during the study period. The weather stations are located in the lowlands, while many study sites are located in mountainous terrain, so the actual peak wind-speeds experienced by the study sites are unknown. Also, peak wind-speed does not address the duration of high winds or soil moisture, which affects the capacity of wind storms to impact riparian buffers.

Table 2. Days with storm- or hurricane-force winds at weather stations near the study sites, by sampling period (NOAA National Centers for Environmental Information 2017).

Station	Harvest−Year 3	Year 3−5	Year 5−10	Harvest−year 10
Days with storm-force winds (55−73 mph)				
Astoria Regional Airport	6	9	20	35
Hoquiam/Bowerman Airport	4	10	21	35
Olympia Airport	0	0	1	1
Portland Int. Airport	0	0	1	1
Total days	10	19	43	72
Days with Hurricane-force (≥74 mph)				
Astoria Regional Airport	0	2	2	4
Hoquiam/Bowerman Airport	0	1	0	1
Total days	0	3	2	5
Combined total days	10	22	45	77
Combined days/year	3.3	11.0	9.0	7.7

Wind speeds ≥55 mph were recorded on 77 days at the four weather stations during the 10-year study period, including 72 days with storm-force winds (55−73 mph) and five days with hurricane-force winds (≥74 mph). Strong winds occurred most frequently at the coastal stations (Astoria and Hoquiam), including all hurricane-force days and 70 of 72 storm-force days. Days with strong winds were less frequent during the initial three years of the study compared to year 3−5 and year 5−10 periods (3.3, 11.0, and 7.7 days/year, respectively). The most notable storm occurred on December 2−3, 2007. This storm produced hurricane-force winds along the Washington coast that resulted in extensive wind damage and intense precipitation further inland, resulting in unprecedented flooding in the Chehalis Valley and eastern Willapa Hills.

Methods

Data Collection

Surveys were conducted in the summer at three, five and ten years post-harvest. We could not sample all sites at each date because five reference sites were harvested prior to the year-10 post-harvest survey and access was denied for one treatment and reference site in year three and another treatment site in year ten (Table 3).

Table 3. Sample size by treatment and survey.

Survey Year	REF	BUF	PIP	CC
YR3	13	12	3	7
YR5	14	13	3	8
YR10	9	12	3	8

A census was done of all standing trees >4 inches diameter at breast height (DBH) within 50 feet of the stream (REF, BUF and CC reaches) and within the 56-foot radius PIP buffers at each survey. The condition (live or dead), species, and DBH were recorded for all trees. The canopy class (overstory, understory, or no competition) was recorded for live trees. Decay class was recorded for all dead trees (Table 4) and a mortality agent was recorded for newly dead trees (e.g. wind, erosion, suppression, fire, insects, disease, and physical damage). Data on tree regeneration were collected at circular understory vegetation plots arrayed on two transects oriented perpendicular to the azimuth of the stream valley. Transects were located at randomly selected locations along the stream in each reach. There were six plots on each transect, three on each side of the stream. The plots were centered on each transect at horizontal distances of 10, 25 and 40 feet from the bankfull channel. Each understory vegetation plot had a radius of 3.72 horizontal feet with an area of 1/1000 acre. Seedlings (trees ≥6 inches high and <1 inch DBH) and saplings (trees 1−4 inches DBH) were tallied by species. Data were taken on factors potentially affecting regeneration success including the percentage of understory vegetation cover, dominant understory vegetation species and percentage of woody debris cover.

Table 4. Decay class categories (from Martin and Benda 2001).

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)

Fallen tree data were collected on trees knocked down or toppled over during the post-harvest period. We defined fallen trees as trees previously standing within the plot boundaries that fell since the last survey. Fallen trees were tagged and painted so that data were collected only once, the first time it was observed. Fallen trees were classified as uprooted trees that toppled over with the roots still attached or broken trees that were sheared off along the stem where the broken portion had a diameter ≥4 inches at the large end. If the base of a broken tree remained standing and was ≥4.5 feet high, it was treated as a standing tree and the broken upper portion was treated as a fallen top (if large enough to qualify). Data were taken on the condition (live/dead), species, DBH, fall azimuth, horizontal distance from stream, recruitment class (upslope, spanning, suspended, or bankfull), and the process that caused tree fall. We recorded the number of trees that recruited to the stream (reached the edge of the bankfull channel) and their diameter at the bankfull channel edge.

We collected data on recruited wood, the portions of uprooted trees or broken stems originating from trees that fell into or over the bankfull channel during the study period. We collected data only for trees that fell since the previous visit, so each was counted only once. The recruited wood from fallen trees had to be ≥4 inches in diameter and intrude into or over the channel for a minimum of 1.6 feet, consistent with the minimum criteria for wood in headwater streams in Gomi et al. (2001). Data included piece type (with or without attached rootwad), recruitment class (within the bankfull channel, spanning the bankfull channel, suspended above the bankfull channel). Measurements were taken only on the portion of the fallen tree that intruding into or over the channel. Length and mid-point diameters were recorded for each of two zones, within the bankfull channel and above the bankfull channel. The in-channel functions provided by each recruited piece were noted, including pool formation, step formation, sediment retention or formation of a functional debris jam. The percentage of the bankfull channel surface area covered by woody debris was visually estimated at transects across the bankfull channel located at 50-foot intervals along the stream.

Shade data were taken at a series of measurement stations systematically located along the channel from a random starting point. We attempted to obtain ten measurements in each treatment reach; however the number of stations varied due to reach length and accessibility. Shade from overhead cover as percent canopy closure was measured with a densiometer held at waist height (3.5 feet) using methods described in Pleus and Schuett-Hames (1998). Four measurements were taken from the center of the bankfull channel at each station, one each facing upstream, towards the left bank, downstream and towards the right bank. Although this measurement is commonly referred to as "canopy closure", it measures obstruction of the view to the sky from any cover object above the height of the instrument, including trees, high shrubs and fallen trees. At each station, the factor providing the majority of cover was noted. Shade from understory plant cover immediately above the channel was documented by estimating the percentage of the bankfull channel surface area obscured from view by low-growing plants less than 3.5 feet above the water surface in a section of the bankfull channel extending two feet upstream and downstream of each shade measurement station.

Data on soil disturbance associated with timber harvest activities were collected at treatment sites in the first year following timber harvest. A complete inventory was made of harvest-related stream-bank erosion and soil disturbance features within 30 feet of the channel edge. The inventory was conducted by a two person crew, one person walking on each side of the stream. Soil erosion features (areas of bare exposed soil) were evaluated to determine if two criteria were met: 1) surface area greater than 10 ft^2; and 2) feature caused by harvest practices (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. Data were collected on soil disturbance associated with each new (post-harvest) root-pit observed within 50 feet of the stream channel. The horizontal distance to the stream channel recorded and evidence of sediment delivery to the stream channel from the disturbance feature (pit and associated mound) was noted.

Data Analysis

Metrics

Stand structural metrics for live trees including density (trees/acre), basal area (ft^2/acre), quadratic mean diameter (QMD), the square root of the sum of the square of the diameters of all the trees divided by the number of trees (Curtis and Marshall 2000) and relative density (Curtis 1982) were calculated using census data for each site. Means for the REF, BUF, PIP and CC treatments were obtained by averaging the site values for each treatment group. Similar calculations were done for dead tree density, basal area and mean diameter. Metrics were calculated at four points in time: immediately post-harvest (IPH), and years three (YR3), five (YR5) and ten (YR10) post-harvest. We reconstructed immediate post-harvest (IPH) stand structure using decay class data. Decay classes 1 and 2 (Table 5) were used to identify post-harvest dead and fallen trees (Martin and Benda 2001, Hennon et al. 2002, Martin and Shelly 2017). Cumulative proportional change in live stem count and basal area (initial value minus the final value/initial value) and cumulative mortality as a percentage of initial live density and basal area that died (excluding ingrowth) were calculated for the IPH-YR5 and IPH-YR10 periods. The annualized rates of change and tree mortality were calculated for the IPH-YR5 and IPH-YR10 periods using the compounding formula of Sheil et al. (1995). Cumulative ingrowth in trees/acre during the IPH-YR5 and IPH-YR10 periods was the total count of new trees reaching the four inch DBH threshold during each period divided by the area of the RMZ or PIP, and the annual ingrowth rate was the cumulative total divided by the number of years. The proportion of regeneration plots with tree regeneration (seedlings or saplings were present) was calculated separately for all trees and for conifers as the percentage of regeneration plots where regeneration was present at the IPH, YR3, YR5 and YR10 surveys.

Cumulative tree fall/acre was calculated separately for recruiting fallen trees, i.e. the subset of fallen trees that fell into or over the channel, by summing the counts for the IPH-YR5 and IPH-YR10 periods and dividing by the area in acres. Tree fall/100 feet of reach length was calculated by dividing the total count by the reach length in feet and multiplying by 100. Annual rates were calculated for the IPH-YR5 and YR5-YR10 periods by dividing the cumulative total by the number of years. Recruited fallen trees pieces were sorted by recruitment classes to determine the proportion that intruded into versus over the channel. To create a source distance curve, recruiting fallen trees were grouped according to their original rooting location in five-foot intervals (0–5 feet, 5–10 feet, etc.) and the count for each interval was divided by the total count to calculate the proportion coming from each interval. To estimate the proportion of recruiting fallen trees that were uprooted vs. broken above the ground for each treatment group, trees were sorted by fall type and the count was divided by the total. The percentage of trees that died was calculated by tallying trees that died and dividing by the initial live tree count for each species.

Since fallen trees often break into multiple pieces, the number of fallen tree pieces 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 piece was estimated using the formula (*volume in feet^3: π* midpoint radius^2*piece length*). Cumulative recruited piece count and volume per 100 feet was calculated by summing the recruited pieces and volume for the IPH-YR5 and IPH-YR10 periods, 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 pieces consisting of stems with attached rootwads (SWAR). The mean percentage of the bankfull channel surface area obscured by wood of any size, both above and within the bankfull channel, was calculated by averaging the values from the stations in each reach for each post-harvest survey (Jackson et al. 2001).

Percent canopy closure was calculated for each shade measurement station by averaging the four readings (upstream, downstream, left bank, right bank) and multiplying by 1.04 (Pleus and Schuett-Hames 1998). The mean percentages of canopy closure and cover from understory plants was the average of the values for all stations within the reach.

We tallied the number of uprooted trees with evidence of sediment delivery to the channel and divided by the total number of uprooted trees to get the proportion of root-pits with sediment delivery. To create a source distance curve for root-pits that delivered sediment for each treatment group, recruiting fallen trees were sorted into distance from stream categories at five-foot intervals (0–5 feet, 5–10 feet, etc.) and the count for each interval was divided by the total count to calculate the proportion coming from each interval. The total number of harvest-related soil disturbance features per 100 feet of stream length was calculated by tallying all features within 30 feet of the stream (the regulatory equipment limitation zone), dividing by the stream length, and multiplying by 100. A similar calculation was done for the sub-set of soil disturbance features that delivered sediment. The surface area of each harvest-related soil disturbance feature was calculated by multiplying the mean width by the length. The percentage of the equipment limitation zone (ELZ) with soil disturbance was calculated by summing the areas of the individual features and dividing by the total ELZ area. Reaches with over 10% soil disturbance exceed the performance target. The percentage of reaches exceeding the performance target was calculated by dividing the number that exceed the target by the total number for each treatment type.

Analysis

Data were processed using queries in a Microsoft Access database. JMP 13 software was used to generate descriptive statistics (e.g. mean, median, standard deviation and standard error) for data grouped by treatment and regulatory zone, and to create box plots showing the distribution of the data.

For the statistical analysis comparing treatments, we used mixed models to estimate means and standard errors (Table 5). Mixed models allow us to calculate treatment contrasts using population means estimated for each treatment within a single model. Mixed models account for missing data as long as the data are randomly missing, as in this dataset. Mixed model analyses were performed in R 3.40 (Core Team 2017) using the lme4 package (Bates et al. 2015) and SAS/STAT software version 9.3 copyright © 2002−2012 by the SAS Institute Inc. 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 5). 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. We used alpha = 0.1 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 produced 5 DDF and may be slightly conservative compared with KR DDF. In each model, the treatments (i.e. BUF, CC and REF) were treated as fixed effect categorical predictors and the site identifier was treated as a random effect or subject. The PIP buffer treatment was not included in the statistical analyses due to the small sample size (n = 3).

Table 5. Mixed model properties.

Response Variable	**Model Type**	**Distribution/Link**	**Contrast DDF**
Live tree basal area/acre (BAPA)*	LMM	Gaussian/Identity	19.2−27.5
Proportion of plots with regeneration	LMM	Gaussian/Identity	19.7–31.5
% Canopy closure	LMM	Gaussian/Identity	19.2−32.3
% Change in live BAPA*	LMM	Gaussian/Identity	8.5−29.1
% Mortality in BAPA*	GLMM	Binomial/Logit	5
Wood recruitment piece count	GLMM	Poisson/Log	5

* Pairwise contrasts were performed on BAPA, but not trees/acre to reduce the overall number of comparisons.

RESULTS

Stand Structure

Immediate post-harvest (IPH) stand structure varied among treatments (Figure 2, Appendix Table 2). Mean density and basal area were greater in REF stands than in (BUF) stands by ~85 trees/ac and ~35 ft^2 of basal area. Consequently, mean relative density was greater in the REF stands, while quadratic mean diameter (QMD) was greater in the BUF stands. The differences in live basal area were significant ($p < 0.05$) for contrast among the REF, BUF and CC treatment groups at the IPH survey. Harvest was not allowed within the buffers and little harvest-related disturbance was observed, except for a few trees in a logging corridor at one BUF site, so differences in IPH stand structure reflected pre-existing differences among the treatment groups. Mean basal area and relative density in the PIP buffers were greater than at either the REF or BUF sites. IPH basal area was very low in the unbuffered CC sites due to harvest of nearly all trees. The majority of stands were dominated by conifers for all treatments. The median percentage of conifer basal area in the PIPs was over 97%. There was greater variability in composition in the REF and BUF groups, where the percentage of conifer ranged from 100% to less than 50% by sites with median values from 80−85%.

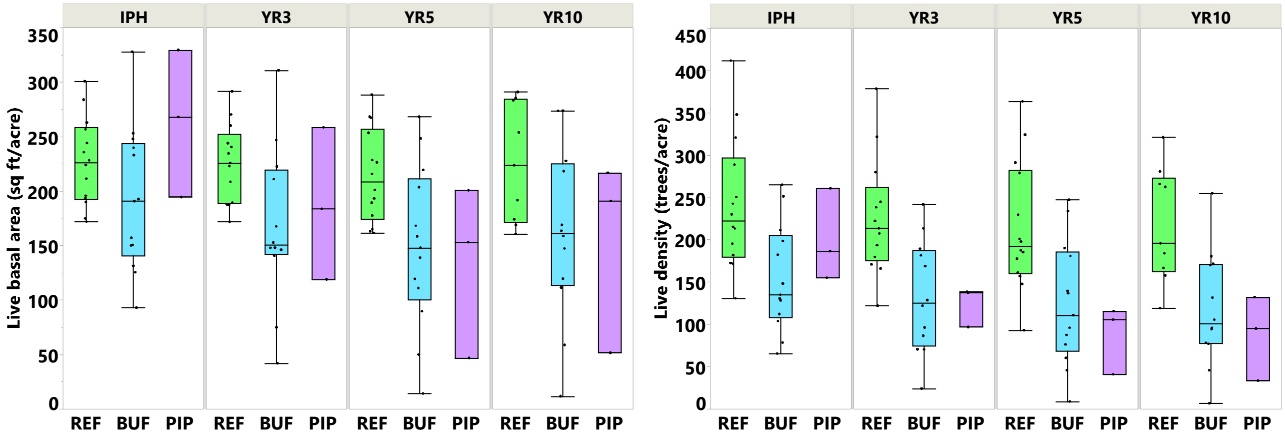

Figure 2. Live basal area (left panel) and density (right panel) by treatment: immediately post-harvest (IPH), and year three (YR3), year five (YR5) and year ten (YR10).

Mean density, basal area and relative density decreased in the BUF and PIP groups over the 10-year post-harvest period, while basal area increased in the REF group (Appendix Table A-2). The annual rate of change was negative for both density and basal area in all three treatment groups during the first five years after harvest (Figure 3, Appendix Table 3). The cumulative percent decrease in basal area in the PIP and BUF groups over the IPH-YR5 period was over 4 and 8 times greater than in the REF group, respectively, and the REF-BUF contrast for mixed-model estimates of percent change in live basal area over the IPH-YR5 period was significant (p = 0.026). During the second five years (YR5-YR10) there was an increase in basal area for all treatment groups and the REF-BUF contrasts for percent change in live basal area over the YR5-YR10 period were no longer significant (Appendix Table 4). The cumulative change in basal area over the entire 10-year period (IPH-YR10) was slightly positive for the REF group, but remained negative for the BUF and PIP groups at -14 and -39% respectively The change in density remained negative for all treatment groups, at -20% for the REF and BUF groups, and -50% for the PIP group.

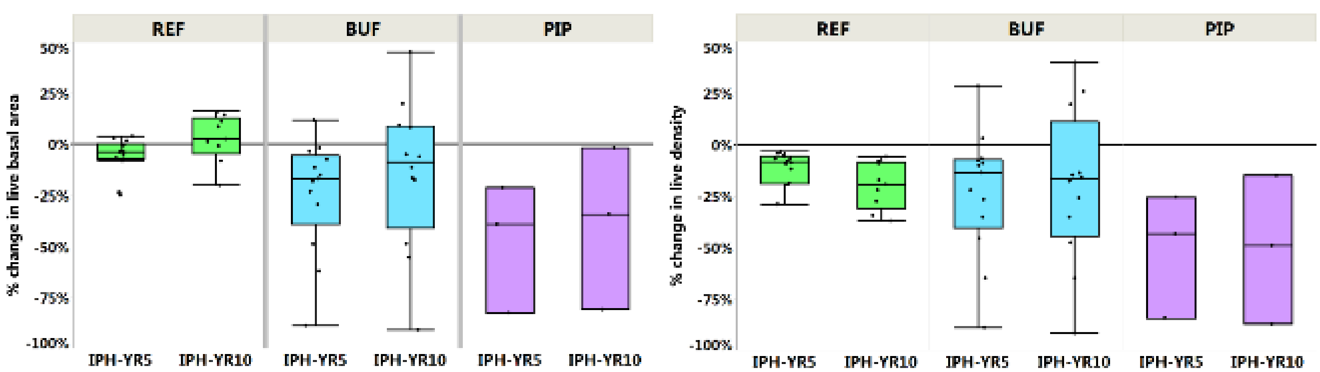

Figure 3. Cumulative percent change in initial IPH live basal area (left panel) and density (right panel) over the IPH-YR5 and IPH-YR10 periods by treatment.

Ingrowth and Mortality

Tree mortality was the major agent of change in stand structure during the post-harvest period. Change in live stand density is determined by the ratio of mortality and ingrowth (the addition of new young trees that reached the four inch DBH threshold during each post-harvest period). Over the 10-year post-harvest period, mortality was greater than ingrowth for all treatments, reducing live stand density (Figure 4, right panel). The reduction in basal area was greater, because the diameter of ingrowth trees is small compared to the diameter of mortality trees (Figure 4, left panel). Over the entire 10-year period, cumulative ingrowth was greater in the BUF group than in the in the REF, PIP or CC groups (Appendix Table 3). Little ingrowth occurred in the CC stands because the trees planted following harvest had not reached the 4-inch minimum diameter threshold by YR10.

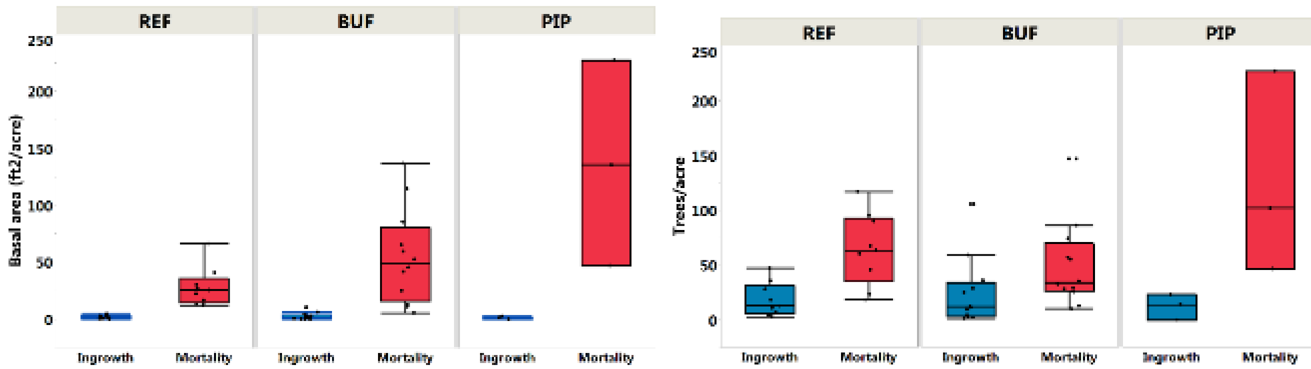

Figure 4. Cumulative ingrowth and mortality by basal area (left panel) and density (right panel) over the 10-year post-harvest period by treatment.

Mean annual tree mortality rates varied among treatments (Appendix Table 3). Annual mortality during the first five years after harvest was highest in the BUF and PIP groups. The annual morality rate for the BUF and PIP groups as a percentage of live basal area was 4 and 7 times the REF rate respectively. The mortality rate decreased sharply after YR5 to <2%/year over the YR5-YR10 period in all treatment groups.

The REF-BUF contrast for cumulative mortality as a percentage of live basal area was significant during the first five years after harvest (p <0.001) and remained significant over the entire 10-year post harvest period (p = 0.002). Mean cumulative mortality as a percentage of initial live basal area over the ten-year post-harvest period was 14%, 31% and 50% in the REF, BUF and PIP groups, respectively, or 2.2 (BUF) and 3.6 (PIP) times greater than in the REF group (Appendix Table 3). There was extensive variation in cumulative tree mortality at the plot-scale over the 10-year post-harvest period, with the greatest range of values in the BUF and PIP groups (Figure 5).

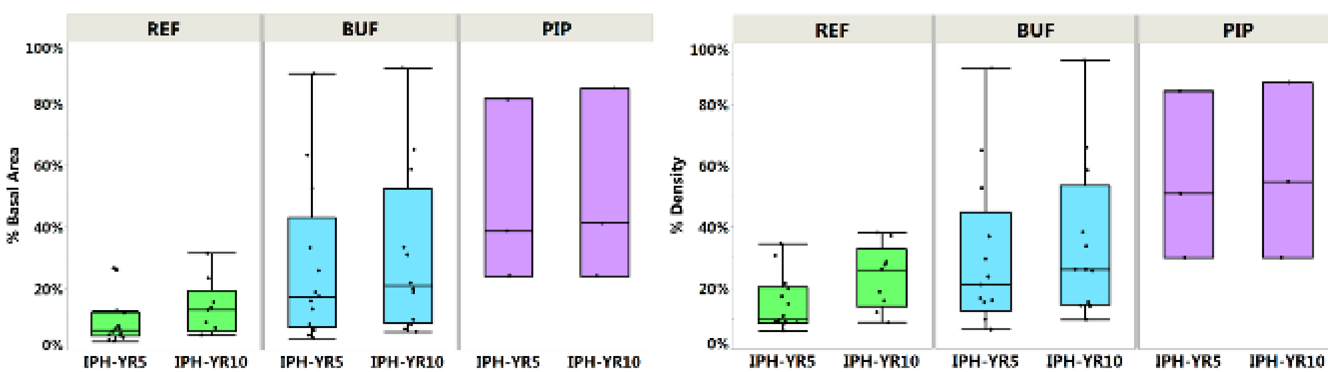

Figure 5. Cumulative post-harvest mortality as a percentage of initial live stem density (left panel) and basal area (right panel) by treatment during the 10-year post-harvest period.

The most frequent source of tree mortality in the BUF and PIP stands during the 10-year post-harvest period was wind and physical damage (typically due to being struck by a falling tree), which accounted for 68% and 94% of mortality by stem count, respectively. Mortality due to yarding through the buffer was observed at one BUF site. In contrast, other mortality agents were the dominant causes of mortality in the REF group (61% by count). Much of the unspecified mortality was likely due to suppression as indicated by the smaller mean DBH of mortality trees (Table 6).

Table 6. Proportion of tree mortality by mortality agent and treatment.

Mortality Agent	% by stem count			% by basal area			Mean diameter		
	REF	**BUF**	**PIP**	**REF**	**BUF**	**PIP**	**REF**	**BUF**	PIP
Wind/physical damage	39.5	67.6	94.0	58.2	73.5	95.3	10.6	13.0	13.4
Other	60.5	32.4	6.0	41.8	26.5	4.7	7.1	11.3	12.1

The percentage of live trees that died during the 10-year post-harvest period varied by species. The proportion of trees that died was greatest (~70%) for the "other broadleaf" category (e.g. cascara or bitter cherry), was >30% by stem count for Pacific silver fir and western hemlock and <30% for all other species (Figure 6).

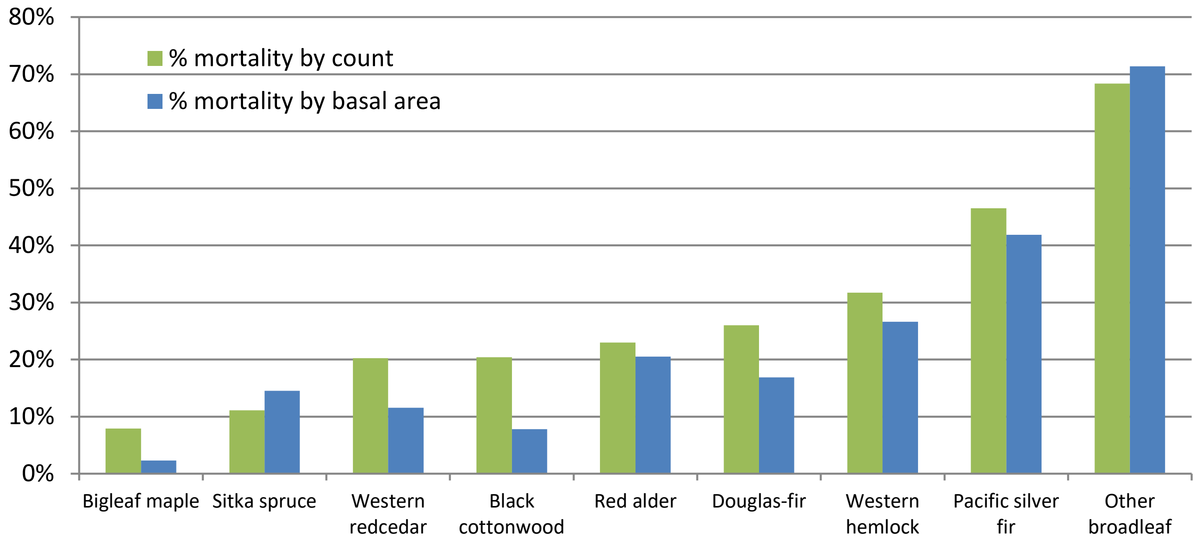

Figure 6. Proportion of live trees that died during the 10-year post-harvest period by species.

The majority of mortality trees were conifers, primarily western hemlock and Douglas-fir. Conifers comprised ~ 80% of REF and BUF mortality trees, and over 94% of PIP mortality trees.

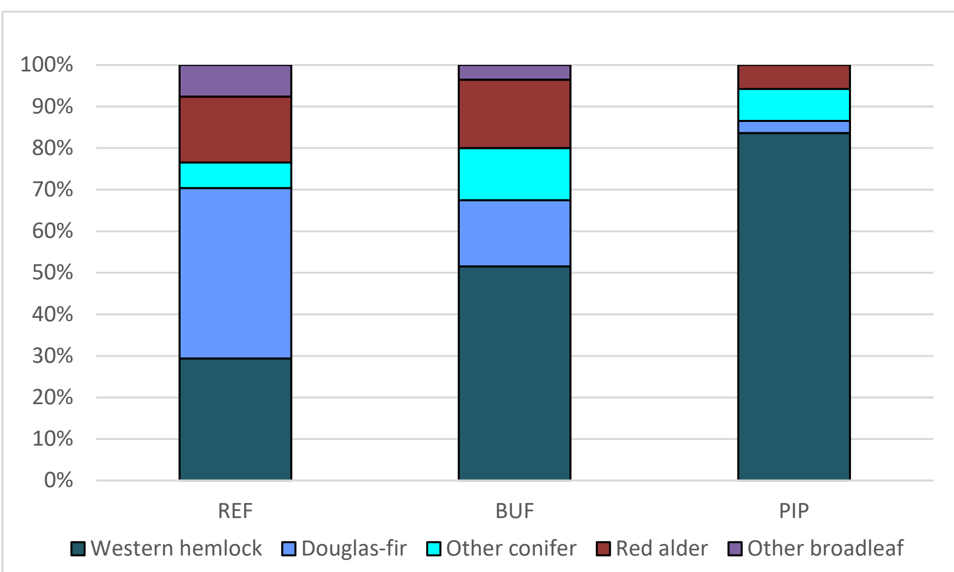

Figure 7. Percentage of mortality trees by treatment and species.

Regeneration

Regeneration includes both seedlings (trees ≥6 inches high and <1 inch and saplings (trees 1−4 inches DBH) of both broadleaf and conifer tree species. Natural seeding was the source of regeneration in the REF, BUF and PIP stands, while regeneration in the CC sites included both natural regeneration and seedlings planted to meet the reforestation requirements of the Forest Practices rules. Immediately after harvest, the mean percentage of plots with tree regeneration was similar in the REF, BUF and CC stands (12−17% of plots) and higher in the PIP stands (28% of plots). The percentage of REF plots with tree regeneration remained relatively stable over the 10-year post-harvest period, while increasing to 41% for the CC group, 42% for the BUF group and 56% for the PIP group (Appendix Table 3). At the YR3 survey, the REF−CC and BUF−CC contrasts were significantly different in response to the increased regeneration in the CC sites (p=<0.001 and 0.023, respectively). At YR5 and YR10, only the BUF and CC contrasts with the REF group were significant (p = 0.02) due to greater regeneration in the BUF and CC sites (Appendix Table 4).

Regeneration of conifers, excluding broadleaf species, remained stable at 8−12% for the REF group, while increasing from 5−30% for the BUF group over the 10-year post-harvest period. The percentage plots with conifer regeneration also increased in the PIP and CC groups, from 28−56% and 15−33% respectively by YR10 (Appendix Table 3, Figure 8.

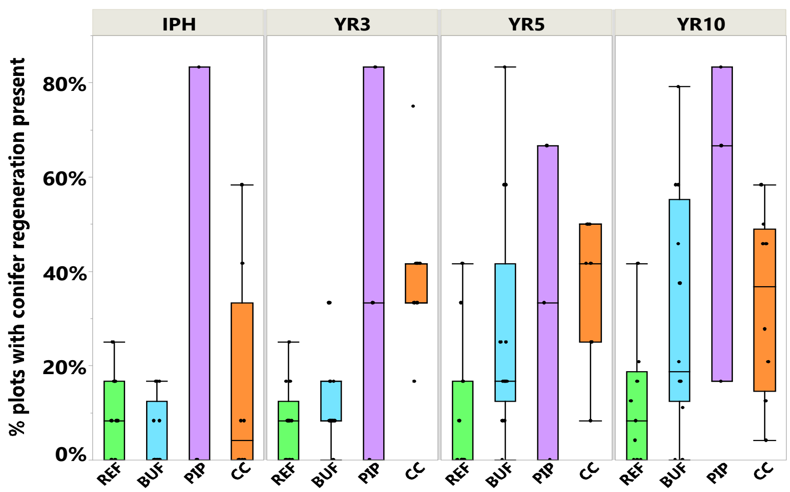

Figure 8. Percentage of plots with conifer regeneration by treatment immediately post-harvest (IPH), and at year three (YR3), five (YR5) and ten (YR10) post-harvest.

Tree regeneration and disturbance

We examined the relationship between mortality and natural conifer regeneration by correlating mean site values for the percentage of plots with conifer regeneration at YR10 with IPH−YR10 mortality rates as the percentage of stems/year (Figure 9). For the combined BUF and PIP sites, there was a positive relationship (R^2 = 0.53) between regeneration (% of plots with conifer regeneration) and mortality rates (percentage of stems/year). For sites with mortality rates of <5%/year, regeneration was highly variable, ranging from 0−60% of plots with a mean of 15.7%. The percentage of plots with regeneration was greater for sites with mortality rates >5%/year, ranging from 45−85% with a mean of 66.7%.

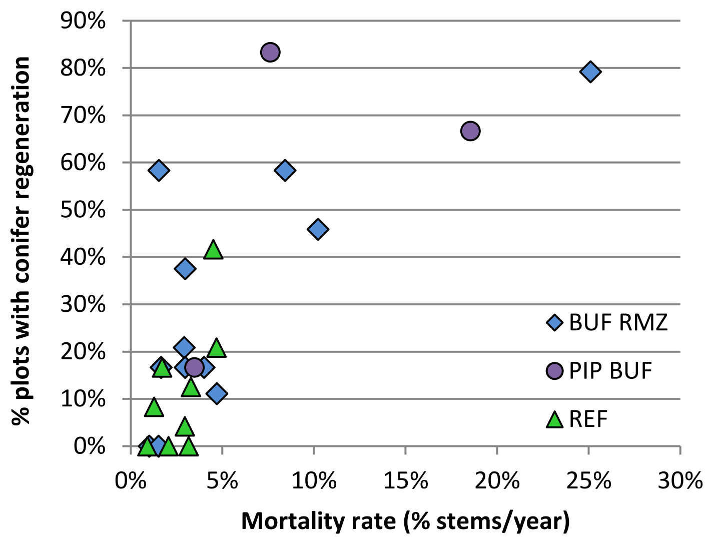

Figure 9. Percentage of plots with conifer regeneration versus tree mortality rate in % stem/year by treatment.

Tree Fall and Wood Recruitment

The rate of recruiting fallen trees (those that reached the channel) for the BUF and PIP groups were highest in the first five years after harvest, double and triple the REF rate, respectively. The recruitment rates for fallen trees and in the BUF and PIP groups decreased sharply after YR5 and were lower than the REF rates in the YR5-YR10 period. Consequently, mean cumulative recruitment of fallen trees was greater in the BUF and PIP groups compared to the REF group in the IPH-YR5 period, however over the entire IPH-YR10 period the rates were similar in the REF and BUF groups while the PIP value was 1.5 times greater (Figure 10; Appendix Table 5). Over two thirds of trees that recruited to the channel were uprooted versus stems broken above the ground, and most (69–86%) came to rest either suspended over or spanning across the bankfull channel (Appendix Table 5). The mean percentage of standing trees that recruited to the channel over the 10-year period in the BUF and PIP groups was >16%; nearly twice the proportion in the REF group (8.4%).

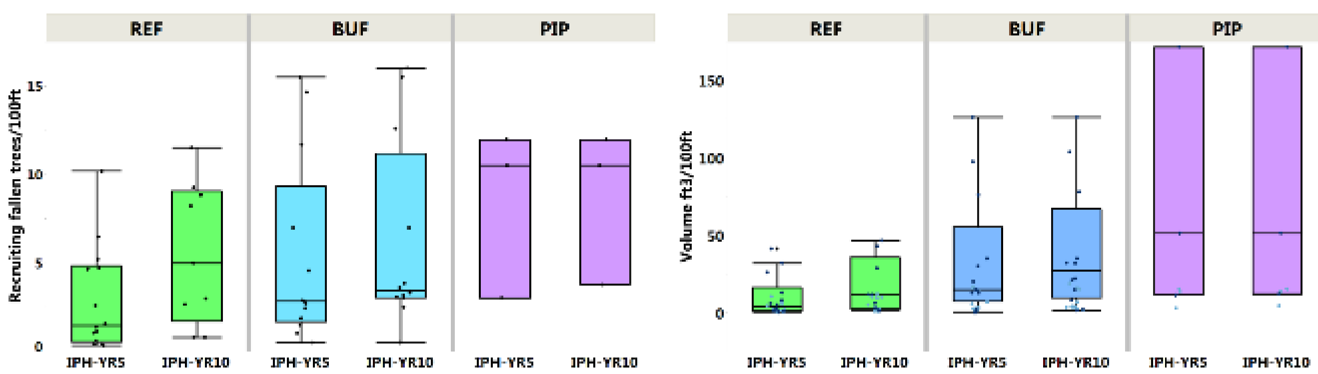

Figure 10. Cumulative IPH-YR10 recruited fallen trees per 100 feet of stream length (left panel) and recruited wood volume per 100 feet of stream length (right panel) by treatment.

The spatial pattern of fallen trees recruiting to the channel within the 50-foot wide RMZs differed between the BUF and REF stands. The proportion of recruited fallen trees that originated within 30 feet was higher for the REF group than the BUF group, while the proportion of recruiting trees originating between 30 and 50 feet was greater in the BUF group (Figure 11).

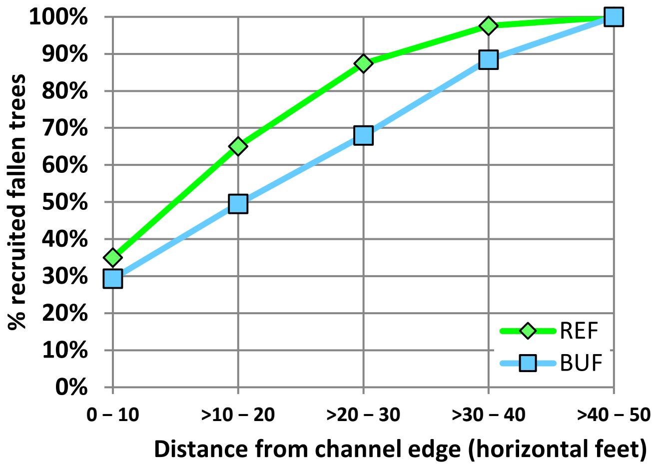

Figure 11. Source distances for recruited fallen trees for the REF and BUF groups.

The recruitment rates for total wood pieces and total volume of wood from fallen trees in the BUF and PIP groups were greatest in the IPH-YR5 period and decreased sharply after YR5 (Appendix Table 5). In the IPH-YR5 period, recruitment rates in the BUF and PIP groups were 2 and 3.5 times the REF rate for piece counts, and 3 and 7 times the REF rate for volume. While the REF rates were greater than the BUF and PIP rates in the YR5-YR10 period, the rates were much lower. Consequently, cumulative recruitment of wood pieces and volume was greater in the BUF and PIP groups than in the REF group over 10-year post-harvest period, but the differences diminished over time. The REF-BUF difference total wood pieces was significant in both the IPH-YR5 and IPH-YR10 periods ($p < 0.001$ and 0.057, respectively). There was little post-harvest wood recruitment from the CC group, and the REF-CC and BUF-CC contrasts were significantly different for both the IPH-YR5 and IPH-YR10 periods ($p < 0.001$).

The majority of the wood pieces recruited to the channel from fallen trees consisted of stems with attached rootwads (SWAR). In the REF and BUF groups, SWAR pieces comprised 62% and 51% of recruiting fallen tree pieces, compared to only 34% in the PIPs. The differences in cumulative recruitment of SWAR pieces between the REF and BUF groups were not significant in either the IPH-YR5 or IPH-YR10 periods, while the REF-CC and BUF-CC contrasts were significant over both the IPH-YR5 and IPH-YR10 periods (Appendix Table 4).

Three years after harvest (YR3), the proportion of plots with >50% of bankfull channel surface area covered by wood was highest in the CC reaches (63%), lower in the BUF and REF reaches (~20%) and lowest in the PIP reaches (8%). The proportion of CC plots with >50% wood cover decreased over time to 43% in YR5 and 36% in YR10, in contrast to the other groups, which remained at ~20% in YR5 and YR10. Less than 5% of the BUF, PIP and REF group plots had >90% wood cover. Throughout the 10-year post-harvest period, 20−30% of CC plots had >90% wood cover where thick accumulations of larger pieces such as broken stems covered the channel (Figure 12, Appendix Table 6).

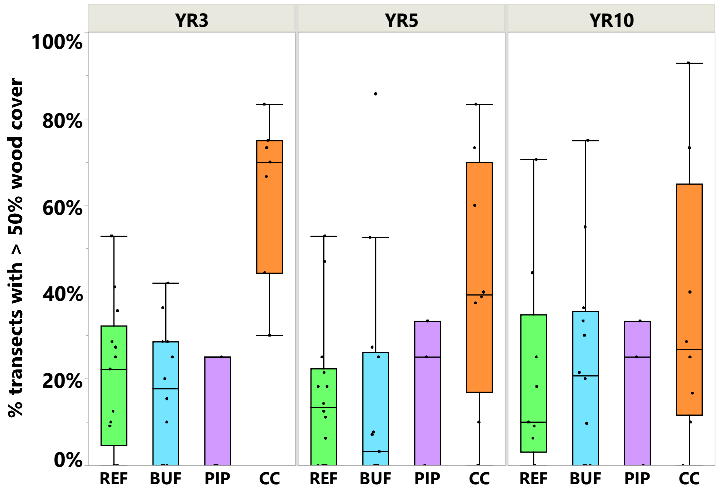

Figure 12. Mean proportion of channel plots with over 50% wood cover at year three (YR3), year five (YR5) and year ten (YR10) by treatment.

Large Wood Recruitment Potential

The pool of standing trees within 50 feet of the stream potentially available for large wood recruitment at YR10 post-harvest consists primarily of live and dead trees present IPH (green and brown in Figure 13). Additional trees were added to the pool by ingrowth (blue) and removed by tree fall during the post-harvest period, including fallen trees that recruited to the channel (red) and those that did not (orange). Overall there was an increase in mean QMD of live trees for all treatments. The combined average of live and dead standing trees per 100 feet of reach length in the REF group at YR10 (61), is nearly double the number available for recruitment in the BUF (32) and PIP stands (25). About 32% of IPH standing trees fell during the post-harvest period in the BUF stands; about double the proportion in the REF stands (15%). Over half (56%) of initially standing trees fell in the PIP stands, over three times the proportion in the REF stands. The small amount of ingrowth (blue) over the 10-year had little influence on the stock of standing trees at YR10 compared to the reduction due to tree fall.

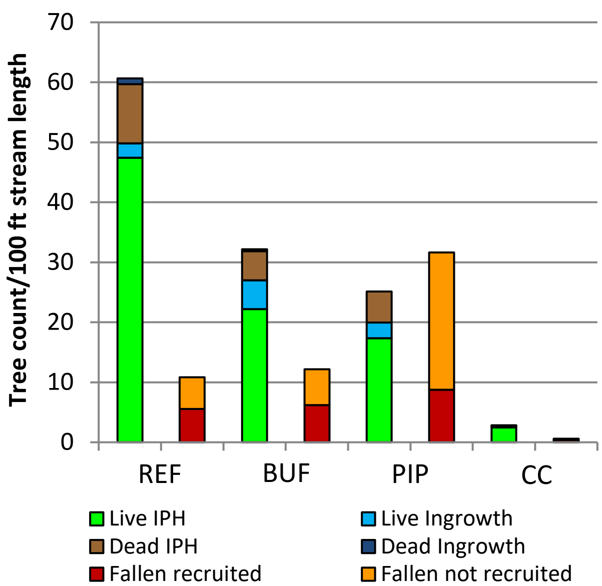

Figure 13. Trees within 50 feet of the stream potentially available for recruitment 10-years post-harvest.

Shade

Mean canopy closure (above 1 m in height) remained at around 90% in the REF reaches throughout the ten-year post-harvest period. YR1 post-harvest canopy closure was 76% in the BUF reaches, increasing to ~90% by YR10, similar to the REF group. YR1 canopy closure in the PIPs (52%) was lower than in the REF and BUF reaches by 37% and 24%, respectively, but increased to 85% at YR10. The change in BUF and PIP values over time appeared to be due to an increase in shrubs and samplings. Canopy closure was lowest in the CC sites at YR1 (12−14%), but increased to 37% in YR5 and 72% by YR10 due to the growth of shrubs and broadleaf saplings with deciduous foliage that provided substantial summer shade in many CC reaches. Median YR10 canopy closure for the CC reaches was ~85%; however low values at two of eight sites lowered the CC group mean (Figure 14, Appendix Table 6).

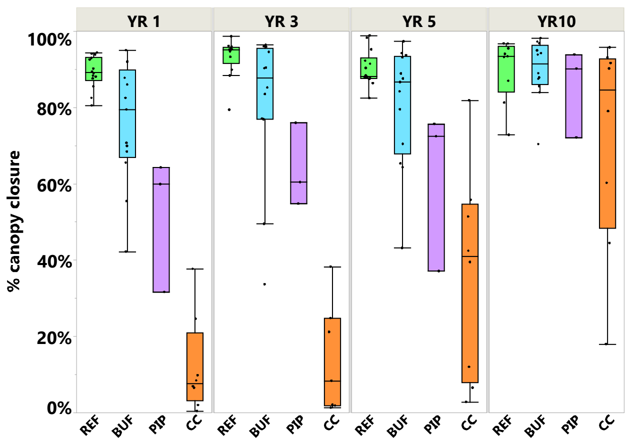

Figure 14. Percent canopy closure at year 1 (YR1), year three (YR3), year five (YR5) and year ten (YR10) by treatment.

The REF-BUF contrasts in percent canopy closure were significant in YR1 and YR3 (p = 0.006 and 0.03, respectively), but were no longer significant in YR5 and YR10. The contrasts between the CC group and the REF and BUF groups were significant through YR5 (p = <0.001), but were no longer significant at YR10 due to increases in canopy closure at the CC sites (Appendix Table 4).

The greatest change in cover provided by understory plants (<3.5 feet above the water surface) over the 10-year post-harvest period was in the CC reaches, followed by the BUF and PIP reaches (Appendix Table 6). In the CC reaches, the proportion of plots with >50% understory cover increased from 9% in YR1 to 45% in YR10 as shrub and herbaceous plant growth occurred following harvest of the trees. The pattern was similar in the BUF and PIP groups; where the proportion increased from 21% and 30% at YR1, respectively, to 60% in YR10. In contrast, the proportion in the REF reaches remained at <20% throughout the entire post-harvest period.

Sediment

Uprooted Trees

Uprooting of trees creates soil disturbance which can potentially deliver sediment to stream channels. About 30% of uprooted trees in the REF and BUF reaches exhibited visual evidence of sediment delivery to the adjacent stream, compared to about 20% of uprooted trees in the PIP and CC reaches (Figure 15).

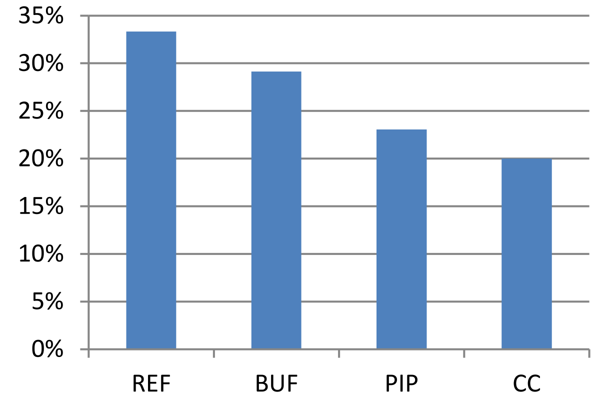

Figure 15. Proportion of uprooted trees with evidence of sediment delivery to the adjacent stream channel.

Nearly 50% of uprooted trees with evidence of sediment delivery were rooted within five horizontal feet of the stream and 75% were within ten feet. Only ~5% of the trees that delivered sediment were located beyond 15 feet from the stream (Figure 16).

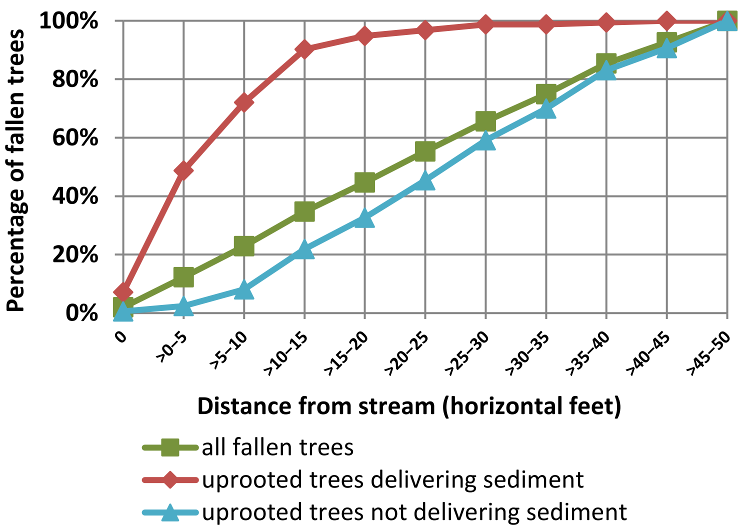

Figure 16. Source distance curve for uprooted trees delivering sediment (left) to the stream channel and proportion of uprooted trees delivering sediment by distance-from-stream category (right).

Surface Erosion

Harvest-related soil and stream-bank disturbance within the 30-foot wide equipment limitation zone (ELZ) on both sides of the stream was more widespread in the CC reaches than the BUF or PIP reaches. The mean frequency of harvest-related soil disturbance features for the CC group (1.3 features per 100 feet of reach length) was over ten times greater than for the BUF group (0.09/100 feet), and no soil disturbance features were observed in the PIPs. On average, soil disturbance features occupied 0.29% of the equipment limitation zone (ELZ) in the BUF reaches compared with 6.2% in the CC reaches, and the frequency of features that delivered sediment in the CC reaches was eight times greater than for the BUF reaches. All BUF and PIP reaches met the soil disturbance performance target of less than 10% of the ELZ with harvest-related soil disturbance (WDNR 2005), but one of eight CC reaches exceeded the target. Most soil disturbance features were associated with falling or yarding of individual trees. The CC site that exceeded the soil disturbance performance target had an incised channel with a steep stream-adjacent slope below a landing. It appeared that as trees were yarded across the stream channel and upslope, the tops combed the hillside, removing the duff and exposing soil.

DISCUSSION

The FPHCP contains three functional resource objectives relevant to the Westside Type Np Riparian Prescriptions (WDNR 2005, Appendix N). The general wording of the resource objectives (Table 7) and lack of meaningful quantitative performance targets for shade and wood input make it difficult to determine with certainty whether the large woody debris and heat/water temperature resource objectives were achieved. Only the sediment resource objective had a quantitative performance target of less than 10% of the ELZ with harvest-related soil disturbance. Although it was not possible to make a quantitative determination of effectiveness in most cases, the following discussion examines the responses we observed in the context of these resource objectives.

Table 7. FPHCP functional objectives relevant to the Westside Type Np Riparian Prescriptions (WDNR 2005).

Key process	Functional objective
Large Woody Debris/ Organic Inputs	Develop riparian conditions that provide complex habitats for recruiting large woody debris and litter.
Heat/Water Temperature	Provide cool water by maintaining shade, groundwater temperature, flow and other watershed processes controlling stream temperature.
Sediment	Provide clean water and substrate and maintain channel forming processes by minimizing, to the extent practicable, the delivery of management-induced coarse and fine sediment to streams by protecting stream bank integrity, providing vegetative filtering, protecting unstable slopes and preventing the routing of sediment to streams.

Unbuffered (Clear-cut) Reaches

The greatest changes to stand structure, shade and wood recruitment occurred in the unbuffered clear-cut reaches. Removal of nearly all trees to the edge of the stream effectively returned the RMZ to the stand-initiation stage of development. Following harvest, clear-cut RMZs were replanted with conifers as required by the Forest Practices rules, and there was additional natural regeneration of conifers and broadleaf trees. Seedling and saplings were present in about 40% of the regeneration plots in clear-cut RMZs at YR10, and planted trees appeared to be growing rapidly, indicating successful re-establishment of young conifer stands.

Both the amount and type of shade available were altered as a result of clear-cut harvest, but the dynamics were complicated. Harvest resulted in a substantial decrease in canopy closure. Mean YR1 canopy closure in the CC reaches was only 12% compared to 89% in the REF reaches, similar to results reported in other studies after clear-cut harvest adjacent to small streams in the Pacific Northwest (Brown and Krygier 1970, Summers 1982, Gravelle and Link 2007, Ehinger et al. 2017). However, there was an increase in wood cover from logging debris input during harvest, which can be substantial when trees are felled towards the stream in steep, narrow headwater valleys and the tops and branches are left in place over the streams (Jackson et al. 2001, Schuett-Hames et al. 2017).

Changes in vegetative shade over the ten year post-harvest period in the clear-cut reaches followed a similar pattern to the response to harvest described by Summers (1982). Cover from live herbaceous plants and shrubs was sparse immediately after harvest but increased rapidly between YR1 and YR3. Rapid growth of tall shrubs, including salmonberry, elderberry and vine maple as well as red alder and conifer saplings, created dense summer cover adjacent to and overhanging narrow channels, increasing canopy closure in the clear-cut RMZs to 36.5% by YR5 and 71.5% by YR10. The rapid revegetation and growth of herbaceous plants, shrubs and saplings adjacent to headwater channels following clear-cut harvest has been commonly observed in moist sites in the Pacific Northwest, increasing shade in four to six years after clear-cut harvest (Brown and Krygier 1970, Gravelle and Link 2007). Summers (1982) observed that canopy shading reached levels similar to old growth stands ten years after harvest in moist sites on small streams in the Sitka Spruce and Western Hemlock zones of the Oregon Coast Range. However, wood cover decreases over time (Young et al. 1999), likely due to the depletion or movement of small branches and pieces (Murphy and Koski 1989). Temperature response following clear-cut harvest in headwater streams varies depending on site-specific factors such as geology, groundwater hydrology and stream-adjacent wetlands, and increases have been observed in some streams (Jackson et al. 2001, Cole and Newton 2013, Ehinger et al. 2017, Klos and Link 2018). Klos and Link (2018) observed that shade from understory vegetation five years after clear-cut or partial-cut harvest intercepted a similar amount of incoming short-wave radiation as did the pre-harvest forest stand. However, stream temperatures did not return to pre-harvest levels because the lower understory vegetation was as not as effective in preventing sensible heat transfer from heated air above the canopy compared to the taller pre-harvest tree canopy (Klos and Link 2018).

Channels adjacent to clear-cut RMZs received variable, but often large, inputs of logging debris during harvest, which initially increased in-channel wood cover. This finding is consistent with other studies documenting large inputs of logging debris where clear-cut harvest occurred adjacent to headwater streams in western Washington (Jackson et al. 2001; Maxa 2009; Schuett-Hames et al. 2017) and western Oregon (Kibler et al. 2013). There was almost no additional wood input in the clear-cut RMZs during the 10-year post-harvest period due to the absence of trees, and wood cover decreased by YR10. The response varied among and within sites; some plots remained buried in logging debris at YR10, while one reach that was buried in logging debris during harvest was scoured to bedrock by a debris flow that originated upslope of the channel. The decrease in wood cover over time was expected, since smaller wood is depleted through transport, abrasion or decomposition (Hassan et al. 2005). The turnover time for small wood pieces ≤10 cm in diameter in a small headwater stream was estimated at 10 years (Wallace et al. 2000), suggesting a reduction in functions such as sediment retention over time.

As replanted trees grow and the stand enters the stem exclusion phase of development, competition mortality will result in the recruitment of small diameter, suppressed stems (Oliver 1981, Liquori 2000). However, if these stands continue to be harvested at 40−50 year intervals, modeling studies indicate that the likely future wood recruitment regime will consist of episodic inputs of slash followed by periods of low wood input. This cycle allows little time for wood recruitment from each reestablished stand before the next harvest, resulting in a decrease in the size and volume of in-channel wood over time (Andrus et al. 1988, Beechie et al. 2000, Bragg 2000, Meleason et al. 2003) and a decrease in sediment retention capacity (Hassan et al. 2005). We observed "legacy" wood pieces that appear to have originated from initial harvest of old-growth stands decades earlier. Since small streams typically have limited capacity to transport wood in the absence of debris flows (May and Gresswell 2003, Hassan et al. 2005), wood input during the initial harvest of large conifers can persist for 50 years or more (Lienkaemper and Swanson 1987, Andrus et al. 1988, Gomi et al. 2001). However, large wood will become less frequent in clear-cut reaches over time, since legacy pieces that are depleted will not be replaced.

Soil disturbance and sediment input from harvest activities was minimal at seven of eight clear-cut RMZs, consistent with the observations of Jackson et al. (2001) with the exception of one site where trees were yarded across an incised channel.

Buffered RMZs and PIPs

The 50-foot RMZ and 56-foot radius PIP buffers provided more shade and large wood recruitment potential than the clear-cut treatment; however there was a reduction in shade and wood recruitment potential when the trees beyond the outer edge of the buffers were removed compared to unharvested reference stands. Estimates of potential wood recruitment volume lost due to harvest of trees outside of a 50-foot wide buffer range from ~15–50% (McDade et al. 1990, Meleason et al. 2003, Burton et al. 2016), likely due to differences in species composition, stand age and tree height, topography and site productivity.

Additional changes in stand structure and wood input occurred during the 10-year post-harvest period due to post-harvest mortality of buffer trees, primarily due to wind. Post-harvest mortality was greatest during the first three years after harvest and declined after year five. Elevated mortality within three years after harvest due to wind is a common response to harvest of adjacent stands in Type N buffers in western Washington (Grizzel and Wolff 1998, Jackson et al. 2007, Schuett-Hames and Stewart 2017). Mean cumulative mortality as a percentage of live stems during the first three years post-harvest for buffered RMZs and PIP buffers in this study (20% and 35%, respectively), was somewhat lower than in these other studies (Table 8). While mortality rates decreased after year five, cumulative mortality reached 35% in the buffered RMZs and 57% in the PIP buffers by year 10 post-harvest. The annual mortality rates for our BUF (8.6%/year) and PIP (17%/year) groups during the first five years post-harvest were much higher than long-term rates of 0.7–1.6%/year reported for unharvested stands in western Washington and Oregon (Pollock and Beechie 2014), however our rates declined to ≤2%/year after year five.

Table 8. Comparison of cumulative post-harvest tree mortality (% stems) reported in studies of buffers on Type N streams in western Washington.

Study	Years post-harvest	Buffered RMZs			PIP Buffers		
		Cumulative mortality (% stems)	Range (%)	REF rate comparison	Cumulative mortality (% stems)	Range (%)	REF rate comparison
Grizzel and Wolff 1998	1–3	33%	2–92%	–	–	–	–
Jackson et al. 2007	2	47%	33–64%	–	–	–	–
Schuett-Hames and Stewart 2017	2	30%	8–52%	2.4 times	48%	14–74%	6.7 times
This study	3	20%	1–69%	4 times	35%	12–63%	7 times
This study	5	30%	6–92%	2 times	55%	30–84%	3.5 times
This study	10	35%	10–94%	1.5 times	57%	30–87%	2.4 times

Temporal mortality patterns respond to the magnitude and timing of wind storms and the increased vulnerability of buffer trees exposed to wind when the adjacent forest is clear-cut (Mitchell et al. 2001, Ruel et al. 2001). Several storm-force windstorms occurred near the coast during the first three years after harvest and many RMZ and PIP buffers lost trees due to wind damage during these storms while the REF stands had little damage. Storm-force winds were more frequent during theYR3−YR5 period and one hurricane-force windstorm affected areas adjacent to the southwest Washington coast in December 2007, causing substantial mortality at REF, BUF and PIP sites near the coast. There were many storm-force wind storms along the coast between years 5 and 10, however mortality rates decreased in the buffered RMZs and PIP buffers during this period and stand structure stabilized. It appears that most vulnerable trees in exposed locations were killed in storms that occurred during the first five after harvest, and mortality was much lower in trees that survived past year five. Reference stand density decreased and basal area increased slightly over the 10-year period. Mortality by density was almost double that of basal area in the reference stands, indicating many of the trees were small due to continued suppression mortality.

There was extensive variation in the mortality rates for buffered RMZs, both among sites and among plots within sites. The effects of wind differ on a regional scale due to physiography and storm patterns (Sinton 1996, Kramer et al. 2001), and at the site scale due to factors affecting the vulnerability of the trees such as stand height, species, soil moisture, and the effect of topographic setting on wind speed and exposure (Ruel et al. 2001, Mitchell 2013). Reilly and Spies (2016) characterized mortality rates in Pacific Northwest forests as chronic (<5% of live trees/year), partial stand replacement (5−25%/year) or stand replacement (>25%/year). Over the 10-year post-harvest period, mortality rates at all REF sites were within the chronic mortality range (<5%/year). In contrast, 75% of the BUF RMZs had mortality rates in the chronic range, two (17%) were in the partial stand replacement range and one (8%) was in the stand replacement range. One PIP buffer (33%) was in the chronic range, while the other two (67%) were in the partial stand replacement range (Table 9).

Differences in cumulative mortality resulted in variable stand structure response. Mean YR10 density in the BUF and PIP stands where mortality rates were in the chronic category was 1.5 times greater than those in the partial replacement category, and density was very low in the single BUF site in the stand replacement category (6.5 trees/acre). The pattern was reversed for tree regeneration because proportion of plots with conifer regeneration was greatest in buffers that experienced stand replacement level mortality, intermediate for partial replacement category sites and lowest in sites in the chronic mortality category (Table 9).

Table 9. Percentage of BUF and PIP sites by mortality category, with stand density, percentage of plots with conifer regeneration and relative density at year 10 post-harvest.

Mortality Category	Percentage of Sites		YR10 density in trees/acre	YR10 % plots with conifer regeneration	YR10 relative density
	BUF	PIP			
Chronic	75%	33%	136	19%	.47
Partial	17%	67%	76	64%	.27
Replacement	8%	0%	7	79%	.03

Differences in mortality rates and the resulting changes in stand structure resulted in different stand development trajectories. Based on relative density at YR10, the majority of BUF sites were either above (25%) or within (50%) the optimal zone for growth, while the remaining 25% were below the minimum threshold to maintain site occupancy (Drew and Flewelling 1979). Two PIPs were in the optimum zone, while one fell below the minimum threshold. Based on stocking (75−255 trees/acre) and relative density (>0.34), 10 of 12 buffered RMZs and two of three PIP buffers are expected to continue to develop as single cohort conifer-dominated stands. In the absence of a severe disturbance event, they should continue to progress through the stem exclusion stage of development with chronic mortality due to competition and self-thinning. The remaining three reaches appear to be stabilizing below the minimum relative density necessary to maintain a single cohort stand (Drew and Flewelling 1979). One PIP and one BUF stand have densities of ~40 trees/acre, similar to densities suggested for two-age shelterwood thinning strategies (Curtis et al. 2004). Since conifer regeneration is widespread at these sites, it is likely a new cohort of conifers will join the remaining trees to form a multi-aged conifer-dominated stand. The remaining buffered RMZ with few live trees has substantial conifer regeneration. It has returned to the stand initiation stage of development and is likely to take an alternative development pathway to a heterogeneous stand structure where a few scattered large trees are intermingled with a newly established young stand (Donato et al. 2012).

These scenarios are based on site averages, however substantial variation in disturbance and resulting stand structure within sites will likely result in fine-scale variation in stand structure. Harcombe et al. (2004) noted that mortality continued over time at sites in topographic settings susceptible to wind disturbance, resulting in the expansion of wind throw patches. We observed continued mortality and expansion of windthrow patches during the first five years after harvest, however rates declined dramatically after YR5 resulting in stabilization of stand structure. The decrease in mortality rates after year five to chronic levels despite continued exposure to storm force winds appears to indicate increasing wind resistance in the surviving trees as more vulnerable trees are removed. Trees respond to changes in wind exposure by adaptive growth and acclimation including changes in root systems to increase anchorage, increased stem strength, and changes in above-ground structure to decrease drag (Nicoll and Ray 1996, Nicoll et al. 2008, Mitchell 2013, Bonnesoeur et al. 2016). Since buffer trees will be taller than the adjacent replanted forest, acclimation from continued wind exposure should increase wind-resistance over time. However stands will remain vulnerable to windthrow during extreme storm events, as well as other catastrophic disturbances such as fire, disease or insect outbreaks (Edmonds et al. 2005).

In the buffered RMZ and PIP buffer sites, percent canopy closure one year after harvest was lower than the unharvested reference reaches by 15% and 40%, respectively. A similar decrease in canopy closure following harvest with an unharvested Type Np buffer was reported by Ehinger et al. (2017). The initial decrease in canopy closure appears to have been off-set to some extent by increases in cover from low growing plants (e.g. shrubs, herbs, grasses) over the 10-year post-harvest period in the buffered RMZ and PIP buffer sites, likely due to an increase in light penetration to the forest floor following harvest of the adjacent stand (Brosofske et al. 1997, Moore et al. 2005, Gravelle and Link 2007). Canopy closure at YR10 in the buffered RMZs was similar to the reference site levels and 5% lower in the PIP buffers, while understory plant cover in the buffered RMZ and PIP buffer streams exceeded the REF values throughout the 10-year post-harvest period. A similar increase in shade to pre-harvest levels was observed in the Cascade and Coast Range of Oregon within 9−24 years (Summers 1982). However, the increase in canopy closure in disturbed RMZ and PIP buffers appeared to be due to increased cover from shrubs and saplings, which may not be as effective as tree canopy in reducing convective heat exchange to the stream from warmer air above and outside the buffer (Klos and Link 2018).

Differences in mortality and tree fall resulted in variation in wood input among and within the buffered RMZs and PIP buffers. The buffers prevented input of slash from harvest of the adjacent forest outside the buffers, as observed in other studies of Type Np buffers in western Washington (Jackson et al. 2001, Schuett-Hames et al. 2017) and we observed little evidence of wood transport in these small channels, consistent with other studies of headwater streams (Webster et al. 1999, Gomi et al. 2001). Consequently, tree fall associated with wind appeared to be the primary source of new wood input to channels adjacent to buffered RMZs and PIP buffers during this period, similar to observations from headwater stream buffers on Oregon (Burton et al. 2016). On average, wood input was greatest in the first five years after harvest due to greater magnitude and frequency of tree fall caused by wind, and streams adjacent to stands with elevated mortality and tree fall received a large pulse of wood input. About half the recruited wood pieces from fallen trees in the BUF reaches were stems with attached rootwads, which are more stable than pieces without rootwads and are more likely to persist and provide in-channel functions over time (Fox and Bolton 2007). Although large wood input rates decreased sharply between YR5 and YR10, the proportion of BUF and PIP plots with >50% wood cover remained stable through the 10-year post-harvest period. This is not surprising, since most wood input in buffered RMZs and PIP buffers consisted of uprooted trees that came to rest suspended over the channel, and these small channels lack stream power and flow volume to transport large wood (Martin and Benda 2001, May and Gresswell 2003).

The effects of wind disturbance on stand trajectory in the buffered RMZs and PIP buffers has implications for future wood recruitment regimes. Mortality during the 10-year post-harvest period reduced the pool of standing trees available for recruitment in many BUF and PIP sites. If mortality continues at chronic rates in the absence of a severe disturbance event, the ten BUF RMZs and two PIP buffers with stocking in excess of 75 trees/acre should provide wood input from mortality of single or small groups of trees as they progress through the stem exclusion stage (Bragg 2000). The pattern of wood input from fallen trees at the other three sites resembles the catastrophic mortality/wood input regime described by Bragg (2000), where an episodic input of wood due to disturbance is followed by a period with limited wood input while a new stand regenerates. In those cases, the magnitude of fluctuation in wood input and loading varies depending on the severity of the disturbance and the residual stocking levels. These three sites received a pulse of wood from wind storms during the first five years after harvest; however most is suspended over the channel. This is common in small headwater channels surrounded by steep valley walls (Bahuguna et al. 2010). We did not collect data on the timeframe for suspended wood to break up and enter these small channels and perform in-channel functions, however Martin and Shelly (2017) observed that the proportion of recruited wood performing in-channel functions increased from 26−30% over three decades in larger streams in SE Alaska. The two sites with residual stocking of ~40 trees/acre have the potential to provide limited near-term wood input, and appear likely to develop as two-cohort stands with increasing wood recruitment potential over time as the young trees increase in size. The highly disturbed site with a residual stand of ~7 trees/acre has little potential for additional large wood input until a new stand develops, which will result in the greatest fluctuation in wood input and loading over time. If these sites are in topographic positions susceptible to high winds they may be subject to repeated wind damage, continuing the pattern of episodic wood inputs followed by periods of low stocking and low input while stands regenerate. However, over the long-term, stands subjected to elevated levels of natural disturbance produce as much or more wood input as stands with chronic mortality regimes, as long as trees are not harvested (Bragg 2000).

Since there was almost no soil disturbance within the buffered RMZs and PIP buffers during harvest, all sites with buffers met the performance target. Post-harvest uprooting of trees due to wind was the most substantial source of soil disturbance in buffered RMZs and PIP buffers, however vegetative filtering appeared to prevent sediment from reaching the channel except when the uprooted trees were in close proximity to the channel. This finding is consistent with the findings of Stewart et al. (2017) and Schuett-Hames et al. (2017), who observed little sediment input from uprooted trees unless they were adjacent to the channel and found that suspended sediment levels were only slightly elevated for a short time at the outlet of Type Np streams following storms that caused substantial windthrow in buffered RMZs.

Summary of Conclusions

The unbuffered clear-cut treatment was least effective in meeting the FPHCP resource objectives for shade/temperature and large woody debris/organic inputs, but did meet the soil disturbance performance targets in most cases. Harvest of streamside trees resulted in greatly reduced canopy shade to adjacent streams and substantial input of logging slash. Shade in unbuffered reaches increased over the 10-year post-harvest period due to growth of streamside herbs, shrubs and saplings, however research indicates that stream temperatures increase from pre-harvest levels following harvest in unbuffered reaches, and changes persist over time (Ehinger 2017, Klos and Link 2018). There was input of logging slash in unbuffered reaches, but almost no additional post-harvest wood input occurred and cover from woody debris decreased over the ten-year post-harvest period. Modeling studies indicate that clear-cut harvest on typical rotation schedule of 40–50 years will result in a continuous cycle of disturbance and rapid changes in stand structure and shade and long-term reductions in large wood loading due to lack of input from large trees (Beechie et al. 2000, Bragg 2000, Meleason et al. 2003).

The RMZ and PIP buffers were more effective than unbuffered reaches in meeting FPHCP resource objectives, but were not as effective as unharvested reference sites in providing canopy shade and future wood recruitment potential due to removal of trees outside of the buffers. Over the 10-year post-harvest period, there was a substantial reduction in stand density and basal area in RMZ buffers (>30%) and PIP buffers (>50%). Mean year 1 post-harvest canopy closure in the RMZ and PIP buffers was 13% and 37% lower than in the reference sites, respectively. Canopy shade returned to levels similar to unharvested reference sites in the RMZ buffers by year-10 post-harvest, but not in the PIP buffers. Large wood input during the 10-year post-harvest period was greater in the RMZ and PIP buffers than the reference sites, but future wood recruitment potential at year 10-post-harvest was lower.

The primary agent of mortality in RMZ and PIP buffers was wind, which affected trees of all sizes. Mortality from wind was a complicating factor in assessing buffer effectiveness. Mortality rates varied in RMZ and PIP buffers, but on average were greater than in reference sites. About one quarter of RMZ buffers and two thirds of PIP buffers had substantial mortality (>5%/year). Wind damage at this level reduced density, canopy shade and provided a pulse of large wood input, but future wood recruitment potential is limited by the low density of remaining trees. The future stand trajectory of these sites is uncertain, but conifer regeneration is occurring so development of multi-age conifer stands is likely over time. The majority (75%) of RMZ buffers had mortality rates of <5%/year, and are on track to continue development as single-cohort conifer dominated stands with greater wood recruitment potential than the buffers with higher mortality.

Over half the fallen trees were uprooted stems with attached rootwads, providing stable pieces that will persist over time (Fox and Bolton 2007). Most fallen trees came to rest suspended or spanning above the channel where they provide cover but will not immediate influence channel conditions and processes. Although the majority of fallen trees were uprooted, sediment input from soil disturbance was limited to trees in close proximity to the channel.

Management Implications

Determining the appropriate balance between the resource objectives of the FPHCP and the economic and operational advantages of timber harvest adjacent to Np streams is a critical policy issue that must be informed by both science and social considerations. Our findings raise several key policy questions for the adaptive management program.

Clear-cut harvest: Is the magnitude of disturbance from clear-cut harvest adjacent to the stream (logging debris input, reduction in and large wood recruitment) consistent with the resource objectives of the FPHCP? Does the proportion of the Type Np stream network subject to clear-cut harvest (≤50%) an appropriate balance between protection of aquatic resources and water quality and economic and operational considerations for forest landowners? Reducing or eliminating the proportion of the Type Np network that is harvested to the edge of the stream would reduce channel disturbance, and increase canopy shade and wood recruitment potential (McIntyre et al. 2017), resulting in better effectiveness in meeting FPHCP resource objectives.

RMZ and PIP buffers. Are the incremental reductions in wood recruitment potential and shade associated with harvest of tree outside the RMZ and PIP buffers consistent with the resource objectives of the FPHCP? More shade and increased wood recruitment potential could be gained by increasing the width of buffers or designing variable width buffers designed to leave additional trees where benefits to shade and potential wood recruitment would be greatest (Pollock and Beechie 2014).

Wind mortality. Is the level of wind damage to RMZ and PIP buffers and the associated wood input and loss of shade consistent with the resource objectives of the FPHCP? Do small patch buffers that are prone to wind damage provide the desired protection for sensitive sites (e.g. PIPs)? There are a number of systems for identifying and managing windthrow-prone sites that could be adapted for western Washington conditions (Mitchell et al. 2001, Scott and Mitchell 2005).

Limitations and Future Directions

The 10-year post-harvest timeframe of this study is longer than most similar studies; however processes such as stand development and wood recruitment operate over time frames of decades or longer, creating uncertainty about long-term effects that can only be addressed by longer monitoring or space-for-time substitution studies. A challenge for longer-term monitoring is obtaining landowner commitment to maintain unharvested reference sites. We focused on assessing the site-scale responses to each of the three most common treatments in the Westside Type Np Riparian Prescriptions (e.g. the 50-foot RMZ buffers, PIP buffers and clear-cut RMZs) in isolation from one another. However, these prescriptions are typically applied together on a basin scale, with interactions and downstream responses that were not evaluated in this study but are the subject of other intensive CMER studies (see McIntyre et al. 2017). Extensive variability in site conditions across the large study area, combined with relatively small sample sizes (particularly for the PIP buffer treatment) limited our ability to determine relationships between site conditions and response. However, our results for RMZ and PIP buffers were consistent with other studies, increasing our confidence in the results. This study is limited in its ability to describe processes, and is best viewed in context of other more intensive studies (Jackson et al. 2007, McIntyre et al. 2017). The sample size was limited by budget constraints. A larger sample size, stratified or blocked by region or physical stream characteristics could help partition and explain variability and improve inference of study results based on local site conditions. The results and limitations of this study suggest future research that would be useful for FPHCP adaptive management, including research on: the effects of a range of buffer widths and buffer thinning regimes on tree mortality and windthrow, wood recruitment, shade and stream temperature; the effects of headwater basin harvest on habitat and water quality in downstream fish-bearing waters; and the effectiveness and persistence of different cover types resulting from FPHCP treatments (e.g. logging debris, herbs and shrubs, fallen trees and tree canopy) in limiting solar radiation input and heat transfer to streams.

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APPENDIX A: DATA TABLES

Appendix Table 1. Study site characteristics.

		Length (feet)											
Site	Type	Total	BUF	PIP	CC	EPA Level III Eco-region	Precipitation (inches)	Elev. (feet)	Valley Aspect (°)	Channel Gradient (%)	Bankfull Width (feet)	Stand Height (ft)[1]	Site Index [2]
13	Reference	300	-	-	-	Cascades	100-120	1460	113	14.8	6.8	81.8	125.6
13	Treatment	452	452	-	-	Cascades	90-100	2880	123	19.1	3.6	101.0	115.8
23[3]	Reference	339	-	-	-	Coast Range	80-90	1475	227	8.1	7.3	120.7	124.8
23	Treatment	494	494	-	-	Coast Range	80-90	1080	268	6.1	3.8	127.7	123.9
24[3]	Reference	800	-	-	-	Coast Range	120-140	565	020	5.1	5.6	60.0	113.1
24	Treatment	787	200	117	470	Coast Range	120-140	600	060	12.1	5.3	86.7	131.3
27[3]	Reference	650	-	-	-	Cascades	100-120	1970	179	14.3	11.4		
27	Treatment	985	669	-	316	Cascades	90-100	2540	188	12.6	10.8	128.2	127.7
29	Reference	500	-	-	-	Coast Range	100-120	2150	343	14.5	5.1	79.9	113.3
29	Treatment	607	607	-	-	Coast Range	100-120	1500	001	22.9	5.0	109.8	104.6
31	Reference	531	-	-	-	Coast Range	100-120	860	180	4.7	5.7		
31	Treatment	848	-	124	724	Coast Range	100-120	860	127	13.5	4.8		
36	Reference	750	-	-	-	Coast Range	120-140	1780	178	9.1	5.9	81.3	111.2
36	Treatment	1475	1475	-	-	Coast Range	120-140	1360	328	11.1	9.2	92.9	131
37[3]	Reference	300		-	-	Coast Range	80-90	190	328	1.6	3.6		
37	Treatment	600	600	-	-	Coast Range	70-80	180	279	5.6	3.0	107.0	115.5
38	Reference	764	-	-	-	Coast Range	120-140	655	070	8.5	6.8	113.7	154.2
38	Treatment	1034	334	-	700	Coast Range	120-140	680	105	18.4	9.5	121.3	122.2
40	Reference	380	-	-	-	Puget Lowlands	40-44	700	026	1.1	5.6	61.8	123.9
40	Treatment	488	488	-	-	Puget Lowlands	40-44	715	003	1.0	3.1	76.4	124.4
47	Treatment	1742	950	-	792	Coast Range	100-120	740	276	8.4	4.7		
50	Reference	500	-	-	-	Coast Range	80-90	295	273	5.8	8.5	116.4	100.1
50	Treatment	853	425	-	428	Coast Range	80-90	215	323	4.5	4.6	113.0	129.6
56[4]	Reference	441	-	-	-	North Cascades	70-80	930	192	17.1	10.5	75.0	147.0
56[4]	Treatment	573	200	-	373	North Cascades	70-80	800	192	11.3	3.7	88.4	126.7
62	Reference	400	-	-	-	Coast Range	120-140	662.5	028	9.4	8.2	80.5	127.3
62	Treatment	420	-	132	288	Coast Range	120-140	875	047	19.3	3.8	90.0	138.4
64	Reference	450	-	-	-	Coast Range	52-56	280	042	9.7	8.2	83.8	144.5
64[5]	Treatment	393	393	-	-	Coast Range	52-56	410	001	7.8	6.2	73.7	57.2

[1]Stand height is the mean height of all recorded co-dominant tree heights, irrespective of species.
[2]Site index is the mean site index (breast height base age 50) of all Douglas-fir and western hemlock (converted to Douglas-fir site index values). Site index values are based on equations contained in the Canadian BC Ministry of Forests and Range SiteTools software: http://www.for.gov.bc.ca/hre/sitetool/
[3] Reference site not sampled in 2013 due to harvest; [4] Access not granted for data collection 2006; [5]Access not granted for data collection 2013.

Appendix Table 2. Mean post-harvest stand structure by treatment.

Survey	REF*	BUF*	PIP*	CC*
		Live density (trees/acre)		
IPH	240.8 (77.5)	154.6 (62.8)	200.7 (54.2)	12.5 (27.4)
YR3	225.9 (68.9)	132.7 (66.4)	124.2 (23.7)	2.6 (4.1)
YR5	213.8 (75.1)	124.1 (72.6)	87.3 (40.5)	12.0 (27.5)
YR10	216.9 (67.5)	117.6 (67.7)	86.8 (49.8)	11.5 (27.2)
		Live basal area (ft^2/acre)		
IPH	226.6 (39.9)	191.7 (65.8)	263.9 (67.5)	6.6 (14.7)
YR3	225.7 (36.0)	167.5 (72.7)	187.0 (69.8)	1.2 (2.1)
YR5	214.2 (42.5)	149.0 (74.4)	133.5 (78.8)	6.1 (14.6)
YR10	225.7 (53.9)	161.1 (79.9)	153.1 (88.8)	8.2 (19.5)
		Live quadratic mean diameter (inches)		
IPH	13.6 (2.9)	15.6 (3.5)	15.6 (2.2)	9.5 (4.0)
YR3	14.0 (2.7)	15.9 (3.5)	16.4 (1.9)	8.1 (3.6)
YR5	14.1 (2.8)	15.6 (3.8)	16.2 (2.2)	8.4 (3.1)
YR10	14.1 (2.1)	16.6 (3.7)	17.8 (2.3)	11.7 (2.2)
		Live relative density		
IPH	61.5 (1.9)	48.6 (4.2)	66.6 (8.5)	2.8 (2.2)
YR3	60.6 (1.9)	42.2 (4.8)	45.7 (8.5)	0.9 (0.4)
YR5	57.4 (2.6)	37.9 (5.0)	32.5 (10.3)	3.9 (3.2)
YR10	60.2 (4.3)	39.7 (5.3)	35.9 (11.7)	6.5 (5.1)
		Dead density (trees/ac)		
IPH	28.5 (17.4)	22.6 (16.2)	19.0 (18.1)	2.3 (3.6)
YR3	35.4 (20.7)	26.3 (18.6)	25.2 (17.8)	1.5 (2.7)
YR5	38.3 (25.2)	24.4 (17.3)	19.0 (9.3)	2.5 (3.9)
YR10	47.4 (31.0)	22.6 (16.5)	22.7 (13.7)	0.8 (1.6)
		Dead basal area (ft^2/ac)		
IPH	26.1 (32.5)	20.2 (16.8)	31.2 (31.7)	2.1 (4.6)
YR3	30.4 (33.3)	26.0 (19.3)	43.2 (22.2)	2.1 (5.0)
YR5	28.9 (30.8)	24.5 (18.2)	45.4 (23.6)	1.4 (2.5)
YR10	25.4 (16.2)	24.1 (21.2)	50.1 (19.5)	0.9 (2.0)
		Dead mean diameter (inches)		
IPH	9.1 (2.8)	10.4 (2.7)	25.1 (30.4)	11.1 (5.9)
YR3	9.1 (2.3)	11.7 (2.0)	17.7 (8.2)	10.4 (5.1)
YR5	9.0 (2.5)	11.4 (2.4)	18.7 (4.4)	8.8 (2.2)
YR10	8.8 (2.9)	11.4 (2.8)	19.6 (7.3)	10.4(2.0)

* Standard error in parenthesis.

Appendix Table 3. Mean cumulative change and annual rates of change in stand structure, mortality, ingrowth and tree regeneration.

Period/ Survey	REF*	BUF*	PIP*	REF*	BUF*	PIP*
	Annual rate of change in % basal area/yr			*Annual rate of change in basal area (ft^2/ac/yr)*		
IPH-YR5	-1.2 (0.5)	-7.0 (2.8)	-14.5 (7.6)	-2.7 (1.2)	-11.6 (3.7)	-39.7 (20.6)
YR5-YR10	1.4 (0.3)	2.1 (0.8)	2.7 (0.9)	3.2 (0.7)	3.3 (0.8)	3.7 (1.8)
	Cumulative change in % basal area			*Cumulative change in basal area (ft^2/ac/yr)*		
IPH-YR5	-5.5 (2.3)	-24.2 (7.6)	-47.7 (18.2)	-12.5 (5.5)	-42.7 (11.2)	-130.5 (51.9)
IPH-YR10	2.7 (3.9)	-14.1 (10.5)	-38.9 (22.9)	7.3 (8.4)	-25.9 (15.9)	-110.9 (61.4)
	Annual rate of change in % density/yr			*Annual rate of change in density (trees/ac/yr)*		
IPH-YR5	-2.6 (0.5)	-6.9 (2.9)	-15.8 (7.7)	-5.8 (1.2)	-8.6 (3.2)	-36.5 (22.3)
YR5-YR10	-2.0 (0.4)	0.3 (0.8)	-1.1 (2.0)	-4.7 (1.0)	0.7 (0.7)	-0.2 (1.7)
	Cumulative change in % live density			*Cumulative change in density (trees/ac)*		
IPH-YR5	-11.9 (2.3)	-23.0 (8.4)	-51.1 (17.4)	-27.0 (5.0)	-30.5 (11.7)	-113.4 (54.5)
IPH-YR10	-20.1 (3.8)	-20.1 (10.9)	-50.4 (20.9)	-54.0 (9.9)	-27.8 (15.1)	-113.9 (59.9)
	Annual ingrowth rate in basal area (ft^2/ac/yr)			*Annual ingrowth rate in density (trees/ac/yr)*		
IPH-YR5	0.2 (0.1)	0.3 (0.1)	0.2 (0.1)	2.2 (0.5)	2.7 (1.0)	1.4 (0.8)
YR5-YR10	0.1 (0.04)	0.3 (0.1)	0.1 (0.1)	0.9 (0.3)	2.2 (0.8)	1.1 (1.1)
	Cumulative ingrowth in basal area (ft^2/ac/yr)			*Cumulative ingrowth in density (trees/ac)*		
IPH-YR5	1.1 (0.3)	1.4 (0.5)	0.8 (0.4)	11.0 (2.6)	13.7 (5.1)	6.9 (4.1)
IPH-YR10	1.9 (0.5)	2.8 (0.9)	1.4 (0.8)	18.6 (5.1)	24.8 (8.9)	12.4 (6.7)
	Annual mortality rate in % basal area/yr			*Annual mortality rate in basal area (ft^2/ac/yr)*		
IPH-YR5	2.0 (0.5)	7.8 (2.8)	14.4 (7.2)	4.5 (1.1)	12.9 (3.7)	39.2 (19.6)
YR5-YR10	1.1 (0.3)	1.2 (0.4)	1.6 (1.3)	2.0 (0.4)	1.2 (0.3)	1.1 (0.6)
	Cumulative mortality in % basal area			*Cumulative mortality in basal area (ft^2/ac/yr)*		
IPH-YR5	9.4 (2.1)	27.2 (7.2)	48.1 (17.2)	20.9 (4.8)	47.9 (10.5)	130.8 (49.5)
IPH-YR10	13.8 (2.9)	31.0 (7.8)	50.0 (18.1)	28.3 (5.6)	54.6 (11.9)	136.5 (52.1)
	Annual mortality rate in % density/yr			*Annual morality rate in density (trees/ac/yr)*		
IPH-YR5	3.3 (0.6)	8.6 (2.9)	17.0 (7.2)	7.6 (1.3)	11.5 (3.1)	38.7 (21.4)
YR5-YR10	2.3 (0.4)	1.6 (0.4)	2.0 (1.1)	5.6 (1.2)	1.7 (0.4)	1.3 (0.7)
	Cumulative mortality in % live density			*Cumulative morality in density (trees/ac)*		
IPH-YR5	14.9 (2.4)	30.1 (7.1)	55.0 (15.9)	34.9 (5.6)	43.0 (9.9)	120.3 (51.6)
IPH-YR10	23.6 (3.5)	35.2 (7.4)	57.2 (16.6)	64.5 (10.9)	49.4 (11.1)	125.1 (53.5)
	% plots with seedling/sapling regeneration			*% plots with conifer regeneration*		
IPH	12.5 (9.7)	14.1 (23.2)	27.8 (48.1)	9.7 (8.6)	5.1 (7.2)	27.8 (48.1)
YR3	10.3 (10.3)	20.1 (12.0)	38.9 (41.9)	7.7 (8.0)	13.9 (10.3)	38.9 (41.9)
YR5	11.3 (13.7)	37.2 (24.0)	38.9 (41.9)	8.3 (13.9)	26.9 (24.3)	33.3 (33.3)
YR10	13.9 (15.2)	41.5 (23.1)	55.6 (34.7)	11.6 (13.6)	30.1 (25.4)	55.6 (34.7)

* Standard error in parentheses.

Appendix Table 4. Treatment contrasts of mixed-model estimates.

Contrast	Period/Survey	Mean Treatment Difference	Standard Error	DF	t-value	p-value*
		Change in live basal area				
REF-BUF	IPH-YR5	0.17	0.06	7.5	2.76	**0.026**
REF-BUF	IPH-YR10	0.11	0.11	7.5	1.02	0.340
		Cumulative mortality as a percentage of initial live basal area				
REF-BUF	IPH-YR5	-1.29	0.09	11	-14.21	**<0.001**
REF-BUF	IPH-YR10	-0.70	0.12	5	-5.67	0.002
		Percentage of plots with tree regeneration				
REF−BUF	YR3	-0.10	0.07	20.6	-1.50	0.150
REF−CC	YR3	-0.31	0.08	25.1	-3.98	**<0.001**
BUF−CC	YR3	-0.21	0.08	26.3	-2.67	**0.013**
REF−BUF	YR5	-0.26	0.08	22.7	-3.26	**0.004**
REF−CC	YR5	-0.28	0.09	27.1	-3.08	**0.005**
BUF−CC	YR5	-0.03	0.09	28.2	-0.28	0.783
REF−BUF	YR10	-0.27	0.09	20.7	-3.10	**0.006**
REF−CC	YR10	-0.25	0.09	20.2	-2.64	**0.016**
BUF−CC	YR10	0.02	0.09	20.3	0.18	0.855
		All recruited fallen tree pieces				
REF-BUF	IPH-YR5	-0.97	0.10	18	-9.52	**<0.001**
REF-BUF	IPH-YR10	-0.23	0.11	12	-2.11	**0.057**
REF-CC	IPH-YR5	3.16	0.34	18	9.23	**<0.001**
REF-CC	IPH-YR10	3.65	0.33	12	11.18	**<0.001**
BUF-CC	IPH-YR5	4.14	0.35	18	11.98	**<0.001**
BUF-CC	IPH-YR10	3.89	0.33	12	11.92	**<0.001**
		Stem with attached rootwad (SWAR) fallen tree pieces				
REF-BUF	IPH-YR5	-0.59	0.47	5	-1.26	0.263
REF-BUF	IPH-YR10	-0.08	0.15	12	-0.54.0	0.596
REF-CC	IPH-YR5	3.71	0.74	5	5.02	**0.004**
REF-CC	IPH-YR10	4.24	0.51	12	8.30	**<0.001**
BUF-CC	IPH-YR5	4.30	0.60	5	7.20	**0.001**
BUF-CC	IPH-YR10	4.32	0.51	12	8.45	**<0.001**
		Percent canopy closure				
REF−BUF	YR1	0.13	0.04	21.6	3.06	**0.006**
REF−CC	YR1	0.75	0.05	25.0	15.12	**<0.001**
BUF−CC	YR1	0.63	0.05	25.8	12.28	**<0.000**
REF−BUF	YR3	0.11	0.05	19.2	2.35	**0.030**
REF−CC	YR3	0.76	0.06	22.1	13.00	**<0.001**
BUF−CC	YR3	0.65	0.06	22.8	10.79	**<0.001**
REF−BUF	YR5	0.09	0.06	22.1	1.48	0.152
REF−CC	YR5	0.53	0.07	26.1	7.29	**<0.001**
BUF−CC	YR5	0.44	0.07	27.2	5.91	**<0.001**
REF−BUF	YR10	**	**	**	**	**
REF−CC	YR10	**	**	**	**	**
BUF−CC	YR3	**	**	**	**	**

* Bolded values significant at alpha = 0.10.
** The ANOVA was not significant so individual comparisons were not done.

Appendix Table 5. Mean cumulative change and annual rates of change in tree fall and wood recruitment from fallen trees.

Period	REF*	BUF*	PIP*	REF*	BUF*	PIP*
	Rate of recruiting fallen trees (trees/100ft/yr)			*Rate of recruiting fallen trees (trees/acre/yr)*		
IPH-YR5	0.6 (0.2)	1.1 (0.3)	1.7 (0.6)	2.6 (0.7)	5.3 (1.6)	8.0 (2.7)
YR5-YR10	0.4 (0.1)	0.2 (0.05)	0.1 (0.1)	1.8 (0.5)	0.8 (0.2)	0.4 (0.4)
	Cumulative recruiting fallen trees (trees/100 ft)			*Cumulative recruiting fallen trees (trees/acre)*		
IPH-YR5	2.9 (0.8)	5.3 (1.5)	8.5 (2.8)	12.7 (3.4)	23.2 (6.3)	37.0 (12.1)
IPH-YR10	5.6 (1.3)	6.2 (1.6)	8.8 (2.5)	24.3 (5.8)	26.9 (6.8)	38.1 (11.0)
	Cumulative percentage of standing trees that fell			***Cumulative percentage of standing trees that recruited to stream***		
IPH-YR5	***8.6 (1.9)***	***25.9 (7.1)***	***57.7 (14.7)***	***5.0 (1.4)***	***13.7 (4.2)***	***15.8 (3.8)***
IPH-YR10	***15.8 (3.2)***	***30.6 (7.3)***	***58.4 (14.1)***	***8.4 (2.3)***	***16.2 (4.4)***	***16.5 (3.1)***
	Percent of fallen trees uprooted/broken			*Percent of fallen trees in-channel/over-channel*		
IPH-YR10	80/20	67/33	69/31	86/14	85/15	69/31
	Total recruitment rate (pieces/100ft/yr)			*SWAR** recruitment rate (pieces/100ft/yr)*		
IPH-YR5	0.6 (0.2)	1.2 (0.3)	2.1 (0.8)	0.4 (0.1)	0.7 (0.2)	1.1 (0.6)
YR5-YR10	0.4 (0.1)	0.2 (0.05)	0.1 (0.1)	0.3 (0.1)	0.07 (0.03)	0.0 (-)
	Total recruitment rate (ft^3volume/100ft/yr)			*SWAR recruitment rate (ft^3volume/100ft/yr)*		
IPH-YR5	2.0 (0.7)	6.8 (2.2)	15.6 (9.6)	1.8 (0.7)	4.6 (1.6)	12.1 (9.2)
YR5-YR10	1.1 (0.4)	0.8 (0.3)	0.05 (0.05)	1.0 (0.4)	0.4 (0.2)	0.0 (-)
	Total cumulative recruitment (pieces/100ft)			*SWAR cumulative recruitment (pieces/100ft)*		
IPH-YR5	3.2 (0.8)	6.0 (1.6)	10.7 (3.9)	2.2 (0.7)	3.5 (1.0)	5.6 (3.0)
IPH-YR10	6.2 (1.5)	7.0 (1.8)	11.2 (3.4)	4.2 (1.3)	3.9 (1.1)	5.6 (3.0)
	Total cumulative recruitment (ft^3volume/100ft)			*SWAR cumulative recruitment (ft^3volume/100ft)*		
IPH-YR5	10.2 (3.6)	34.1 (11.2)	78.2 (48.1)	9.2 (3.4)	23.2 (7.9)	60.7 (45.8)
IPH-YR10	17.2 (5.9)	39.8 (11.8)	78.4 (47.9)	15.1 (5.6)	27.0 (8.1)	60.7 (45.8)

* Standard error in parentheses.

Appendix Table 6. Mean post-harvest shade and cover from wood and understory plants.

Survey	REF*	BUF*	PIP*	CC*
% canopy closure				
YR1	89.2 (1.1)	75.9 (4.4)	51.9 (10.2)	12.0 (4.5)
YR3	93.2 (1.4)	80.8 (5.7)	63.7 (6.3)	14.0 (5.4)
YR5	90.2 (1.2)	80.6 (4.4)	61.7 (12.4)	36.5 (9.8)
YR10	90.1 (2.7)	89.9 (2.3)	85.4 (6.7)	71.5 (10.0)
% plots >50% understory plant cover				
YR1	4.2 (1.7)	20.6 (5.6)	30.0 (15.3)	9.4 (3.9)
YR3	5.5 (2.2)	22.7 (7.7)	17.8 (9.7)	35.0 (12.5)
YR5	9.1 (5.8)	28.1 (7.3)	44.4 (29.4)	32.5 (11.9)
YR10	17.7 (8.6)	59.8 (9.3)	60.0 (30.6)	45.0 (11.3)
% plots >50% wood cover				
YR3	20.3 (4.7)	17.2 (4.4)	8.3 (8.3)	63.3 (7.2)
YR5	16.2 (4.5)	16.1 (7.3)	19.4 (10.0)	42.9 (10.2)
YR10	20.4 (7.8)	23.4 (6.9)	19.4 (10.0)	35.8 (11.3)
% plots >90% wood cover				
YR3	4.5 (2.0)	2.4 (1.1)	0.0 (0.0)	29.4 (9.9)
YR5	1.7 (1.2)	2.9 (2.0)	0.0 (0.0)	21.8 (5.4)
YR10	1.3 (1.3)	4.1 (1.5)	0.0 (0.0)	26.1 (9.3)

* Standard error in parentheses.