Results of the Westside Type N Buffer Characteristics, Integrity and Function Study
Final Report

Dave Schuett-Hames, Ashley Roorbach, Robert Conrad

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

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December 2012

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Washington State Forest Practices Adaptive Management Program
Cooperative Monitoring, Evaluation, and Research Committee (CMER)
Report

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Prepared by:

Dave Schuett-Hames, Ashley Roorbach, Robert Conrad

Prepared for the

The Cooperative Monitoring, Evaluation, and Research (CMER) Committee
Washington State Forest Practices Board
Adaptive Management Program
Washington State Department of Natural Resources
Olympia, Washington

December 2012 **CMER 12-1201**

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.

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.

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Full Reference

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Executive Summary

This report presents final results from the Westside Type N Buffer Characteristics, Integrity and Function study. The study was sponsored by Washington's Cooperative Monitoring, Evaluation and Research Committee (CMER). The purpose of the study was to determine the magnitude of change in FFR resource objectives (riparian stands, tree mortality, wood recruitment, channel debris, shade and soil disturbance) when the westside riparian prescriptions for Type Np (perennial non-fish-bearing) streams were applied in an operational setting.

Experimental Design. Treatment sites were randomly selected from approved forest practice applications. Three different Np riparian prescription treatments were evaluated. Eight sites had clear-cut harvest to the edge of the stream (clear-cut patches), thirteen had 50 foot wide no-cut buffers on both sides of the stream (50-ft buffers), and three had circular no-cut buffers with a 56 foot radius around the perennial initiation point (PIP buffers). An un-harvested reference reach was located in close proximity to each treatment site. Statistical tests were used to compare the clear-cut or 50-ft buffer treatments with the reference patches to determine the magnitude of the treatment effect. PIP buffer data were not used in the statistical analysis due to the small sample and lack of PIP buffer reference sites. Comparisons were done for three time periods, the first three years after harvest, years 4-5 after harvest, and for the entire first 5 years after harvest.

Riparian Stand Response. The mean density of live trees in the 50-ft buffers and reference patches decreased over the 5 year post-harvest period because tree mortality exceeded in-growth of young trees. During the first three years after harvest, tree mortality was higher in the 50-ft buffers than in the reference reaches. The mean percentage of live trees that died per year in the 50-ft buffers was 3.5 times that of the reference patches, a statistically significant difference. Wind was the dominant mortality agent in the 50-ft buffers, while suppression mortality exceeded wind mortality in the reference reaches. During years 4-5 after harvest, the difference between mortality rates for the 50-ft buffers and reference patches was not significant due to increased mortality in the reference reaches. Three storms with winds greater than 60 mph occurred during this period, including one of the strongest storms on record, and wind was the dominant mortality agent in both the reference and buffer patches. The cumulative percentage of live trees that died over the entire five year period was 27.3% in the 50-ft buffers compared to 13.6% in the reference reaches, but the difference was not statistically significant. Wind-throw contributed to a reduction in the proportion of western hemlock and an increase in western red cedar in the buffers. The higher tree fall rates in the 50-ft buffers compared to the reference patches during the first three years after harvest indicate that the newly established buffers were susceptible to wind mortality after the adjacent timber was harvested. However, the data from years 4-5 indicate that during high magnitude wind events the treatment effect is less evident due to increased wind damage in reference stands. The mean tree mortality rate for the three PIP buffers about twice as high as the rate for the 50-ft buffers in all time periods.

Large Woody Debris Recruitment. The pattern of large woody debris (LWD) recruitment was similar to that of tree mortality. During the first five years after harvest, the mean volume of LWD recruited into and over the bankfull channel was 3 times greater in the 50-ft buffers than the reference patches. As expected, LWD recruitment was very low in the clear-cut patches; one-half had no recruitment from fallen trees in the first five years after harvest. Only a small percentage of newly recruited pieces initially provided in-channel functions such as sediment storage (8%), debris jam formation (4%), step formation (3%), or pool formation (3%) because most pieces were suspended over or spanning the channel.

Channel Debris. The mean percentage of the channel area covered by woody debris (slash, small and large woody debris) three years after harvest was similar for the reference and 50-ft buffer patches, because the buffers prevented slash from the adjacent clear-cuts from entering the channel. Woody debris cover was highest in the clear-cut patches due to logging debris, averaging 65% three years after harvest and decreasing to about 50% after five years.

Stream Shade. Two metrics were used to evaluate cover that provides shade and thermal buffering for stream channels; overhead shade (e.g., trees and tall shrubs) and shade from live understory plant cover. There was a reduction in overhead cover associated with the treatments. One year after harvest, mean overhead shade was lower in the 50-ft buffer streams (76%) than in the reference patches (89%). Mean overhead shade in the clear-cut streams was 12% one year after harvest, but increased to 37% five years after harvest in response to growth of shrubs and saplings. The greatest change in understory plant cover occurred in the clear-cut streams, which increased from a mean of 18% one year after harvest to 41% by year five. Understory plant cover remained relatively consistent in the 50-ft buffer and reference streams.

Harvest-related Soil Disturbance. Soil disturbance from timber harvest within the 30 ft wide equipment limitation zone (ELZ) was minimal in the 50-ft buffers and PIP buffers because few harvested trees fell into the buffers. On average, soil disturbances occupied 0.29% of the ELZ area in the 50-ft buffers compared with 6.2% for the clear-cut patches. All 50-ft and PIP buffers met the performance target (less than 10% of the ELZ area with soil disturbance) and one of eight clear-cut patches exceeded the target. The average distance to the stream for erosion features that delivered sediment was 1 ft and the maximum was 7.7 ft.

Soil Disturbance from Uprooted Trees. The rate of soil disturbance from uprooted trees during the first five years after harvest was about twice the reference rate in the 50-ft buffers and higher in the PIP buffers. The percentage of root-pits with evidence of sediment delivery was greater in the reference patches (26%) than the 50-ft buffers (19.8%). Mean horizontal distance to the stream for root-pits that delivered sediment was 8.2 ft compared to 28.0 ft for those that did not deliver.

Implications. Riparian stands and processes in the clear-cut patches were directly affected by timber harvest due to removal of trees, input of logging debris, and soil disturbance. Retention of trees in the 50-ft and PIP buffers prevented most direct effects from timber harvest, but tree mortality during the first five years after harvest, primarily from wind, resulted in reduced stand density and changes in overhead shade and LWD recruitment. Three distinct disturbance scenarios were observed that had different implications for the FFR resource objectives, including: 1) clear-cut harvest, 2) buffers with less than 33% mortality and 3) buffers with over 50% mortality.

<u>Clear-cut scenario.</u> Harvest of nearly all trees in the clear-cut patches has implications for the wood input regime. Channels receive logging debris during harvest (branches, tops and the broken stems), but a period of low wood recruitment is expected as young trees become reestablished. Most overhead shade was removed during clear-cut harvest; however logging debris provided extensive channel cover, and shrubs and understory vegetation increased after harvest. Overhead shade should increase as the stand becomes established. There was evidence of sediment delivery from harvest-related soil disturbance; but the performance targets were met at seven of eight clear-cut reaches.

<u>50-ft buffers with over 50% mortality.</u> Mortality rates exceeded 50% at three of the 50-ft buffers. Mean tree mortality was 68.3% for these buffers over the five year period, and exceeded 90% in one case. The mean density of the remaining live trees was 62.8 trees/acre. Natural regeneration,

if successful, will result in development of a multi-cohort stand over time, however competition from shrubs and broad-leafs could reduce conifer regeneration, increasing the range of future stand conditions. These channels received a large pulse of LWD input from wind-thrown trees, however most wood was suspended over or spanning the channel and mortality has reduced the supply of trees available to provide future LWD. Mean overhead shade five years after harvest was about 30% lower than the reference reaches; however cover from understory plants and channel debris increased. Soil disturbance from uprooted trees in the first five years after harvest was over five times the rate for the reference reaches, but most root-pits did not deliver sediment.

<u>50-ft buffers with less than 33% mortality.</u> The majority of 50-ft buffers (10 of 13) had tree mortality rates less than 33% over the five year post-harvest period. Mean tree mortality for these buffers was 15%, and the mean density of live trees was 140 trees/acre five years after harvest (range 59-247). These stands are expected to continue developing as single-age stands. LWD recruitment was 40% higher than the reference rate for the five years after harvest. The remaining live standing trees will provide a source of future LWD input, and the mean diameter of recruited LWD should increase as trees continue to grow over time. Overhead shade in this group of buffers was 10-13% less than the reference reaches, and they should continue to provide high levels of overhead shade over time unless mortality rates increase. These buffers had minimal soil disturbance from uprooted trees in the first five years after harvest.

Limitations. This study had a number of limitations that should be considered when interpreting and extrapolating the results. A larger sample would be needed to capture the range of regional and local variation in site conditions and determine the effect of site conditions on riparian response to the treatments. The sample size was particularly limited for the PIP buffers (3 sites) and further sampling will be needed to confidently characterize the PIP buffer response. The analysis of PIP buffer response would also be improved by selecting reference sites with PIPs for comparison with the PIP buffer sample. Some other limitations of this study were the lack of ability to conduct pre-harvest sampling, the limited duration (five years) of post-harvest sampling, the harvest-unit scale of analysis and the lack of stream temperature data.

Future Research. Recommendations for future research included: 1) data collection over a longer timeframe to document the response of shade and channel debris in the clear-cut patches and the fate of buffers, including future tree mortality rates, tree regeneration success, shade and suspended woody debris; and 2) data collection at a large number of sites to document how variation in regional and local site conditions effect sensitivity and response to the prescriptions, including buffer survival and wind mortality, loss and recovery of shade, and LWD recruitment and function.

Conclusions. This study provides insights into the harvest unit-scale effects of the westside Type Np riparian prescriptions on riparian stand condition, and riparian processes and functions including tree fall, wood recruitment, channel debris, shade, and soil disturbance. The nature and magnitude of responses varied, depending on whether the reaches were clear-cut or buffered, and in the case of the buffered reaches, on the magnitude of post-harvest disturbance from wind-throw. Many of the performance targets for Type Np streams were confusing, so the study evaluates prescription effectiveness by comparing the treatments with unharvested reference sites of similar age. Since many of the FFR resource objectives for Type Np streams are intended to protect amphibians and downstream fish and water quality, the results of this study do not provide a complete story of prescription effectiveness. Combining the results of this study with sub-basin scale studies that examine the effects of the prescriptions on aquatic organisms and the export of heat, sediment and nutrients to fish-bearing streams will provide a more complete assessment of prescription effectiveness.

INTRODUCTION

In 2001, new regulations were approved for timber harvest on Type Np (perennial non-fish-bearing) streams on state and private forest lands in Washington State as recommended in the Forest and Fish Report (USFWS et al., 1999). The forest practice regulations for Type Np streams in western Washington require 50 foot wide no-harvest riparian buffer strips along at least 50% of the stream length in each Type Np basin. Buffers are required around all sensitive sites (e.g. stream confluences, perennial initiation points, seeps and springs) and for at least 300 feet upstream of the point where a Type Np stream enters a fish-bearing stream. In cases where the required buffers are less than 50% of the stream length being harvested in the basin, landowners select additional locations for buffers so that the total stream length buffered equals 50%. Trees may be harvested along the remaining portions of the Type Np stream network as long as soil disturbance is minimized within 30 feet of the stream. The intent of the rule is to meet the Forest and Fish Report (FFR) resource goals and objectives (maintain the viability of stream-associated amphibian populations, meet water quality standards, and maintain the productivity of downstream fish habitat) while providing opportunities for timber harvest and flexibility in harvest unit design.

The FFR Cooperative Monitoring, Evaluation and Research Committee (CMER) determined that research was needed to reduce uncertainty about the effectiveness of the Type Np riparian strategy in meeting the FFR resource objectives for headwater streams. In 2003 CMER approved a study plan titled “Type N/F riparian prescription monitoring to evaluate the effectiveness of FFR riparian prescriptions”. This document presented a strategy to evaluate performance of the FFR riparian management prescriptions and proposed a series of studies to address riparian effectiveness questions. One component of this strategy was the riparian Buffer Characteristics, Integrity and Function (BCIF) study. The purpose of the BCIF study was to begin to evaluate the effectiveness of the FFR riparian prescriptions by monitoring changes in stand conditions (stand development and trajectory), tree mortality and tree fall, shade, wood recruitment, and soil disturbance following timber harvest.

The BCIF study design included separate components to cover each of the four major riparian prescription groups: westside Type N (non-fish-bearing streams), eastside Type N, westside Type F (fish-bearing streams) and eastside Type F. In 2003, RSAG initiated the first phase of the BCIF study, which focused on the westside Type Np riparian prescriptions. This report presents the results of five years of post-harvest data collection for the Westside Type N BCIF study.

Report Organization

The first section of the report presents the study design, site selection procedures and analytic approach. Because of the large number of metrics analyzed in this study, the results are presented topically in a series of sections. The initial results section covers riparian stand response; including riparian stand conditions, tree regeneration and tree mortality. The following sections present information on changes in riparian processes and conditions affecting adjacent stream channels including tree fall processes, wood recruitment, channel debris loading, stream shade and soil disturbance. The final section synthesizes the findings and discusses their implications.

STUDY DESIGN AND ANALYTIC APPROACH

Objectives

The overall objectives of the Westside Type N BCIF study are to:

1. Obtain an unbiased estimate of post-harvest conditions associated with the western Washington Type Np riparian prescriptions,
2. Evaluate the magnitude and duration of change in comparison to untreated reference sites,
3. Identify site and stand attributes (covariates) that influence response, and
4. Determine the proportion of Type Np riparian prescription treatment sites that meet FFR performance targets for soil disturbance.

Experimental Design

Treatment sites were randomly selected from Forest Practice Applications (FPAs) approved by the Washington Department of Natural Resources (DNR) for timber harvest on Type Np streams (non-fish-bearing, perennial) in the western hemlock zone of western Washington. The random sampling design was chosen to provide an unbiased estimate of variability associated with the prescriptions when applied in an operational timber harvest setting under a range of site conditions across western Washington. Random 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. Each treatment site was paired with a similar un-harvested reference site in close proximity. Treatment site data were compared with the reference site data to determine the magnitude of the treatment effect over a five year period after harvest and to distinguish changes associated with the treatments from variation from other sources.

Study Site Selection

<u>Treatment Sites</u>

Potential treatment sites were identified by querying the DNR 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 located in western Washington that involved 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 to assess if they were suitable for inclusion in the study.

To be selected as a treatment site, both sides of a Type Np stream had to be harvested under the westside Type Np riparian buffer prescriptions for at least 300 ft (except for circular perennial initiation point buffers) 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 data from the Washington Department of Fish and Wildlife (WDFW) gap analysis program. 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 and the site selection criteria were met.

The fifteen treatment sites that were selected contained a mixture of the various treatments allowed under the westside Type Np prescriptions (Table 1). Thirteen sites included reaches (referred to as patches) with 50 foot wide, no-cut buffers on both sides of the stream (50-ft buffer patches). Eight sites included patches where timber was harvested to the edge of the stream using clear-cut harvest methods (clear-cut patches). Three sites had perennial initiation points (PIPs), the uppermost point of perennial flow identified according to criteria in the forest practices rules. The PIP buffer patches consisted of a circular buffer with a 56 ft radius surrounding the PIP.

Reference Sites

After each treatment site was accepted for inclusion in the study, a search was conducted to find an un-harvested reference site in close proximity that had similar stand and stream characteristics to the treatment site and was similar in length. Each reference site was required to be separated by at least 100 feet of forest from adjacent harvest units and roads, and not be scheduled for harvest for at least five years. Ideally, the reference site would be on the same stream as the treatment site, however in many cases this was not possible. Many Np streams are short so harvest units often encompassed most or all of an entire Np stream. In addition, it was difficult to find sites on the managed forest landscape that had timber of harvest age that were are not scheduled to be harvested in the next five years. Consequently, only 3 of 15 treatment sites had the reference located on the same stream (Table 1). In the other cases, the reference site was located as close as possible to the treatment site. A field visit was conducted at each potential reference site to collect information on site and stand characteristics. One reference site was harvested during the study period, reducing the number of useable reference sites to 14.

Analytical Approach

To determine the magnitude of change associated with the prescriptions in comparison to the reference sites, the original study design proposed a paired-sample analysis where each treatment site was paired with an un-harvested reference site in the same vicinity with similar channel and stand conditions. The paired-sample approach was proposed because there might be considerable variability in the starting conditions of the treatment sites which would add to the variability in the response to the prescriptions. The paired-sample design was a way to control for this potential source of additional variability. However, because of the difficulty in finding the one-to-one pairings where the reference sites and the corresponding treatment sites were located on the same stream, we used an independent samples test approach for comparing treatment and reference sites. This approach allowed a fuller use of available data.

Study Design and Analytic Approach

Table 1. Summary of the prescription treatments by site.

Site Number	Treatment Patch Types 50-ft Buffer	PIP Buffer	Clear-cut	Paired Reference
13	X			X
23	X			X
24	X	X	X	X
27	X		X	X
29	X			X
31		X	X	X
36	X			X
37	X			X
38	X		X	X
40[a]	X			X
47	X		X	
50[a]	X		X	X
56	X		X	X
62		X	X	X
64[a]	X			X
Total	13	3	8	14

[a] Sites where the reference and treatment patches were located on the same stream.

The Mann-Whitney (MW) test, the nonparametric equivalent of the independent samples t-test, was used to compare the means for each treatment type to the reference means across sites. The MW test selected because of concerns that the data were not normally distributed. Sample sizes for each group were small (<15) which did not provide sufficient data to test for data normality with reasonable power (e.g., power ≥ 0.80), so even if the data were transformed we would still be uncertain whether they were normally distributed or not. Many of the metrics were percentages (percent tree mortality, percent tree fall, the debris loading and obstruction metrics, stream shade metrics) so we know they are not normally distributed. An examination of the box plots for many of the metrics shows that the median is often very near the upper or lower edge of the central 50% of the data box (rather than in the middle of the box) indicating that the data are skewed. Finally, the asymptotic relative efficiency (ARE) of the MW test relative to the t-test is reasonable even when the data are normally distributed, but the converse is not true when the data are not normally distributed (Conover 1980).

Response Variables

The following groups of metrics are used to evaluate effectiveness of the Type Np riparian prescriptions:

1. Riparian stand response (changes in riparian stand conditions, tree regeneration, and tree mortality)
2. Tree fall and large woody debris (LWD) recruitment rates
3. Channel debris loading (including small debris and harvest slash)
4. Shade condition indicators
5. Harvest-related soil disturbance
6. Soil disturbance associated with uprooted trees

STUDY AREA AND CLIMATIC CONDITIONS

Study Sites

The study sites were located on non-fish bearing headwater streams in the western hemlock zone of western Washington (Figure 1). 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. Table 2 shows characteristics of the study sites.

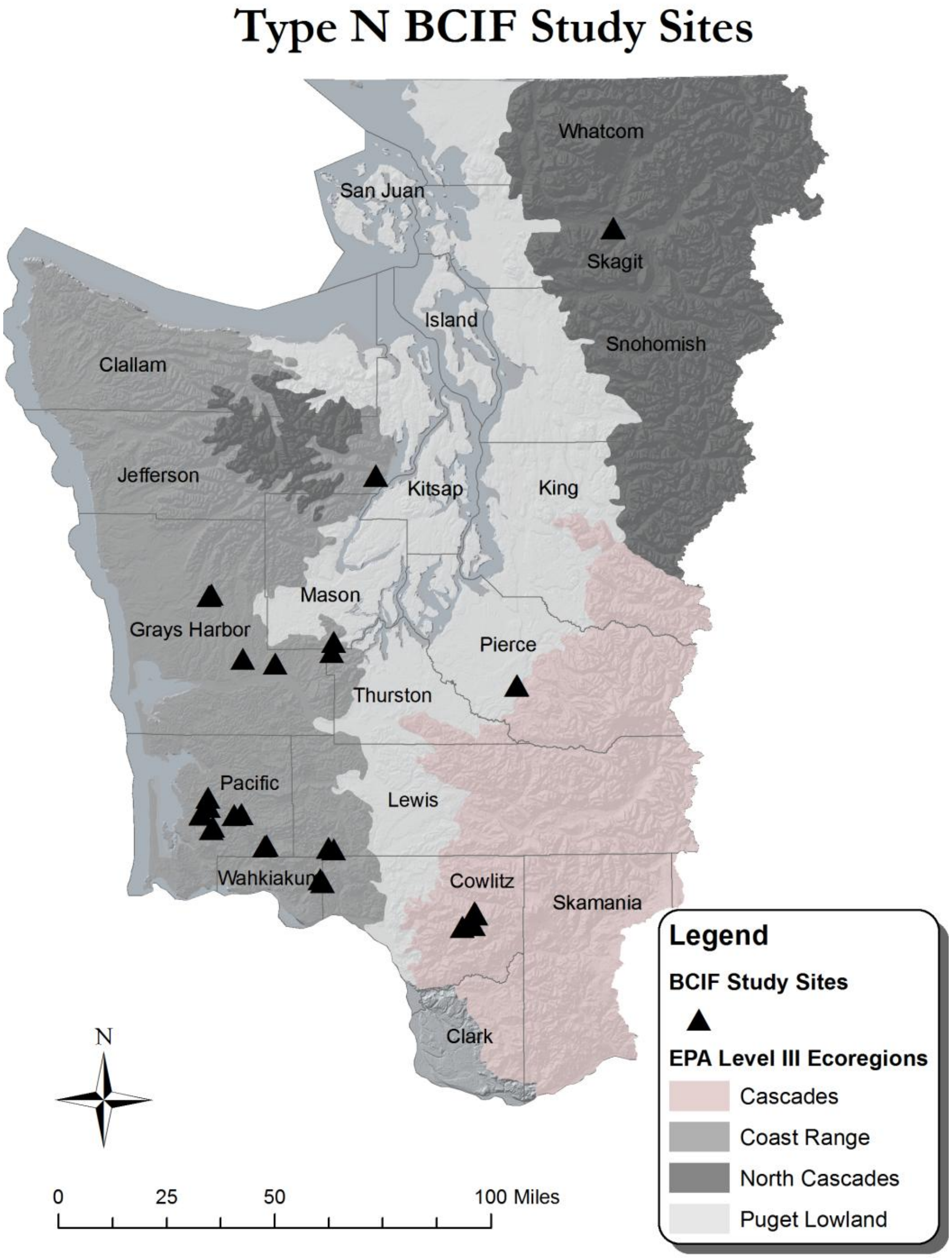

Figure 1. Westside Type N BCIF study site locations in western Washington.

Table 2. Study site attributes.

Site	Type	County	Length (ft)				EPA Level III Eco-region	Precip-itation Band (inches)	Mean Elevation (ft)	Valley Aspect (facing upstream)	Mean Channel Gradient (%)	Mean Bankfull Channel Width (ft)	Mean co-com tree ht (ft)[1]	Site Index[2]
			Total	50-ft buffer	PIP buffer	Clear-cut								
13	Reference	Cowlitz	300	-	-	-	Cascades	100-120	1460	113	14.8	6.8	81.8	125.6
13	Treatment	Cowlitz	452	452	-	-	Cascades	90-100	2880	123	19.1	3.6	101	115.8
23	Reference	Wahkiakum	339	-	-	-	Coast Range	80-90	1475	227	8.1	7.3	120.7	124.8
23	Treatment	Wahkiakum	494	494	-	-	Coast Range	80-90	1080	268	6.1	3.8	127.7	123.9
24	Reference	Pacific	800	-	-	-	Coast Range	120-140	565	020	5.1	5.6	60	113.1
24	Treatment	Pacific	787	200	117	470	Coast Range	120-140	600	060	12.1	5..3	86.7	131.3
27	Reference	Cowlitz	650	-	-	-	Cascades	100-120	1970	179	14.3	11.4		
27	Treatment	Cowlitz	985	669	-	316	Cascades	90-100	2540	188	12.6	10.8	128.2	127.7
29	Reference	Lewis	500	-	-	-	Coast Range	100-120	2150	343	14.5	5.1	79.9	113.3
29	Treatment	Lewis	607	607	-	-	Coast Range	100-120	1500	001	22.9	5.0	109.8	104.6
31	Reference	Pacific	531	-	-	-	Coast Range	100-120	860	180	4.7	5.7		
31	Treatment	Pacific	848	-	124	724	Coast Range	100-120	860	127	13.5	4.8		
36	Reference	Pacific	750	-	-	-	Coast Range	120-140	1780	178	9.1	5.9	81.3	111.2
36	Treatment	Pacific	1475	1475	-	-	Coast Range	120-140	1360	328	11.1	9.2	92.9	131
37	Reference	Grays Harbor	300		-	-	Coast Range	80-90	190	328	1.6	3.6		
37	Treatment	Grays Harbor	600	600	-	-	Coast Range	70-80	180	279	5.6	3.0	107	115.5
38	Reference	Grays Harbor	764	-	-	-	Coast Range	120-140	655	070	8.5	6.8	113.7	154.2
38	Treatment	Grays Harbor	1034	334	-	700	Coast Range	120-140	680	105	18.4	9.5	121.3	122.2
40	Reference	Pierce	380	-	-	-	Puget Lowlands	40-44	700	026	1.1	5.6	61.8	123.9
40	Treatment	Pierce	488	488	-	-	Puget Lowlands	40-44	715	003	1.0	3.1	76.4	124.4
47	Treatment	Pacific	1742	950	-	792	Coast Range	100-120	740	276	8.4	4.7		
50	Reference	Thurston	500	-	-	-	Coast Range	80-90	295	273	5.8	8.5	116.4	100.1
50	Treatment	Mason	853	425	-	428	Coast Range	80-90	215	323	4.5	4.6	113	129.6
56	Reference	Skagit	441	-	-	-	North Cascades	70-80	930	192	17.1	10.5	75	147
56	Treatment	Skagit	573	200	-	373	North Cascades	70-80	800	192	11.3	3.7	88.4	126.7
62	Reference	Pacific	400	-	-	-	Coast Range	120-140	662.5	028	9.4	8.2	80.5	127.3
62	Treatment	Pacific	420	-	132	288	Coast Range	120-140	875	047	19.3	3.8	90	138.4
64	Reference	Jefferson	450	-	-	-	Coast Range	52-56	280	042	9.7	8.2	83.8	144.5
64	Treatment	Jefferson	393	393	-	-	Coast Range	52-56	410	001	7.8	6.2	73.7	57.2

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[1] Tree height estimates are based on the mean height of all recorded co-dominant tree heights, irrespective of species.

[2] Site index based on mean site index (breast height age; base age 50) of all Douglas-fir ex values from western Hemlock were also included in those mean values, after being 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/

Climatic Conditions

Appendix Tables A-1 and A-2 show the mean summer (June-August) and winter (November–February) temperatures and precipitation for the 2003-2008 study period as a percentage of the long-term average (Western Regional Climate Center, 2009). The summer of 2003 was drier than normal (about 30 % of the long-term average precipitation). Temperature and precipitation were above average in the summer of 2004. The summer of 2006 was drier than normal, while the summers of 2007 and 2008 were cooler and wetter. The winters of 2003-2004 and 2004-2005 were warmer and drier than average. The winter of 2005-2006 was slightly warmer and much wetter than normal. The winter of 2007-2008 was colder than average.

Major Wind Storms

The frequency and magnitude of wind-storms during the study period were evaluated by examining records from five weather stations located near the study sites (Office of the Washington State Climatologist, 2009). The peak wind-speeds from these weather stations provide an indication of the magnitude of wind-storms affecting the study sites. The weather stations are located in the lowlands, while many study sites are located in mountainous terrain. Since peak wind-speeds are affected by topography (Ruel et al., 2001), the actual peak wind-speeds experienced by the study sites are unknown. Also, peak wind-speed does not address the duration of high winds, which affects the capacity of wind-storms to impact riparian buffers.

Seven wind storms with peak wind-speeds over 39 mph (gale strength or greater) were recorded at one or more of the five weather stations (Table 3). Tree mortality was calculated for two periods (fall 2003-summer 2006 and fall 2006-summer 2008), so we examined the frequency and magnitude of wind storms for each of these periods. Four of these storms occurred during the first period, and three occurred during the second period. Table 3 shows the peak wind-speeds recorded during these storms at the five weather stations. The highest peak wind-speeds were recorded during windstorms that occurred between fall 2006 and summer 2008. The December 2007 windstorm was one of the strongest storms on record, with wind-speeds reaching 94 mph in Astoria and 81 mph in Hoquiam.

Table 3. Peak wind-speeds (in miles/hour) for major windstorms at weather stations near the study sites, by sampling period (Office of the Washington State Climatologist, 2009).

Storm Event	**Astoria**	**Hoquiam**	**Kelso**	**Olympia**	**Everett**
	South Coast	Central Coast	South Cascades	Puget Lowlands	North Cascades
Fall 2003-Summer 2006 sampling period					
January 29-30, 2004	47	48	33	37	45
December 25, 2005	54	52	28	41	48
January 1, 2006	46	47	35	45	45
February 3-4, 2006	59	55	36	43	52
Fall 2006-Summer 2008 sampling period					
December 14-15, 2006	**69**	**63**	43	53	**66**
October 18, 2007	**60**	56	43	46	56
December 1-3, 2007	**94**	**81**	43	44	49

Wind-storms with peak wind-speeds between 40 and 60 mph occurred regularly in the study area. No stations recorded winds greater than 60 mph between 2003 and 2006. In contrast, during the 2006-2008 period, three stations had wind-storms with peak winds between 60-80 mph and two stations recorded wind speeds greater than 80 mph (values in bold font in Table 3).

RIPARIAN STAND RESPONSE

This component addresses uncertainty about response of riparian stands after application of Type Np riparian prescriptions; including effects of harvest and post-harvest tree mortality and tree regeneration on both live tree and dead (snag) stand components.

Critical Questions

1. What are the characteristics of riparian stands after application of the westside Type Np riparian prescriptions?
2. What is the magnitude and duration of change in riparian stands following application of the westside Type Np riparian prescriptions compared to un-harvested reference sites?
3. What are tree mortality rates after application of westside Type Np riparian prescriptions?
4. What is the magnitude and duration of change in tree mortality rates associated with the westside Type Np riparian prescriptions compared to un-harvested reference sites?

Data Collection Procedures

Standing Trees

Standing tree data were collected in 2006 (three years after harvest), and in 2008 (five years after harvest), except for one site (56) which was not sampled in 2006 due to access problems. Data were collected for all live and dead standing trees that were 4 inches or more in diameter at breast height (DBH). A census was done of all trees within 50 ft of the stream in each patch. The species, condition (live or dead), canopy class and DBH were recorded for each standing tree.

We originally planned to use low altitude aerial photography to collect tree data immediately following timber harvest. Low altitude photos were collected the spring following harvest, however technical difficulties were encountered and suitable data were not obtained from the photos. Consequently, it was necessary to reconstruct stand conditions immediately before and after harvest using the 2006 field data (2008 data for site 56). This process involved using decay class data for standing dead trees, fallen trees and stumps to determine if the trees would have been standing immediately before and after harvest in 2003. See Appendix B for a detailed description of the procedure. There is a possibility of overestimating tree counts using this approach since some trees large enough to count in the 2006 sampling event would have been too small (< 4 inch DBH) to be counted in the earlier sampling event. To avoid this, trees that would have been too small to count in 2003 (in-growth) were identified using a diameter growth rate of 0.1 inch per year, based on rates reported for understory trees in McArdle et al. (1961) and the yield tables in Wiley (1978). This corresponded with diameter growth rates from a sample of small trees collected from several study sites in 2008. Live trees with diameters ≤ 4.3 inches were categorized as in-growth for data collected in 2006 (≤ 4.5 for the site with only 2008 data). Trees designated as in-growth were not included in the 2003 stand reconstruction tables.

Tree Regeneration

Data on tree regeneration and factors affecting regeneration were collected immediately after harvest (2003), three years after harvest (2006), and five years after harvest (2008). Circular understory vegetation plots were 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 patch. 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 edge of the bankfull channel. Each understory vegetation plot had a radius of 3.72 horizontal feet (1/1000 acre). Seedlings (trees ≥ 6 inches high and < 1 inch DBH) and saplings (trees 1 to 4 inches DBH) were tallied by species. Data were taken on factors affecting regeneration success including the percentage of understory vegetation cover, dominant/sub-dominant understory vegetation species, mean shrub height and percentage of small woody debris cover.

Tree Mortality

Changes in live tree counts between sample events were used to calculate tree mortality rates.

Metrics, Hypotheses and Methods of Statistical Analysis

Live and Dead Standing Trees

The objectives for the standing tree data analysis included: 1) characterizing the riparian stand conditions for each patch type at each sample event, 2) comparing differences in stand conditions for each prescription to the reference patches at each sample event, and 3) comparing differences in the magnitude of change between sample events.

The following metrics were used to evaluate changes in stand conditions:

Trees per acre. Trees/acre was calculated by tallying the number of standing live trees (or standing dead trees) in each patch and dividing by the patch acreage.

Basal area per acre. The basal area for each tree was calculated using the formula: *basal area* $(ft^2) = 0.005454 * dbh^2$ *(in)*. The stand basal area/acre was calculated by summing the basal areas of all standing live trees (or standing dead trees) and dividing by the patch area in acres.

Mean breast height diameter. This parameter was calculated by averaging the DBH of all standing live trees (or standing dead trees) in each patch.

Quadratic mean diameter. Quadratic mean diameter (QMD) in inches was calculated for the standing live trees in each patch using the formula: *QMD = square root of the mean basal area of the patch divided by 0.005454*.

Percentage of live conifer. The percentage of live conifer trees/acre was calculated by summing the live conifer trees/acre and dividing by the total live trees/acre for the patch. Percent live conifer by basal area/acre was calculated in a similar fashion using basal area/acre data.

Box-and-whiskers plots (Hoaglin et al., 1983) were used to compare the distribution of measurements for each metric at each sample event by patch type. The central quartiles of the data (the central 50% of the data) are encompassed in the shaded box with the median value indicated by the black line. The whiskers include all data values not considered outliers or extreme values. Outliers (values between 1.5 and 3 box lengths from the upper or lower edges of the box) are marked with open circles. Extreme values are more than three box lengths from the upper or lower edges of the box and are marked by asterisks.

A one-tailed hypothesis test was used to compare stand conditions of prescription groups to the reference group at each sample event. The one-tailed null hypothesis was stated as:

> H_o: the average condition for patches receiving a particular prescription is equal to or greater than (or is equal to or less than) the average reference patch condition.

A two-tailed hypothesis was used to compare changes in conditions between sample events. The two-tailed hypothesis was stated as:

H_o: average <u>change</u> in conditions between sample events for patches receiving a particular prescription = average <u>change</u> in conditions for the reference patches.

Because the data were usually not normally distributed, the non-parametric two-sample Mann-Whitney (MW) test (Conover, 1980) was used to test for differences between the reference patches and patches receiving one of the treatments. The MW test did not require a data normality assumption or a transformation of the data. The level of significance was 0.10.

Tree Regeneration

Percentage of plots with regeneration. Because of the prevalence of plots with zero values for seedling and sapling density, and very low densities when seedling or saplings were present, statistical analysis of these density data was not appropriate. Consequently, the analysis focused on the percentage of plots where regeneration was present (combined seedling and sapling count > 0). The percentage of understory vegetation plots with regeneration was calculated for each patch by counting the number of plots where at least one seedling or sapling was present and dividing by the total number of plots in the patch. The two-tailed hypothesis was stated as:

H_o: the relative frequency of plots with regeneration for a prescription type = the relative frequency of plots with regeneration for reference patches.

Fisher's Exact test was used to compare the mean percentage of plots where regeneration was observed for the prescription patches versus reference patches at each sample event. The level of significance was 0.10.

Percent understory vegetation cover. The mean percentage of shrub and herb cover for each patch was calculated by averaging the values for all the understory vegetation plots in the patch. The two-tailed hypothesis was stated as:

H_o: average condition for patches for a Type Np prescription = average condition for the reference patches

As percentages, these metrics are bounded by 0% and 100%. Examination confirmed that these data should not be considered normally distributed, so the MW test was used to test for differences between reference patches and patches receiving one of the prescription treatments. The level of significance was 0.10.

Tree Mortality

The following metrics were used to evaluate changes in tree mortality rates:

Mortality in trees per acre per year. The tree mortality rate in trees/acre/year was calculated for three periods: the first three years immediately after harvest (2003 to 2006), years 4 through 5 after harvest (2006 to 2008), and the entire first five years after harvest (2003 to 2008). The number of trees that died in each period was calculated by subtracting the number of live standing trees/acre present at the end of the period from the live standing trees/acre present at beginning of the period. Annual rates for each period were calculated by dividing by the number of years in the period. Each year included a winter storm season. To avoid underestimating mortality due to in-growth of young trees, we did not include trees that would have been too small to be counted at the beginning of the period (based on a growth rate of 0.1 inch/year) when calculating mortality rates.

Percent mortality per year. This metric was calculated for each of the three time periods by dividing tree mortality in trees/acre during each period by the live standing trees/acre at the start of the period, and then dividing by the number of years in the period.

Riparian Stand Response

The objectives for the tree mortality analysis included: 1) characterizing the annual standardized rates for each patch type for the 2003 to 2006 period, the 2006 to 2008 period, and for the entire 2003 to 2008 period, and 2) comparing the prescription patch rates to the reference patch rates.

Mortality in trees/acre/year. A two-tailed hypothesis was used to compare the standardized annual rates for each of the three time periods stated as:

H_o: average standardized annual rate between sample events for a prescription patch type = average standardized annual rate for the reference patches.

The distribution of tree mortality rates was heavily weighted toward rates at or near zero, with an extended right tail to the distribution. Examination confirmed that these data should not be considered normally distributed so the non-parametric, two-sample MW test was used to test for differences between the reference patches and patches receiving one of the prescription treatments. The level of significance was 0.10.

Percent mortality per year. A two-tailed hypothesis was used to compare the standardized annual rates for each of the three time periods stated as:

H_o: average standardized annual rate between sample events for the prescription patches = average standardized annual rate for the reference patches.

This metric was calculated as a proportional decrease, bounded by 0 and 1. Examination confirmed these data should not be considered normally distributed. Therefore, the MW test was used to test for differences between the reference patches and patches receiving one of the prescriptions. The level of significance was 0.10.

Results

Live Standing Trees

Overview of Patterns in Live Standing Tree Metrics

Immediately after harvest in 2003, mean live tree density in the reference patches was higher than the 50-ft buffers due to pre-existing differences in riparian stand conditions prior to harvest (Table 4, Figure 2). Mean live tree density decreased by about 25 trees/acre in both the reference and 50-ft buffers over the first five years following harvest. On average, the 50-ft buffers lost more basal area between 2006 and 2008 than the reference patches. Live tree density and basal area/acre were low in the clear-cut patches following harvest, indicating that few trees remained after harvest. Mean diameter breast height and quadratic mean diameter were greater in the 50-ft buffers than the reference patches in 2006 and 2008 (Table 4).

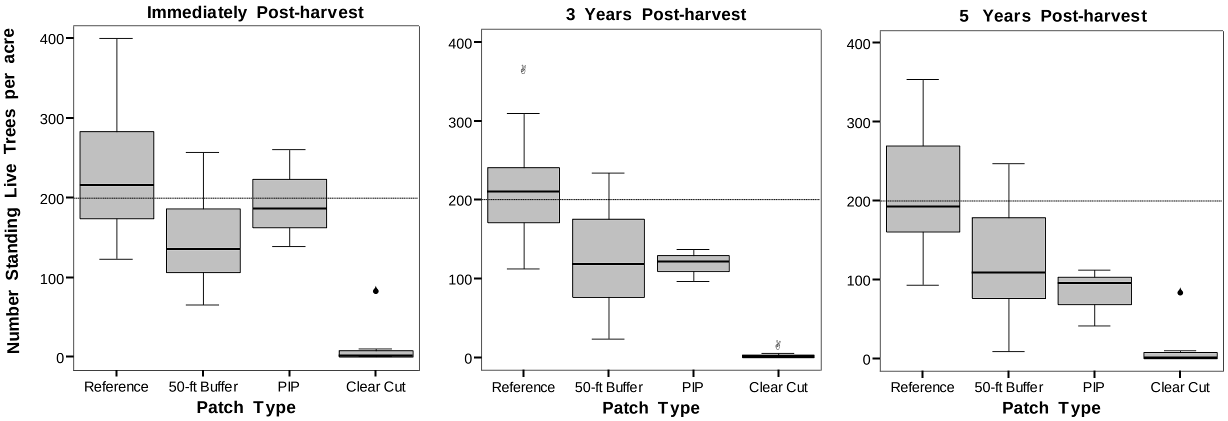

Figure 2. Distributions of standing live trees per acre by patch type, at each sample event.

Riparian Stand Response

Table 4. Descriptive statistics for live standing tree metrics by patch type; immediately (2003), three years (2006) and five years (2008) after harvest.

Patch Type	**n**	**Live trees/acre**		**Basal area/acre (ft^2)**		**Live DBH (in)**		**Live QMD (in)**	
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
2003									
Reference	14	234.5	76.9	-[2]		-[2]		-[2]	
50-ft buffer	13	149.3	60.7	-[2]		-[2]		-[2]	
Clear-cut	8	12.5	27.3	-[2]		-[2]		-[2]	
PIP buffer	3	195.2	61.5	-[2]		-[2]		-[2]	
2006									
Reference	13	217.8	66.2	218.1	35.8	12.9	2.6	14.0	2.8
50-ft buffer	12	127.5	64.0	160.5	68.1	14.3	3.2	15.9	3.5
Clear-cut	7	2.7	3.9	1.8	2.2	11.5	8.1	11.9	8.1
PIP buffer	3	118.7	20.4	178.3	72.0	14.9	1.2	16.3	2.0
2008									
Reference	14	210.4	72.7	212.3	43.3	13.0	2.7	14.1	2.8
50-ft buffer	13	122.2	71.1	148.0	74.2	13.9	3.5	15.7	3.8
Clear-cut	8	12.0	27.5	6.1	14.6	7.9	2.7	8.4	3.1
PIP buffer	3	82.7	37.2	130.8	76.8	14.9	1.6	16.5	2.7

[1] SD = standard deviation; 2 data not available for the 2003 post-harvest event.

Conifers were dominant over broad-leaf trees in all patch types (Table 5). There was little change in percentage of conifers in the reference and 50-ft buffer patches over the five year period, despite mortality and in-growth. The percentage of conifers was lower in the clear-cut patches and decreased over time.

Table 5. Mean percentage of conifer (trees/acre and basal area/acre) by patch type.

	Percent conifer trees/acre		**Percent conifer basal area/acre**
	Immediately after harvest	**5 years after harvest**	**5 years after harvest**
Reference	78.3	78.4	82.8
50-ft buffer	70.5	70.6	77.9
Clear-cut	82.5	68.2	64.9
PIP buffer	95.6	96.0	95.3

The mean percentage of live standing trees by species immediately after harvest (2003) and after five years (2008) is shown in Table 6. Initially after harvest, western hemlock and Douglas-fir were the dominant species by tree count in the reference stands, each with slightly over one-third of the total tree count, and red alder ranked third. Western hemlock was the most common species in the 50-ft buffers, followed by red alder and Douglas-fir. Western hemlock and western red cedar were the dominant species following harvest in the clear-cut and PIP buffer patches. Over the five year period, the percentage of western hemlock decreased in the buffer patches, and the percentage of western red cedar increased. Species composition remained stable in the reference patches.

Riparian Stand Response

Table 6. Mean percent live tree count by species for each patch type.

Species	Reference		50-ft buffer		PIP buffer		Clear-cut	
	2003	**2008**	**2003**	**2008**	**2003**	**2008**	**2003**	**2008**
Western hemlock (Tsuga heterophylla)	34.62	34.91	39.29	36.08	70.78	57.60	38.73	20.74
Douglas-fir (Pseudotsuga menziesii)	36.39	37.01	19.24	20.07	1.73	0.00	2.38	25.00
Red alder (Alnus rubra)	16.44	16.42	22.36	22.54	4.44	4.01	10.78	19.34
Western red cedar (Thuja plicata)	4.33	4.61	6.75	9.01	21.29	31.35	23.38	15.00
Big-leaf maple (Acer macrophylla)	2.23	2.38	4.93	5.32	0.00	0.00	6.76	12.43
Sitka spruce (Picea sitchensis)	1.98	1.00	2.92	4.10	1.75	7.04	2.38	5.00
Pacific silver fir (Abies amabilis)	0.73	0.00	1.68	0.01	0.00	0.00	14.29	0.00

Hypothesis Testing for Live Standing Tree Metrics

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches in the live standing tree metrics at each sample event. A second test was conducted to determine if the change in values between sample events for each prescription were significantly different from the changes observed in the reference patches. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. reference comparison

There was a large difference between the reference and clear-cut patches in mean live trees/acre and live basal area/acre immediately after harvest in 2003 because most trees in the clear-cut patches were cut (Table 4). These differences persisted for the entire five year period and were significant for all sample events ($P < 0.001$), so the null hypotheses were rejected and we concluded that live tree density and live basal area/acre were significantly lower in the clear-cut patches after harvest.

50-ft buffer versus reference comparison

Mean live tree density was higher in the reference patches than the 50-ft buffers immediately after harvest. The difference was statistically significant so the null hypothesis was rejected (Table 7). The difference is due to the higher density of the reference patches at the start of the study rather than to harvest-related mortality in the 50-ft buffers. The initial difference in mean live tree density persisted and was significant in 2006 and 2008 despite decreases in live tree density for both the 50-ft buffer and reference patches. Live basal area/acre was also significantly lower in the 50-ft buffers in 2006 and 2008.

Riparian Stand Response

Table 7. 50-ft buffer prescription versus reference patch comparison for mean live trees/acre and mean live basal area/acre by sample event with results of the Mann-Whitney test.

Sample Event	50-ft Buffer Mean	Reference Mean	Difference (50-ft Buffer–Reference)	*P*-value of the MW test[a]
Standing Live Trees per Acre				
2003	149.3	234.5	-85.2	**0.003**
2006	127.5	217.8	-90.3	**0.002**
2008	122.2	210.4	-88.2	**0.002**
Standing Live Tree Basal Area per Acre				
2006	160.5	218.1	-57.6	**0.007**
2008	148.0	212.3	-64.3	**0.010**

[a] One-sided test of H_o: prescription ≥ reference. Tests significant with $P \leq 0.10$ are in bold.

The mean change (decrease) in live trees/acre was nearly three times greater for the 50-ft buffers than the reference patches in the 2003 to 2006 period, and the difference was significant so the null hypothesis was rejected (Table 8) and we concluded that there was a treatment effect. However the differences were not significant for the 2006 to 2008 period or for the entire five year period so the null hypothesis was not rejected for these periods.

Table 8. 50-ft buffer prescription versus reference patch comparison of mean change between sample events for live trees/acre and basal area/acre, with results of the Mann-Whitney test.

Time Period	Mean Change 50-ft Buffer	Mean Change Reference	Difference (50-ft buffer–Reference)	*P*-value of the MW test[a]
Change in Standing Live Trees per Acre				
2003-2006	-23.0	-8.0	-15.0	**0.051**
2006-2008	-6.6	-16.2	9.6	0.437
2003-2008	-27.1	-24.1	-3.0	1.000
Change in Standing Live Tree Basal Area per Acre				
2006-2008	-7.5	-2.2	-5.3	0.406

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold

There was not a significant difference between the 50-ft buffer and reference patches in the percentage of live conifer, by trees/acre or basal area/acre.

PIP Buffer Observations

The three PIP buffer patches followed the pattern of declining trees/acre and basal area/acre observed in the 50-ft buffer patches over the post-harvest period, however the rate of decrease was greater in the PIP buffers (Table 4). Immediately after harvest in 2003, mean live trees/acre was greater in the PIP buffer patches than the 50-ft buffer patches but by 2008 the mean density for the PIP buffers had decreased by over 50% and was 40 trees/acre less than the mean for the 50-ft buffers. Mean basal area/acre also decreased between 2006 and 2008 in the PIP buffers.

Dead Standing Trees

Overview of Patterns in Dead Standing Tree Metrics

Table 9 shows dead tree metrics by patch type, immediately after harvest (2003), three years after harvest (2006) and after five years (2008). Immediately after harvest, mean dead standing tree density was higher in the reference patches than the 50-ft buffers. Over the next five years, the increase in dead trees/acre was greater in the reference patches than in the 50-ft buffers. Mean dead tree density and basal area/acre were low in the clear-cut patches because most trees were cut.

Table 9. Descriptive statistics for dead standing tree metrics by patch type; immediately (2003), three years (2006) and five years (2008) after harvest.

Patch Type	n	Dead trees/acre		Dead basal area/acre (ft^2)		Dead DBH (in)	
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
2003							
Reference	14	28.9	17.0	[2]		[2]	
50-ft buffer	13	21.8	15.7	[2]		[2]	
Clear-cut	8	2.3	3.6	[2]		[2]	
PIP buffer	3	19.0	18.1	[2]		[2]	
2006							
Reference	13	37.1	21.5	31.9	35.2	9.2	2.5
50-ft buffer	12	24.8	18.2	23.1	17.1	11.3	1.5
Clear-cut	7	1.5	2.7	2.1	5.0	10.4	5.1
PIP buffer	3	25.2	17.8	43.2	22.2	17.7	8.2
2008							
Reference	14	38.0	25.3	28.8	30.8	9.0	2.5
50-ft buffer	13	24.7	17.1	24.6	18.0	11.4	2.3
Clear-cut	8	2.5	3.9	1.4	2.5	8.8	2.2
PIP buffer	3	19.0	9.3	43.3	25.2	18.2	5.2

[1] SD = standard deviation; [2] data were not available for the 2003 post-harvest event.

Hypothesis Testing for Dead Standing Tree Metrics

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches in the dead standing tree metrics at each sample event. A second test was conducted to determine if the changes in values between sample events for each prescription were significantly different from the changes observed in the reference patches. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. reference comparison

Immediately after harvest in 2003, dead standing tree density was very low in the clear-cut patches (Table 9), and dead tree density and basal area remained very low in the clear-cut patches in 2006 and 2008. The differences between the clear-cut and reference patches were statistically significant for all sample events ($P < 0.001$), so the null hypotheses were rejected and we concluded that dead standing tree density and basal area/acre were significantly lower in the clear-cut patches after harvest.

50-ft buffer vs. reference comparison

Mean dead tree density in the 50-ft buffers immediately after harvest in 2003 was lower than the reference patch value but the difference was not significant (Table 10). Mean dead standing tree density increased in the reference patches between 2003 and 2006, while there was little change in the 50-ft buffers. The differences were statistically significant for the 2006 and 2008 sample events, so the null hypothesis was rejected. Despite the differences in density, mean dead basal area/acre for the 50-ft buffer and reference patches was similar in 2008 due to the smaller mean DBH of dead trees in the reference stands.

Table 10. 50-ft buffer prescription versus reference comparison for mean dead standing trees/acre and dead basal area/acre by sample event, with results of the Mann-Whitney test.

Sample Event	50-ft Buffer Mean	Reference Mean	Difference (50-ft Buffer–Reference)	*P*-value of the MW test[a]
Standing Dead Trees per Acre				
2003	21.8	28.9	-7.1	0.160
2006	24.8	37.1	-12.3	**0.084**
2008	24.7	38.0	-13.3	**0.047**
Standing Dead Basal Area per Acre				
2006	23.1	31.9	-8.8	0.384
2008	24.6	28.8	-4.2	0.453

[a] One-sided test of H_o: prescription ≥ reference. Tests significant with $P \leq 0.10$ are in bold.

PIP Buffer Observations

Immediately after harvest in 2003, the mean density of dead standing trees in the three PIP buffer patches was similar to that of the 50-ft buffer patches (Table 9). Dead tree density in the PIP buffer patches increased between 2003 and 2006 and then decreased in 2008. Mean dead basal area/acre in the PIP buffers was greater than in the 50-ft buffer patches due to the greater mean diameter of dead trees in the PIP buffers.

In-growth

In-growth occurs when saplings grow and reach the 4 inch DBH threshold to be classified as trees. In-growth of new trees in trees/acre was similar in the reference and 50-ft buffer patches and much lower in the clear-cut and PIP buffer patches during the first five years after harvest (Table 11). However, as a percentage of total live trees/acre the rate of in-growth in the 50-ft buffers was double the rate of in-growth in the reference patches. Because the diameter of these young trees is small (4 - 4.5 in), in-growth contributed less than 1 ft^2 of basal area/acre, making up less than 1% of the total live basal area for the reference patches and 50-ft buffers.

Table 11. In-growth in trees/acre and basal area/acre as a percentage of total live trees first five years after harvest by patch type.

Patch type	Trees/acre	Percent of total live trees/acre	Basal area/acre	Percent of total live basal area/acre
Reference	7.8	3.3%	0.8	0.4%
50-ft buffer	8.8	7.0%	0.9	0.7%
Clear-cut	0.8	6.5%	0.1	2.2%
PIP buffer	3.4	3.4%	0.4	0.2%

Seedling and Sapling Regeneration

The percentage of understory vegetation plots where seedlings or saplings were present is shown in Table 12. Immediately after harvest in 2003, seedlings/saplings were present in a similar percentage of understory vegetation plots in the reference and 50-ft buffer patches. There was little change over time in the mean percentage of plots with regeneration for the reference patches, while the percentage tripled in the 50-ft buffers patches. The percentage of plots with seedlings and samplings in the clear-cut patches increased between 2003 and 2006; however the 2006 and 2008 clear-cut data include seedlings from reforestation planting required by the forest practices rules.

Table 12. Percentage of understory vegetation plots with seedlings or saplings by patch type.

	2003	**2006**	**2008**
Reference	12.5%	10.0%	11.1%
50-ft buffer	11.8%	21.0%	36.8%
Clear-cut	16.7%	42.3%	39.6%
PIP buffer	27.8%	38.9%	38.9%

The mean percentages of shrub and understory plant cover by patch type are shown in Table 13. Immediately after harvest in 2003, the percentage was similar for the 50-ft buffer and reference patches and lower in the clear-cut patches. Three years after harvest in 2006, mean shrub and plant cover increased for all patch types, with the greatest change in the 50-ft buffer (+19.8%) and clear-cut patches (+32.5%). Plant cover in the reference and 50-ft buffer patches decreased at year five, while remaining steady in the clear-cut patches.

Table 13. Descriptive statistics for percent shrub and understory plant cover by patch type; immediately (2003), three years (2006) and five years after harvest (2008).

Patch Type	**n**	**2003**		**2006**		**2008**	
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
Reference	14	33.1%	14.7	43.4%	16.1	25.7%	10.4
50-ft buffer	13	29.3%	23.4	49.1%	17.2	32.7%	16.0
Clear-cut	8	10.8%	10.9	43.3%	20.4	41.9%	17.1
PIP buffer	3	12.6%	3.1	28.5%	11.4	30.6%	16.2

[1] SD = standard deviation

Hypothesis testing for regeneration metrics

This section presents results of Fisher's Exact test that was conducted to determine if there were significant changes in the percentage of plots with regeneration and in the percentage of shrub and understory plant cover at each sample event in the 50-ft buffer and clear-cut patches in comparison to the reference patches. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. reference comparison

There was not a significant difference in the mean percentage of understory vegetation plots with regeneration between the clear-cut patches and reference patches immediately after harvest in 2003 (Table 12). However, the mean percentage for the clear-cut patches increased to about 4 times the reference patch level in 2006 and 2008 and the differences were statistically for these events. Young conifers were planted in the clear-cut patches as required by the forest practices rules, and the regeneration data for the clear-cut patches included both planted stock as well a natural regeneration in 2006 and 2008.

Riparian Stand Response

The differences between the clear-cut and the reference patches in percent shrub and understory plant cover were statistically significant for the 2003 and 2008 sample events ($P \leq 0.035$), however the mean clear-cut patch value was lower than the reference immediately after harvest and higher after five years (Table 13). Consequently, we rejected the null hypotheses for those events and concluded there was an increasing trend in percent shrub and understory plant cover in the clear-cut patches over the first three years following treatment.

50-ft buffer vs. reference comparison

The percentage of understory vegetation plots where regeneration was observed was similar for the 50-ft buffer and reference patches immediately after harvest (Table 12). The percentage of plots with regeneration increased in 2006 and 2008 for the 50-ft buffers to 2 and 3 times the reference rates, respectively. These differences were statistically significant, so we concluded that regeneration was greater in the 50-ft buffer patches in 2006 and 2008. There were no significant differences between the 50-ft buffers and the reference patches in mean percentage of shrub and understory plant cover for any time period so the null hypotheses were not rejected.

PIP Buffer Observations

The mean rate of in-growth during the first five years after harvest for the three PIP buffer patches was lower than for the 50-ft buffer patches (Table 11). The mean percentage of plots with regeneration was greater initially greater in the PIP buffer patches than in the 50-ft buffers (Table 12). Although the percentage of PIP buffer plots with regeneration increased from 27.8% immediately after harvest to 38.9% in 2008, the rate of increase was greater in the 50-ft buffer patches, and by 2008 the percentages were similar. The mean percentage of shrub and understory plant cover in the PIP buffers was about half that of the 50-ft buffers immediately after harvest in 2003, but increased over time and was similar to the percentage in the 50-ft buffers by 2008 (Table 13).

Tree Mortality

Overview of Patterns in Tree Mortality

This section describes patterns in tree mortality for years 1-3 after harvest (2003-2006), years 4-5 after harvest (2006-2008) and the first five years after harvest (2003-2008). Mortality includes live trees that died during the period, regardless of whether they fell or not. Table 14 shows mean tree mortality by patch type as the percentage of live trees that died per year and in trees/acre/yr. The distribution of patch values is shown in Figure 3. During the first three years after harvest (2003-2006), mean tree mortality in the 50-ft buffer patches was over twice the reference patch rate in trees/acre/yr and over three times the reference patch rate as a percentage of live trees that died per year (due to the lower starting density in the 50-ft buffer patches). During years 4-5 after harvest (2006-2008), tree mortality as a percentage of live trees increased for all patch types, but the increase was greater in the reference patches than the 50-ft buffer patches. Over the entire 5 year period, percent mortality in the 50-ft buffers (5.5%/year) was nearly double the rate for the reference patches (2.7%/year), although there was little difference in mortality expressed as trees/acre/yr. Mortality as a percentage of live trees was greater in the clear-cut patches than in the reference or 50-ft buffer patches for all time periods, however the mortality rate in trees/acre/yr was low because the density of live trees available as potential mortality was low.

Riparian Stand Response

Table 14. Descriptive statistics for tree mortality metrics by patch type for years 1-3 (2003-2008), years 4-5 (2006-2008) and the entire first five years (2003-2008) after harvest.

Patch Type	n	Tree Mortality			
		Percent mortality/yr		**Mortality in trees/acre/yr**	
		Mean	SD[1]	Mean	SD[1]
2003-2006					
Reference	14	1.9 %	1.5 %	4.5	4.7
50-ft buffer	13	6.8 %	6.9 %	9.6	9.3
Clear-cut	8	12.1 %	16.6 %	0.2	0.2
PIP buffer	3	11.7 %	8.6 %	26.3	25.4
2006-2008					
Reference	13	4.1 %	4.1 %	8.5	8.9
50-ft buffer	12	7.4 %	10.2 %	5.1	5.1
Clear-cut	7	16.0 %	22.9 %	0.3	0.3
PIP buffer	3	16.8 %	11.7 %	18.5	10.9
2003-2008					
Reference	14	2.7 %	1.7 %	6.4	4.4
50-ft buffer	13	5.5 %	5.2 %	7.4	7.0
Clear-cut	8	10.0 %	9.5 %	0.3	0.3
PIP buffer	3	10.6 %	6.3 %	23.2	19.2

[1] SD = standard deviation

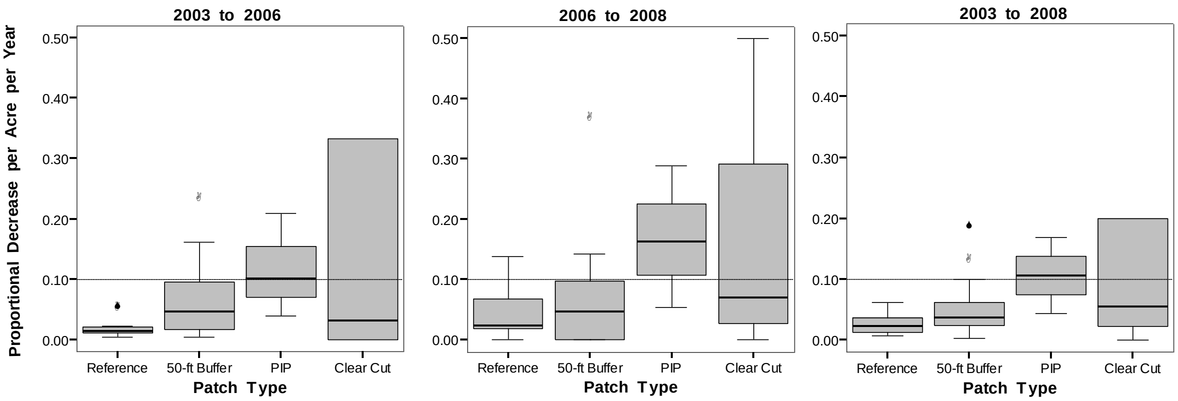

Figure 3. Distributions of proportional rates of tree mortality by patch type for the 2003-2006 (left panel), 2006-2008 (center panel) and 2003-2008 (right panel) time periods.

Hypothesis Testing for Tree Mortality Metrics

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches for mean annual rates of tree mortality in trees/acre/yr and percent/yr for each of three post-harvest time periods. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. reference comparison

Tree mortality in trees/acre/yr for the clear-cut patches was very low for all time periods because few live trees remained after harvest (Table 14). The differences between the clear-cut and reference rates for tree mortality on a trees/acre basis were statistically significant for all time periods ($P \leq 0.003$). In contrast, the percentage of the live trees that died during each period was high for the clear-cut patches, 6 times the reference rate for the first three years after harvest, and about 4 times the reference rate for years 4-5 and the entire five year period. However, the difference between the clear-cut and the reference patches in percent mortality was not statistically significant so the null hypothesis was not rejected for any time period.

50-ft buffer vs. reference comparison

Mean tree mortality as the percentage of live trees that died per year during the first three years after harvest (2003-2006), was 3.5 times greater in the 50-ft buffers than the reference rate. This difference was statistically significant so the null hypothesis was rejected (Table 15). Although mean mortality in trees/acre/yr was twice as high in the 50-ft buffers as in the reference patches during the first three years, the probability level ($P = 0.148$) did not reach the threshold of significance so the null hypothesis was not rejected. Tree mortality increased in the reference patches between 2006 and 2008, and the difference in the percentage of live trees that died was not significant. Because the mean starting density in the 50-ft buffers was lower at the start of the second period, mortality in trees/acre/yr was lower in the 50-ft buffers. Over the entire five year period, mean tree mortality as a percentage of live trees is nearly twice as high for the 50-ft buffers as the reference patches, while mean mortality in trees/acre/yr was only slightly higher in the 50-ft buffers. Neither difference was significant, so the null hypothesis was not rejected.

Table 15. 50-ft buffer versus reference comparison for tree mortality rates as percentage of live trees that died in each period with results of the Mann-Whitney test.

Sample Event	50-ft buffer Mean	Reference Mean	Difference (50-ft buffer–Reference)	*P*-value of the MW test[a]
Tree mortality (percent per year)				
2003-2006	6.8%	1.9%	4.9%	**0.044**
2006-2008	7.4%	4.1%	3.3%	0.688
2003-2008	5.5%	2.7%	2.8%	0.169
Tree mortality (trees per acre per year)				
2003-2006	9.6	4.5	5.1	0.148
2006-2008	5.1	8.5	-3.4	0.252
2003-2008	7.4	6.4	1.0	0.991

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold.

PIP Buffer Observations

Tree mortality rates in the three PIP buffers were consistently higher than rates in the 50-ft buffers during all time periods. Over the five year period, the PIP buffer mortality rate was about twice as high as the rate for the 50-ft buffers in terms of percent mortality and three times as high in terms of trees/acre/yr (Table 14). The mean percentage of live trees that died in the PIP buffers was greater in 2006-2008 period than in the 2003-2006 period, although mortality in trees/acre decreased. This was due to the lower density of live trees in the second period due to high mortality in the previous period.

Riparian Stand Response

Tree Mortality Processes

Tree mortality processes were grouped into five categories: wind, suppression, physical damage (knocked down by other falling trees), other (erosion, insect, lightening, etc.) and unknown. Table 16 shows the percentage of tree mortality attributed to each category.

During the first three years after harvest (2003-2006), wind was the primary cause of mortality in the 50-ft buffers and PIP buffers. In contrast, wind was a minor factor the reference patches during this period while suppression accounted for a greater proportion of the mortality.[3] During years 4-5 after harvest (2006-2008), wind continued to be the primary tree mortality agent in the 50-ft buffers (51.9%) and PIP buffers (97.2%), and mortality from wind increased to 34.7% in the reference patches, exceeding mortality attributed to suppression. Over the entire five year period (2003-2008), wind accounted for about half of the mortality in the 50-ft buffers and 86.8% of mortality in the PIP buffers compared to 28.5% in the reference patches.

Table 16. Percentage of tree mortality by mortality processes, patch type and time period.

Time period	Patch type	Wind	Suppression	Physical	Other	Unknown
2003 to 2006	Reference	6.8	23.7	4.8	9.5	55.1
	50-ft buffer	55.5	0.93	12.5	1.4	29.7
	PIP buffer	73.7	0	26.3	0	0
2006 to 2008	Reference	34.7	26.3	6.7	1.4	30.8
	50-ft buffer	51.9	5.7	5.7	1.2	35.5
	PIP buffer	97.2	0	2.8	0	0
2003 to 2008	Reference	28.5	23.9	6.9	4.7	36.0
	50-ft buffer	49.5	2.9	10.0	1.8	35.8
	PIP buffer	86.8	0	13.2	0	0

Discussion

Changes in Riparian Stands Following Harvest under the Prescriptions

The mean density of live trees decreased over time in both the 50-ft buffer and reference patches over the five year period. During the first three years after harvest, the decrease in live tree density was greater in 50-ft buffers than the reference patches, and the difference was statistically significant. However, over the entire five year period, mean change in density for the 50-ft buffers was similar to that in un-harvested reference stands. The decrease in mean density was greater for PIP buffers than for the 50-ft buffer or reference stands for all time periods.
The clear-cut patches had very low densities of live or dead standing trees after harvest. Although this finding appears obvious, it addresses uncertainty about the number of riparian trees voluntarily left along Type Np streams in clear-cut reaches due to operational considerations.

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[3] In all likelihood mortality from suppression is under-estimated because it was difficult to determine the mortality process for dead standing trees, so it is likely some trees that died from suppression were reported as ‘unknown’

Effect of Tree Mortality Rates on Riparian Stand Trajectory

The decreasing trend in tree density and basal area over time indicates that tree mortality processes had a greater effect on stand conditions than in-growth (growth of saplings into trees) for all patch types. Over the first five years after harvest, mortality on a percentage basis was about 4 times greater than in-growth for the reference and 50-ft buffer patches, over 8 times higher for the clear-cut patches and over 15 times higher for the PIP buffers (Table 17).

Table 17. Comparison of mean mortality and in-growth rates for the first five years harvest.

Patch type	Mortality		In-growth	
	Trees/acre	Percentage	Trees/acre	Percentage
Reference	31.9	13.6%	7.8	3.3%
50-ft buffer	36.9	27.3%	8.8	7.0%
Clear-cut	1.4	50.0%	0.8	6.5%
PIP buffer	116.0	52.8%	3.4	3.4%

Factors Contributing to Differences in Mortality Rates Among Patch Types

Wind-throw was the dominant mortality process over time and strongly influenced patterns in tree mortality. The primary factors influencing wind-throw rates appear to be: 1) differences in vulnerability to wind damage associated with timber harvest treatment and topographic setting, and 2) differences in the strength of wind storms that occurred during the two sampling periods. These factors, and the interaction between them, appear to explain much of the variation in tree mortality rates. However, there was extensive variability in tree mortality, both within prescription groups and within sample periods, indicating that site-specific factors affecting wind speed or the sensitivity of trees to wind damage influence tree mortality rates at individual sites.

Vulnerability of riparian buffers to wind damage

The tree mortality data from the first three years after harvest highlight the vulnerability of newly established buffers to wind damage after the adjacent timber is harvested. During this period four wind-storms of moderate intensity (40-60 mph peak wind speed) were recorded at weather stations in the area and tree mortality rates followed a distinct pattern. The reference patches, riparian stands embedded in continuous second-growth forests, had the lowest mean tree mortality rates (1.9%/yr). Tree mortality rates were higher (6.8%/yr) in the 50-ft buffers, which consisted of 50-foot wide bands of trees left along both sides of the stream and in the PIP buffers (11.7%/yr), small circles of trees surrounded by clear-cuts located at the upper end of the drainage. The higher tree mortality rates in the 50-ft buffers in comparison to the reference patches appear to be explained by differences in wind exposure (Scott and Mitchell, 2005). Greater wind-throw rates have been documented on the edges of recently harvested stands, particularly when the edge of the cut-block is perpendicular to the direction of prevailing winds (Rollerson et al., 2005; Liquori, 2006). Abrupt forest edges act as solid bodies that divert the approaching airflow upward, causing accelerated velocity and turbulence as wind is forced up and over the stand (Ruel et al., 2001; Dupont and Brunet, 2008). Trees growing in a dense stand are not wind-firm when the adjacent trees are removed (Oliver and Larson, 1996), so wind damage is common in buffer strips and along the edges of cut-blocks until the edge trees have adjusted to the change in exposure and become more wind-firm through mechanisms such as increased root growth or loss of branches (Ruel et al., 2001; Rollerson et al. 2005; Scott and Mitchell, 2005). In contrast, the reference stands had the protection of surrounding trees.

Riparian Stand Response

The PIP buffers appear to be more vulnerable than the 50-ft buffers to wind damage due to the smaller size of the patches of trees and greater exposure to wind because they are located on upper slopes and the surrounding trees have been clear-cut. This is consistent with studies that have documented greater wind damage in small, isolated patches of trees surrounded by clear-cut (Rollerson et al., 2005; Scott and Mitchell, 2005) and to trees in upper slope locations due to increased wind exposure and greater fetch distance (Nowacki and Kramer, 1998; Rollerson et al. 2005). Ruel et al. (2001) observed that wind speed accelerated moving upslope on hills facing the prevailing winds, with the wind speed doubling by the time it reached the hilltop. In contrast, the 50-ft buffer patches were often located in lower slope locations that typically have more topographic protection from high winds except when the valley orientation concentrates and funnels approaching winds.

Increased wind damage associated with high intensity winds

There was a different pattern of tree mortality in years 4-5 after harvest due to the high intensity wind storms during that period. In the December 2007 storm, winds reached hurricane force with recorded wind speeds in excess of 90 mph at Astoria and as high as 140 mph on Naselle Ridge in the Willapa Hills. High winds associated with this storm were sustained for an unusually long duration (Office of the Washington State Climatologist, 2009). This storm caused widespread wind-throw of trees, both along cut edges of forests and in patches within continuous stands. Wind damage at the study sites was highly variable; with high mortality in some reference and buffer patches but not in others. Instead of the decrease in mortality rates we expected as the buffers became wind firm, the biggest change was a large increase in tree mortality in the reference patches, where the mean tree mortality rates were twice the rates for the previous period and mortality from wind exceeded mortality from suppression. Mortality in the 50-ft buffers and PIP buffers increased in terms of percentage of trees that died but decreased during this period in terms of trees/acre/yr and the differences in mortality rates between the 50-ft buffers and the reference patches was not significant. The more muted response in the buffer patches during the second period may have been due to the fact that many vulnerable trees had already blown down during the previous three years, and the surviving trees had become more wind firm after being exposed to the wind for three years. Widespread tree mortality from extremely strong wind storms has been widely documented (Oliver and Larsen, 1986; Nowacki and Kramer, 1998; Ruel et al., 2001; Rollerson et al., 2005). Ruel et al. (2001) documented a large increase in tree mortality in buffers associated with an extreme wind storm that occurred five years after harvest, following a period in which post-harvest mortality rates were stabilizing. Wind damage associated with their extreme event was patchy in distribution due to differences in wind exposure and wind-speed related to upwind topography, which accelerated and concentrated the wind in some locations causing heavy wind damage while providing shelter from approaching winds in other areas which had little wind damage. Nowacki and Kramer (1998) observed similar differences in wind disturbance determined by topography in relation to the prevailing direction of wind storms in SE Alaska.

In summary, our data indicate that during the period with wind-storms of moderate magnitude, tree mortality rates in the buffers following harvest were greater than in the reference patches. However, during the period with high magnitude wind events, the treatment effect was less evident. This is consistent with the findings of Ruel et al. (2001), who found that the majority of mortality in new buffers occurs in the first few years following creation of a new forest edge, but during severe windstorms factors such as topographic exposure were more important than buffer width in determining wind-throw rates. More time is needed to determine if tree mortality rates in the buffer and reference patches will stabilize and decrease over time following the large wind storms of the 2006-2008 period.

Variation in Tree Mortality Rates and Implications for Future Stand Conditions

Figure 4 shows the distribution of tree mortality rates by patch type as a percentage of trees that died per year during the first five years after harvest. Variability in tree mortality rates was lowest in the reference patches. Nearly 80% of the reference patches had low cumulative mortality (0-20%) over the five year period and the remaining patches had 20-40% mortality. The distribution of mortality rates for the 50-ft buffers resembles the reference patch distribution for the low mortality categories; about 50% of the 50-ft buffers had low mortality (0-20%) and another 25% had 20-40% mortality. However, the distribution for the 50-ft buffers differs because there is more variability and higher mortality rates for a sub-set of sites. About 25% of the 50-ft buffers had mortality in excess of 40% over the five year period, compared to none of the reference patches. The distribution of the PIP buffers is also variable, with one patch in the 0-20% category, one in the 40-60% category, and one in the 80-100% category.

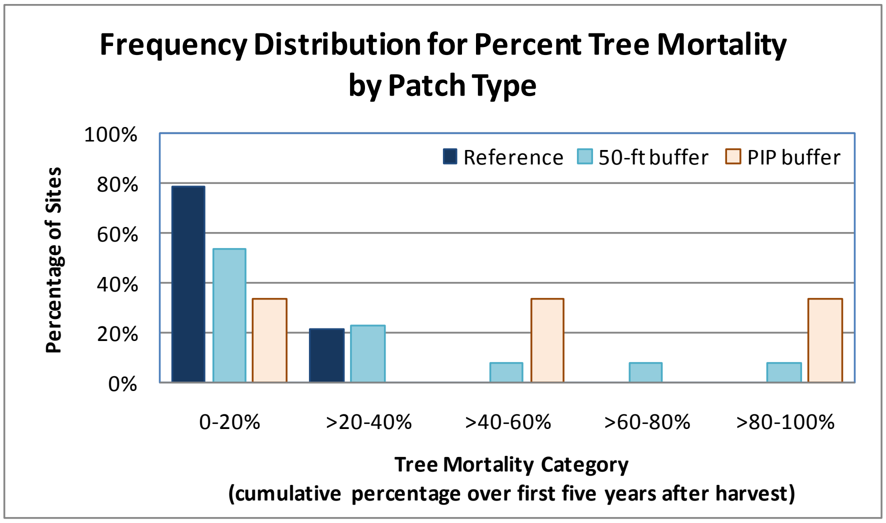

Figure 4. Cumulative tree mortality over the first 5 years after harvest by patch type.

This variability in tree mortality rates among patch types is contributing to increased variability in riparian stand conditions in young forests typical of managed forest land in western Washington. The reference patch data indicate that young (35-50 year old) riparian stands are typically dense (mean of about 200 trees/acre), and mortality is dominated by suppression (in the absence of extreme wind-storms). Higher and more variable mortality rates in the buffers are, on average, reducing density and increasing variability in stand conditions. Mortality also appeared to contribute to changes in the species composition in the 50-ft buffer and PIP buffers, where there was a decrease in the percentage of western hemlock and an increase in western red cedar (apparently due to the greater susceptibility of western hemlock to wind-throw). Dead tree density did not increase over time in the PIP buffers and 50-ft buffers despite substantial mortality, while dead tree density increased in the reference patches. This response appears due to differences in the mortality processes. Wind was the dominant mortality process in the buffer patches. Trees uprooted by the wind do not create new snags, and apparently the number of new snags created by stem breakage was roughly equal to the number of existing snags that were knocked over by wind or other fallen trees. Suppression mortality typically results in standing dead trees, which appears to explain the increase in dead tree density in the reference patches.

Oliver and Larsen (1996) identify four stand development stages: stand initiation, stem exclusion, understory re-initiation and old growth. These stands initiated approximately 40-60 years ago, and prior to this latest harvest were single-aged stands in the stem exclusion stage, as indicated by the suppression mortality in the reference stands. The difference in cumulative mortality following harvest affects the current condition and trajectory of these stands over time. The reference and 50-ft buffers with low mortality should continue to progress through the stem exclusion stage as single-aged stands, with reduced mortality from competition where wind-throw has thinned the stands (Liquori, 2000). In contrast, the density of remaining trees is lower in the buffers with higher mortality. Nowacki and Kramer (1998) identified two scenarios for stands impacted by large wind-throw events. Stands where most trees are killed return to the stand initiation stage and generate a new single-aged stand if conifer regeneration is successful. Stands with partial mortality undergo understory re-initiation in the gaps, and continue development as a multiple-cohort stand with patches of new trees interspersed with the surviving older trees (Nowacki and Kramer, 1998; Liquori, 2000). The success of natural conifer regeneration will be a critical factor determining future stand conditions in buffers with high mortality. Competition from shrubs and broad-leafs may limit regeneration in some cases, increasing range of future stand conditions (Oliver and Larson, 1986; Liquori, 2000).

Implications for FFR Resource Objectives

Post-harvest stand conditions, and patterns in tree mortality rates over time, have implications for recent and future riparian processes and conditions including tree fall and LWD recruitment, channel debris loading, shade, soil disturbance and channel debris loading that help determine to what extent the FFR resource goals and functional objectives are achieved. These are discussed in the following sections, and in the synthesis and conclusion section at the end of the report.

TREE FALL

This analysis addresses uncertainty concerning changes in tree fall (uprooting and stem breakage) rates following timber harvest under the Type Np riparian prescriptions.

Critical Questions

1. What are tree fall rates after application of westside Type Np riparian prescriptions?
2. What is the magnitude and duration of change in tree fall rates associated with the westside Type Np riparian prescriptions compared to un-harvested reference sites?

Data Collection Procedures

Uprooted trees are either living or dead trees that fell with the roots attached (the roots no longer support the weight of the tree). Broken trees are living or dead trees that broke off along the stem (with the broken piece ≥ 4 inches in diameter at the large end). When the upper portion of a tree broke off but the stem remained standing and was at least 4.5 ft high, the standing portion was treated as a standing tree and the broken portion treated as a broken tree (if large enough to qualify). Data were collected only on uprooted and broken trees that originated within 50 ft of the stream; those that originated outside of the survey area were not included. Data on each uprooted or broken tree was collected only once, the first time it was observed. Attribute data included condition (live/dead), species, DBH, fall type (uprooted or broken), felling process, decay class, landform, fall direction, distance-to-stream, and recruitment class.

Metrics, Hypotheses and Methods of Statistical Analysis

The objectives for the tree fall analysis included: 1) characterizing the annual standardized rates for each patch type for the 2003 to 2006 period, the 2006 to 2008 period, and for the entire 2003 to 2008 period, and 2) comparing the annual rates for the three prescription patches to the reference patch rates.

The following metrics were used to evaluate changes in tree uprooting and stem breakage rates:

Uprooted trees per acre per year and broken trees per acre per year. These metrics were calculated for each of three time periods: the first three years after harvest (2003 to 2006), years 4-5 after harvest (2006 to 2008) and for the entire five year period (2003 to 2008). To calculate uprooted trees/acre/year for each period, the number of trees that were newly uprooted during the period in each patch was counted, divided by the patch area in acres and divided by the number of years between sampling events. To calculate broken trees/acre/year for each period, the number of trees newly broken during the period in each patch was counted, divided by the patch area in acres and divided by the number of years between sampling events. The combined fallen trees/acre/yr was calculated by adding the uprooted and broken trees/acre/year.

P*ercentage of standing trees uprooted per acre per year.* This metric was calculated by summing the uprooted trees/acre for each time period, dividing by the total standing trees/acre at the beginning of the sample period, and then dividing by the years in the period.

P*ercentage of standing trees that were broke per acre per year.* This metric was calculated by summing the broken trees/acre for each time period, dividing by the total standing trees/acre at the beginning of the sample period, and then dividing by the years in the period.

P*ercentage of standing trees that fell (combined uprooted and broken) per acre per year).* This metric was calculated by summing the uprooted and broken trees/acre/yr for each period.

Uprooted trees/broken trees/combined fallen trees/acre/year. A two-tailed hypothesis was used to compare the standardized annual rates for each of the three time periods stated as:

H_o: average standardized annual rate between sample events for a prescription patch type = average standardized annual rate for the reference patches.

The distribution of tree fall rates was heavily weighted toward rates at or near zero, with an extended right tail to the distribution. Examination confirmed that these data should not be considered normally distributed so the non-parametric, two-sample MW test was used to test for differences between the reference patches and patches receiving one of the prescription treatments. The level of significance was 0.10.

Percent uprooted trees/broken trees/combined fallen trees per year. A two-tailed hypothesis was stated as:

H_o: average standardized annual rate between sample events for the prescription patches = average standardized annual rate for the reference patches.

These metrics were calculated as proportional decreases, so they are bounded by 0 and 1. Examination confirmed these data should not be considered normally distributed. Therefore, the MW test was used to test for differences between the reference patches and patches receiving one of the prescriptions. The level of significance was 0.10.

Tree Fall

Results

Overview of Patterns in Tree Fall

Tree fall includes both live and dead trees that were uprooted or broken, unlike tree mortality metrics which includes only previously live trees. Nonetheless, uprooting and stem breakage rates followed a similar pattern to tree mortality rates. Table 18 shows mean tree fall rates in trees/acre/yr and percent of standing trees/yr for uprooted trees, broken stems and the combined total. Figure 5 shows the distribution of values for combined tree fall by patch type. During the first three years after harvest (2003-2006), the mean rate for uprooted and broken trees in the 50-ft buffer patches were over 8 times (uprooted) and 5 times (broken) the reference patch rate in trees/acre/yr and 12 times (uprooted) and 8 times (broken) the reference patch rate as a percentage of standing trees that fell per year. The rate of uprooting in trees/acre/yr was about double the rate of stem breakage for all patch types. During years 4-5 after harvest (2006-2008), the rate of both uprooted and broken trees increased in the reference patches on both a trees/acre/yr and percent of standing trees basis. Uprooted trees decreased in the 50-ft buffer patches during this period but broken trees increased, so the combined total was similar both periods. During years 4-5 the rate of tree uprooting/acre/yr in the reference patches was about double the rate of stem breakage, however the rate of stem breakage increased and was nearly equal to the rate of tree uprooting for the 50-ft buffer, PIP buffer and clear-cut patch types.

Over the entire 5 year period, the rates for both uprooted and broken trees in the 50-ft buffers was about double the rate for the reference patches in trees/acre/yr and triple for percent of standing trees/yr. Uprooted and broken trees/acre/yr was much lower in the clear-cut patches than in the reference patches because the density of live trees available as potential mortality was low in the clear-cut patches but the contrast was not so great on a percentage basis.

Table 18. Tree uprooting and stem breakage by patch type for years 1-3 (2003-2008), years 4-5 (2006-2008) and the entire first five years (2003-2008) after harvest.

Patch Type	**n**	**Trees/acre/yr**						**Percent of standing/yr**					
		Uprooted		**Broken**		**Combined**		**Uprooted**		**Broken**		**Combined**	
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
2003-2006													
Reference	14	**0.9**	0.8	**0.5**	0.5	**1.4**	1.1	**0.4**	0.3	**0.2**	0.2	**0.6**	0.4
50-ft buffer	13	**7.9**	9.2	**2.9**	2.5	**10.8**	11.1	**4.8**	6.1	**1.6**	1.2	**6.4**	6.8
Clear-cut	8	**0.03**	0.08	**0.1**	0.2	**0.2**	0.2	**5.6**	13.6	**5.9**	13.5	**11.4**	17.0
PIP buffer	3	**20.6**	19.4	**9.2**	5.8	**29.8**	25.2	**8.2**	6.7	**4.0**	1.6	**12.2**	8.2
2006-2008													
Reference	13	**6.1**	8.2	**2.7**	3.7	**8.8**	10.5	**2.7**	3.4	**0.9**	1.1	**3.6**	4.0
50-ft buffer	12	**4.9**	5.2	**4.0**	4.5	**8.9**	8.6	**3.8**	4.2	**3.8**	5.9	**7.6**	8.9
Clear-cut	7	**0.1**	0.3	**0.1**	0.3	**0.3**	0.5	**2.3**	3.6	**2.3**	3.6	**4.5**	7.3
PIP buffer	3	**12.7**	11.0	**11.5**	3.8	**24.2**	8.6	**8.5**	7.3	**8.1**	3.0	**16.6**	4.7
2003-2008													
Reference	14	**3.2**	3.1	**1.4**	1.5	**4.5**	4.0	**1.3**	1.3	**0.5**	0.4	**1.8**	1.5
50-ft buffer	13	**6.3**	6.7	**3.2**	3.1	**9.4**	9.3	**3.7**	4.0	**1.8**	1.6	**5.5**	5.3
Clear-cut	8	**0.2**	0.2	**0.2**	0.2	**0.3**	0.4	**3.6**	7.3	**3.7**	7.3	**7.4**	8.9
PIP buffer	3	**17.4**	15.4	**10.1**	2.0	**27.6**	17.4	**7.0**	5.5	**4.9**	0.6	**11.9**	4.8

[1] SD = standard deviation

Tree Fall

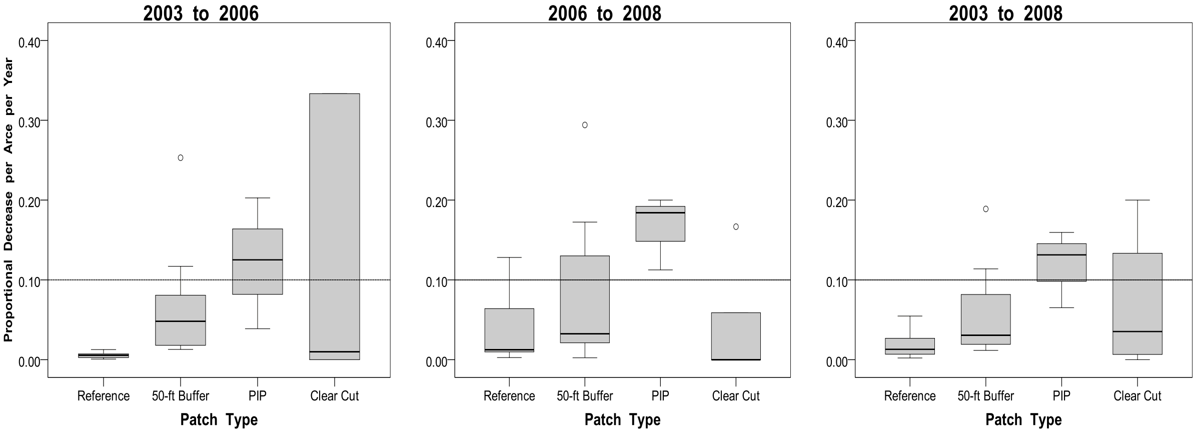

Figure 5. Distributions of proportional tree fall rates by patch type for the 2003-2006 (left), 2006-2008 (center), and entire 2003-2008 (right) time periods.

Hypothesis Testing for Tree Fall Metrics

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches for mean annual rates of uprooting, breakage and combined fall (uprooting and breakage) in trees/acre/yr and percent of standing trees/yr that fell for each post-harvest time period. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. reference comparison

Rates of uprooted and broken trees/acre/yr for the clear-cut patches was very low for all time periods because few live trees remained after harvest (Table 18). Consequently, the differences between the clear-cut and reference rates for all three metrics (uprooted, broken and combined fallen trees) on a trees/acre basis were statistically significant for all time periods. In contrast, the percentage of the standing trees that fell was higher in the clear-cut patches in all time periods except for the percentage broken in 2006-2008. However, the differences between the clear-cut and the reference patches were not statistically significant except for the percentage of uprooted trees in the 2003-2006 period ($P = 0.065$).

50-ft buffer vs. reference comparison

The mean annual rate for uprooted, broken and combined fallen trees in the 50-ft buffers during the first three years after harvest (2003-2006) was over 8 times the reference rate as a percentage of standing trees and over 5 times higher in trees/acre/yr. The differences for all three categories of fallen trees were statistically significant ($P = \leq 0.001$) so the null hypothesis was rejected and we conclude that tree fall rates were significantly higher in the 50-ft buffers during the first three years after harvest (Table 19).

The rates of both tree uprooting and stem breakage increased in the reference patches during the second time period (2006-2008), however in the 50-ft buffers the rate of tree uprooting decreased while the rate of stem breakage increased. The only statistically significant difference between the 50-ft buffers and the reference patches in this period was the percentage of standing trees that were broken, which was higher in the 50-ft buffers. Over the entire five year period, the percentages of standing trees that were uprooted and broken (as well as the combined total) were significantly greater in the 50-

ft buffers (Table 19). In trees/acre/yr, although the mean rate of uprooted, broken and combined fallen trees was greater in the 50-ft buffers, the difference was statistically significant only for broken trees.

Table 19. 50-ft buffer versus reference comparison for uprooted, broken and combined tree fall rates with results of the Mann-Whitney test.

Sample Event	50-ft buffer Mean	Reference Mean	Difference (50-ft buffer–Reference)	*P*-value of the MW test[a]
Uprooted trees per acre per year				
2003-2006	7.9	0.9	7.0	**0.001**
2006-2008	4.9	6.1	-1.2	0.548
2003-2008	6.3	3.2	3.1	0.332
Percentage of standing trees uprooted/year				
2003-2006	4.8%	0.4%	4.4%	**<0.001**
2006-2008	3.8%	2.7%	1.1%	0.327
2003-2008	3.7%	1.3%	2.4%	**0.043**
Broken trees per acre per year				
2003-2006	2.9	0.5	2.4	**<0.001**
2006-2008	4.0	2.7	1.3	0.301
2003-2008	3.2	1.4	1.8	**0.037**
Percentage of standing trees broken/year				
2003-2006	1.6%	0.2%	1.4%	**<0.001**
2006-2008	3.8%	0.9%	2.9%	**0.061**
2003-2008	1.8%	0.5%	1.3%	**0.001**
Combined fallen (uprooted and broken) trees per acre per year				
2003-2006	10.8	1.4	9.4	**<0.001**
2006-2008	8.9	8.8	0.1	0.728
2003-2008	9.4	4.5	4.9	0.141
Percentage of standing trees fallen (combined uprooted and broken)/year				
2003-2006	6.4%	0.6%	5.8%	**<0.001**
2006-2008	7.6%	3.6%	4.0%	0.186
2003-2008	5.5%	1.8%	3.7%	**0.009**

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold.

PIP Buffer Observations

The data from the three PIP buffers followed a similar pattern to the 50-ft buffers; however the rates in the PIP buffers were typically over double those in the 50-ft buffers (Table 18). The rate of tree uprooting in trees/acre/yr and as a percentage of standing trees was highest in the first three years following harvest, about double the rate of stem breakage. However the rate of stem breakage increased in years 4-5 and was similar the uprooting rate.

Tree Fall Characteristics and Patterns

Characteristics of fallen trees

Uprooted trees were encountered about twice as frequently as broken trees, making up 66.5% of the combined fallen tree count and 65.1% of the combined fallen tree basal area (Table 20).

Tree Fall

Table 20. Fallen trees by fall type (broken vs. uprooted).

	Uprooted trees	Broken trees	Combined fallen	Percent Uprooted	Percent Broken
Tree count	758	381	1139	66.5%	33.5%
Basal area	753.3	404.6	1157.9	65.1%	34.9%
Mean DBH	11.74	11.79			

Several other studies observed a higher proportion of uprooting (around 80%) in second-growth forests in western Washington (Grizzel and Wolff, 1998; Roberts et al., 2007) and British Columbia (Scott and Mitchell, 2005), while stem breakage appears to be more common in the mature and old-growth forests in SE Alaska (Nowacki and Kramer, 1998).

Table 21 shows the proportion of fallen trees by fall type (uprooted vs. broken) and tree type (conifer vs. broad-leaf). Conifers made up the majority of the combined fallen tree count (86.4%) and basal area (90.6%), while the broad-leaf proportion was 13.6% and 9.4%, respectively. The proportions were similar for uprooted and broken trees, although broad-leafs made up a slightly higher proportion of the broken trees (16.7%) than of the uprooted trees (12.0%). The proportion of uprooted vs. broken trees was higher for conifers (67.8%) compared to broad-leafs (58.8%), indicating that broad-leafs may be somewhat more susceptible to stem breakage than conifers.

Table 21. Proportion of fallen trees by fall type (uprooted vs. broken) and tree type (conifer vs. broad-leaf).

	Tree Count				Basal Area			
Tree type	conifer	broad-leaf	% conifer	% broad-leaf	conifer	broad-leaf	% conifer	% broad-leaf
Uprooted trees	662	90	88.0%	12.0%	688.2	62.7	91.7%	8.3%
Broken trees	314	63	83.3%	16.7%	357.9	45.8	88.7%	11.3%
Combined fallen	976	153	86.4%	13.6%	1046.1	108.5	90.6%	9.4%
Percent uprooted	67.8%	58.8%			65.8%	57.8%		
Percent broken	32.2%	41.2%			34.2%	42.2%		

The mean diameter of fallen conifers was greater than fallen broad-leaf trees for the uprooted, broken and combined fallen categories. The mean diameter of broken trees was greater than that of uprooted trees for both conifers and broad-leafs (Table 22). The mean diameter of standing trees was greater than any category of fallen trees for both conifer and broad-leafs. This is consistent with the finding that trees with higher height: diameter ratios (smaller DBH) are more vulnerable to wind-throw (Scott and Mitchell, 2005).

Table 22. Mean DBH of fallen trees by fall type and tree type.

Tree type	Conifer	Broad-leaf
Uprooted trees	11.97	10.30
Broken trees	12.12	10.48
Combined fallen	12.02	10.37
Standing tree	12.78	10.53

Tree Fall

Percentage of initially standing conifers that fell was nearly twice the percentage of broad-leaf trees that fell for the combined fallen trees and uprooted trees (Table 23), but the difference was not as great for broken trees. The percentage of standing conifers that were uprooted (12.0%) was about twice the percentage that were broken (5.7%), while the percentage of standing broad-leafs that were uprooted was only about 1.5 times the percentage that were broken.

Table 23. Percent of standing tree count that fell by fall type and tree type (conifer vs. broadleaf).

Tree type	Uprooted	Broken	Combined fallen
Conifer	12.0%	5.7%	17.7%
Broad-leaf	5.6%	3.9%	9.5%

The percentage of standing trees that fell during the first five years after harvest is shown in Table 24 for major species. Pacific silver fir, western hemlock and western red cedar had the highest percentage of standing trees that fell (combined uprooted and broken trees), ranging from 18 to 28%. Red alder and Douglas-fir had intermediate fall rates of around 10%. Black cottonwood, big-leaf maple and Sitka spruce had the lowest rates (less than 6%). The pattern of higher tree fall rates for western hemlock and Pacific silver fir relative to red alder and Douglas-fir has been well documented (Rot, 1993; Grizzel and Wolff, 1998; Liquori, 2006; Roberts et al. 2007), but the fall rate of western red cedar varied (Rot 1993; Liquori, 2006). Pacific silver fir had highest proportion of uprooted to broken trees (88.2%), and the proportion of uprooted trees ranged between 50% and 70% for all the remaining species with one exception. For big-leaf maples, stem breakage was much more frequent than uprooting and only 28.6% of the combined fallen trees were uprooted.

Table 24. Tree fall for the first five years as a percentage of standing trees for major species.

Species	Combined fallen	Uprooted	Broken	Percent uprooted
Pacific silver fir	28.1%	24.8%	3.3%	88.2%
Western hemlock	22.6%	15.2%	7.4%	67.3%
Western red cedar	18.0%	12.4%	5.6%	68.8%
Red alder	10.6%	6.2%	4.4%	58.6%
Douglas-fir	10.4%	6.7%	3.6%	64.9%
Black cottonwood	5.9%	2.9%	2.9%	50.0%
Big-leaf maple	3.2%	0.9%	2.3%	28.6%
Sitka spruce	1.9%	1.2%	0.6%	66.7%

Wind was the dominant tree fall process, accounting for nearly 75% of combined fallen trees (Table 25). Another 11% of fallen trees were knocked down when other trees fell against them, often due to wind. Bank erosion accounted for only 1.8% of fallen trees. The tree fall process could not be determined about 10% of the time. The mean DBH of trees fallen by wind was larger than the mean DBH of trees fallen by most other processes, so wind accounted for about 88% of tree fall in basal area/acre. The percentage of the trees felled by wind that were uprooted (68.8%) was about twice the percentage that was broken (31.2%).

The pattern of tree fall dominated by wind-throw is consistent with other studies in the coastal areas of the Pacific Northwest (Nowaski and Kramer, 1998; Grizzel and Wolff, 1998; May and

Gresswell, 2003). Tree fall rates due to bank erosion are lower adjacent to small streams than large streams, because small streams typically have less stream power and lateral movement than larger streams (Jackson et al., 2001; May and Gresswell, 2003). May and Gresswell (2003) documented that mass wasting can be an important mechanism of tree fall, however it occurs sporadically in time and space and we did not observe tree fall due to mass wasting in this study.

Table 25. Combined tree fall rates by processes causing tree fall.

Process	Percent of total fallen count	Percent of total fallen basal area	Mean DBH (inches)
Wind	74.8%	88.2%	12.8
Knocked down	11.2%	5.5%	8.4
Bank erosion	1.8%	0.5%	6.9
Rot	1.1%	0.4%	7.4
Other	0.5%	0.7%	13.5
Unknown	10.6%	6.28%	9.1

Wind was the dominant tree fall process for all patch types, followed by trees knocked down by other fallen trees. These two processes accounted for all tree fall in the clear-cut patches, 96.5% in the PIP buffers, 87.2% in the 50-ft buffers and 80.1% in the reference patches (Table 26).

Table 26. Percentage of tree fall by fall process and patch-type in the first 5 years.

Process	Reference	50-ft buffer	Clear-cut	PIP buffer
Wind	71.5%	74.4%	66.7%	88.7%
Knocked down	8.6%	12.8%	33.3%	7.8%
Erosion	4.6%	0.5%	-	-
Rot	2.4%	0.5%	-	-
Other	0.5%	0.6%	-	0.9%
Unknown	12.4%	11.3%	-	2.6%

Table 27 shows the percentage of the fallen trees (all sites combined) that fell in each of eight equal sectors based on the cardinal and ordinal compass directions. There was a tendency toward a northerly direction of tree fall. Over 64% of the trees fell in half the area consisting of the W, NW, N and NE sectors, and over 36.4% of the trees fell into two sectors (N and NW).

Table 27. Percentage of fallen trees by direction of fall.

Fall Direction Sector	Percentage of fallen trees
E	8.9%
SE	8.5%
S	9.0%
SW	8.8%
W	14.0%
NW	17.9%
N	18.5%
NE	14.4%

Tree Fall

The pattern of tree fall predominately to the north has been documented by several other studies in western Washington (Rot, 1993; Mobbs and Jones, 1995; Grizzel and Wolff, 1998; Liquori, 2006), western Oregon (Andrus and Froehlich, 1986) and western British Columbia (Scott and Mitchell, 2005). This appears to be due to the prevailing winds from the south associated with the large cyclonic low-pressure winter storm systems that typically generate high winds in the coastal area of the Pacific Northwest. However tree fall occurred in all eight sectors, indicating that other factors also influence tree fall direction.

Fallen trees were grouped in three fall direction categories relative to the orientation of the stream. When the direction of tree fall (either upstream or downstream) was within 30 degrees of parallel to the channel, the fall direction was classified as “parallel”. Trees that fell at an angle outside of the parallel zone were classified as “towards the channel” if they fell in the direction of the channel stream, or as “away from the channel” if they fell away from the stream. Each category encompassed a total of 120 degrees. Nearly half of combined fallen trees were classified as falling towards the channel (Table 28). This appears to indicate a tendency for trees to fall in a downhill direction towards the channel. About a quarter of the trees fell “away from the channel”, similar to the proportion of trees falling parallel to the channel. The results were similar for both the uprooted and broken tree categories. This pattern of a greater tendency for trees to fall towards the channel was observed by Sobota and Gregory (2003) and Liquori (2006), who observed that the tendency of riparian trees to fall towards the channel increased with proximity to the channel.

Table 28. Percentage of fallen trees by fall direction relative to the stream channel.

Fall Direction Category	Combined Fallen Tree Count	Uprooted	Broken
Towards channel	48.9%	49.7%	47.2%
Away from channel	24.6%	24.7%	24.4%
Parallel to channel	26.5%	25.6%	28.4

When the rooting locations of fallen trees were sorted into categories by horizontal distance to the channel, differences were observed between patch types. Nearly two-thirds of the fallen trees in the reference patches came from within 25 feet of the channel, while one-third originated from between 25 and 50 feet (Table 29). For the 50-ft buffer patches, the proportion of fallen trees originating within 25 feet of the channel was similar to the proportion originating in the 25-50 foot zone. The differences between the reference patches and the 50-ft buffers may be due to the fact that the 50-ft buffers have openings on the outside as well, and are more vulnerable to disturbance near the outer edge of the buffer. Grizzel et al. (2000), Rollerson et al. (2005) and Liquori (2006) found higher wind-throw rates on the outer edges of buffers; however the buffers in their studies were wider and likely resisted wind penetration more effectively than the 50-ft buffers in this study.

Table 29. Percent fallen trees by distance-to-stream zone for reference and 50-ft buffer patches.

Distance to Stream Zone	Reference	50-ft buffer
0-25 feet	63.7%	51.6%
25-50 feet	36.3%	48.1%

The proportion of broken vs. uprooted trees was higher in the 25-50 ft zone in both the reference and the buffer patches (Table 30).

Tree Fall

Table 30. Percentage of uprooted vs. broken trees by distance-to-stream zone for the reference and 50-ft buffer patches.

	Reference		**50-ft buffer**	
Distance to Stream Zone	Uprooted	Broken	Uprooted	Broken
0-25 feet	72.0%	28.0%	68.1%	31.9%
25-50 feet	64.4%	35.6%	64.5%	35.5%

Factors affecting recruitment of fallen trees to the stream channel

About 50% of fallen trees reached the edge of the bankfull channel (Table 31), about twice the percentage of fallen trees reaching the stream from the wider buffers studied by Liquori (2006), but similar to the proportion recorded by Andrus and Froehlich (1986) and Mobbs and Jones (1995). Only 7.0% of fallen trees landed so a portion intruded down into the bankfull channel, compared to 11.2% that landed with one end suspended over the channel and 30% that spanned the channel, touching both sides. This is consistent with other studies noting that 73% - 87% of the fallen trees that reach the channel that are suspended or bridging above the channel (Andrus and Froehlich, 1986; Grizzel and Wolff, 1998; Liquori, 2006).

Table 31. Characteristics of fallen trees reaching the channel by recruitment class.

Recruitment Category	Percentage of fallen trees	Mean DBH (in)	Mean diameter at bankfull channel (in)	Mean distance to stream (ft)a
Recruited into bankfull channel	7.0%	11.8	10.0	19.1
Spanning across channel	30.0%	12.9	10.6	20.0
Suspended over channel	11.2%	10.2	7.5	22.5

The mean percentage of fallen trees that reached the channel was similar for the reference, 50-ft buffer and clear-cut patches (Table 32), but in terms of trees/acre, the number reaching the channel was higher for the 50-ft buffers than for the reference or clear-cut patches because of the greater total number of fallen trees in the buffers. The percentage of fallen trees that actually intruded into the bankfull channel (in-channel category) was around 10% for the reference and 50-ft buffer patches and less for the clear-cut and PIP buffer patches.

Table 32. Mean tree fall rates and percentages by channel location and patch type.

Patch Type	Total Reaching Channel		In-channel		Over-Channel	
	Trees/acre	Percent	Trees/acre	Percent	Trees/acre	Percent
Reference	12.8	50.8%	1.8	9.2%	11.0	41.6%
50-ft buffer	23.9	51.3%	3.0	11.0%	21.0	40.2%
Clear-cut	0.8	48.7%	0.1	4.0%	0.6	44.7%
PIP buffer	37.0	27.8%	12.1	6.6%	24.9	21.2%

The percentage of fallen trees reaching the channel decreased with increasing distance from the bankfull channel, from 60.9% for the 0-10 ft zone to 45.0% for the 30-40 ft zone, with an abrupt decrease (26.9%) in the 40-50 ft zone (Table 33). The contribution of each zone to the cumulative total of trees reaching the stream dropped from 27.3% in the 0-10 ft zone to 7.8% in the 40-50 ft zone. This is consistent with studies that found the probability of a fallen tree recruiting to the channel decreases with increasing distance from the stream in buffers (Andrus and Froehlich, 1986; Liquori, 2006) and unmanaged riparian stands (May and Gresswell, 2003).

Tree Fall

The mean diameter of the stem where it crossed the plane of the bankfull channel tended to decrease with increasing distance from the stream (Table 33).

Table 33. Percentage of fallen trees reaching the channel by distance-to-stream zones.

Distance to Stream Zone	Percentage of fallen trees reaching the channel	Contribution of zone to total trees reaching channel	Mean diam. where stem crosses plane of bankfull channel (in)
0-10 feet	60.9%	27.3%	11.7
10-20 feet	55.1%	25.1%	8.9
20-30 feet	48.1%	20.7%	9.6
30-40 feet	45.0%	19.2%	9.2
40-50 feet	26.9%	7.8%	8.0

Table 34 shows differences between the 50-ft buffer and reference patches in percentage of fallen trees reaching the channel by distance-to-stream zone, and the contribution of each zone to the total fallen trees reaching the channel. For the area within 30 feet of the stream (0-10, 10-20, and 20-30 zones), the percentage of fallen trees reaching the channel and the contribution to the total trees reaching the channel is higher for the reference patches than the 50-ft buffers. In contrast, a higher proportion of fallen trees in the 50-ft buffers reached the channel from the area between 30 to 50 feet. For example, 36.4% of the fallen trees in the 40-50 foot zone of the 50-ft buffers reached the stream compared to 12.5% for the reference patches, and the 40-50 foot zone contributed 11.8% of all fallen trees reaching the stream for the 50-ft buffers, compared to only 2.5% of the total for the reference patches. The greater proportion of recruitment coming from beyond 30 feet in the 50-ft buffers appears to be due to the higher overall rate of tree fall near the outer edge of the 50-ft buffers due to the edge effect (T). This pattern has been observed in other studies (Liquori, 2006; Martin and Grotefendt, 2007). For example, Grizzel et al. (2000) observed that 40% of trees recruited to the channel from buffers less than 60 ft wide came from beyond 33 ft.

Table 34. Reference versus 50-ft buffer comparison of percentage of fallen trees reaching the channel and contribution to total reaching the channel by 10 foot distance-to-stream zones.

Distance to Stream Zone	Percent of fallen trees in zone that reached channel		Contribution of zone to total trees reaching channel	
	Reference	50-ft buffer	Reference	50-ft buffer
0-10 feet	67.8 %	58.6 %	30.5 %	26.9 %
10-20 feet	64.1 %	47.1 %	33.0 %	18.7%
20-30 feet	57.3 %	48.4 %	21.5 %	20.0 %
30-40 feet	44.6 %	47.9 %	12.5 %	22.6 %
40-50 feet	12.5 %	36.4 %	2.5 %	11.8 %

Not surprisingly, trees with a fall direction fell towards the channel comprised the majority of the total trees recruited in or over the stream channel (78.8%), although 17.2% of trees that recruited were from trees with a fall direction parallel to the channel and 4% were trees that fell away from the channel (Table 35). This occurred when trees that originated next to the channel fell in an upslope direction and then slid or rolled down the slope so the base of the tree entered the channel. A higher percentage of the trees that fell towards the stream reached the channel (77.7%), compared to trees that fell parallel to the channel (31.2%) or away from the channel (7.9%).

Tree Fall

Table 35. Percentage of fallen trees reaching the bankfull channel by fall direction relative to the orientation of the stream.

Fall Direction Category	Contribution to total trees reaching channel	Percentage of fallen trees that reached channel
Towards channel	78.8 %	77.7 %
Away from channel	4.0 %	7.9 %
Parallel to channel	17.2 %	31.2 %

Over 50% of uprooted trees reached the bankfull channel compared to only 38.3% of stems that broke. This is likely due to the fact that whole (uprooted) trees are longer than broken pieces, and are more likely to reach the channel from a greater distance (Table 36). Nearly 75% of the total fallen trees reaching the channel were uprooted.

Table 36. Percentage of fallen trees reaching the bankfull channel by fall type.

Fall Type Category	Percentage of fallen trees reaching channel	Contribution to total trees reaching channel
Broken	38.3%	26.5%
Uprooted	53.3%	73.5%

The proportion of uprooted and broken trees that recruited into the bankfull channel was similar, 55% vs. 45% respectively. In contrast, the proportion of uprooted trees was much higher for spanning or suspended categories, 81% and 64.8% respectively (Table 37).

Table 37. Proportion of uprooted and broken trees recruiting to the channel by recruitment class.

	Uprooted	Broken
Into bankfull channel	55.0%	45.0%
Spanning across channel	81.0%	19.0%
Suspended over channel	64.8%	35.2%

The percentage of trees reaching the channel varied by fall process (Table 38). The percentage of trees that reached the channel when felled by erosion (75.0%) was high because they are located beside the channel. The percentage of fallen trees that reached the channel was lower for wind (49.9%), rot/decay (41.7%) and trees knocked down by other trees (36.2%). This may be explained by differences in the source distances for various recruitment processes. For example, May and Gresswell (2003) observed large differences in the source distance for trees felled by bank erosion (2 m) natural mortality or wind-throw (18-20 m) and mass wasting (40 m). Trees felled by wind made up the majority of fallen trees reaching the channel (77.3%).

Table 38. Percentage of fallen trees reaching the bankfull channel by fall process.

Process	Percent of fallen trees reaching channel	Contribution to total trees reaching channel
Erosion	75.0%	2.7%
Wind	49.9%	77.3%
Rot/decay	41.7%	0.9%
Knocked down	36.2%	8.4%
Unknown/other	46.5%	10.7%

Tree Fall

The percentage of fallen conifer trees that reached the channel was lower than the percentage of broad-leafs (Table 39). However, since conifers were much more numerous, over 88% of all fallen trees reaching the channel were conifers.

Table 39. Percentage of fallen trees reaching the bankfull channel by tree type.

Tree type	Percent of fallen trees reaching channel	Contribution to total trees reaching channel
Broad-leaf	58.6%	11.5%
Conifer	45.6%	88.2%
Unknown	37.2%	0.2%

Discussion

Comparison of Tree Mortality and Tree Fall Rates

Tree fall rates followed a similar pattern to tree mortality rates, although tree fall includes both live and dead standing trees that fall while the mortality includes only live trees that die (and do not necessarily fall). Table 40 compares tree mortality and tree fall rates over the entire five year period by patch type. Processes such as suppression tend to kill trees and create standing snags, which increases the tree mortality rate but not the tree fall rate, while processes such as wind-throw fell both live and dead trees. Consequently, tree mortality was 1.5 times the tree fall rate for the reference patches where suppression mortality was more common, while in the 50-ft buffers and PIP buffers where wind-throw was dominant, the tree mortality and tree fall rates were nearly equal (Table 40).

Table 40. Comparison of tree mortality and combined tree fall rates by patch type over the first five years after harvest (2003-2008).

Patch Type	Tree Mortality Rate (percent/yr)	Combined Tree Fall Rate (percent/yr)
Reference	2.7%	1.8%
50-ft buffer	5.5%	5.5%
PIP buffer	10.6%	11.9%

Other studies have documented tree mortality or tree fall rates in riparian buffers in the Pacific Northwest (Andrus and Froehlich, 1986; Rot, 1993; Mobbs and Jones, 1995; Grizzel and Wolff, 1998; Grizzel et al. 2000; Jackson et al., 2001; Scott and Mitchell, 2005; Liquori, 2006; Martin and Grotefendt, 2007). However, it was not possible to compare tree rates between studies due to variation in buffer widths, buffer design, buffer age, and differences in tree mortality metrics.

LARGE WOODY DEBRIS RECRUITMENT RATES

This analysis addresses uncertainty concerning changes in large woody debris (LWD) recruitment rates following timber harvest under the Type Np riparian prescriptions. The assumption for riparian stands managed under the Type Np prescriptions is that the overall Np buffer strategy will provide adequate LWD recruitment to provide channel functions (e.g. habitat formation and sediment/nutrient routing) within the Type Np network and will export adequate amounts of LWD to fish-bearing streams to maintain habitat for harvestable fish populations. There is uncertainty about the amount and the characteristics of LWD that will be recruited as a result of different Np prescription treatments and how future LWD recruitment potential will be affected by changes in riparian stand conditions over time. This analysis provides information on the magnitude of change in LWD recruitment over the near-term (first five years after harvest) associated with the westside Type Np riparian prescriptions.

Critical Questions

1. What are large woody debris recruitment rates and processes associated with riparian stands following application of westside Type Np riparian prescriptions?
2. What is the magnitude and duration of change in large woody debris recruitment rates and processes following application of the westside Type Np riparian prescriptions compared to untreated reference sites?

Data Collection Procedures

Data were collected on LWD pieces from trees rooted within 50 ft of the stream (horizontal distance) if a portion of the piece landed within or over the bankfull channel (including pieces suspended over the channel). To qualify for measurement a piece must be at least 4 inches in diameter at the largest end and at least 1 foot in length. Data attributes recorded for LWD pieces included species, piece type (with or without root wad), length and midpoint diameter for recruited portions by channel zone, and channel functions.

Metrics, Hypotheses and Methods of Statistical Analysis

The objectives of the LWD recruitment analyses were to: 1) characterize the annual rates for each patch type for the 2003-2006 period, 2006-2008 period, and for the entire 2003-2008 period, and 2) compare these annual rates for each prescription to the reference patch rate.

Two metrics were used to evaluate the rate of LWD recruitment to the stream channel.

LWD pieces recruited per acre per year. This metric is computed by counting the new LWD pieces recruited between sample events for each patch, and dividing by the patch area in acres and by the number of years between sample events. The mean for each patch type is the average of the individual patch values.

LWD volume recruited per acre per year. This metric is computed by summing the volume (in or over the channel) of new LWD pieces recruited between sample events for each patch, and dividing by the patch area in acres and by the number of years between sample events. The mean for each patch type is the average of the individual patch values.

A two-tailed hypothesis was used to compare the standardized annual rates for each time period. The two-tailed hypothesis was stated as:

H_o: average annual rate for patches from a Type Np prescription = average standardized annual rate for the reference patches.

The distribution of LWD recruitment rates was weighted toward rates at or near zero and had an extended right tail. Examination of the data confirmed that these data should not be considered normally distributed. Therefore, the non-parametric, two-sample MW test was used to test for differences between the reference patches and the patches receiving one of the prescriptions. The level of significance was 0.10.

Results

Overview of Patterns in Large Woody Debris Metrics

Table 41 shows LWD recruitment rates calculated on a piece/acre and volume/acre basis for three time periods: years 1-3 after harvest (2003-2006), years 4-5 after harvest (2006-2008) and the entire first five years after harvest (2003-2008). Variability in tree fall rates for each patch type is shown by the box-and-whiskers plots in Figure 6 and Figure 7.

Table 41. Descriptive statistics for large woody debris metrics by patch type for years 1-3 (2003-2008), years 4-5 (2006-2008) and the entire first five years (2003-2008) after harvest.

Patch Type	n	Mean LWD pieces/acre/yr		Mean LWD pieces/100 ft of stream/yr		Mean LWD volume/acre/yr (cu ft)		Mean LWD volume/100 ft of stream/yr	
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
2003-2006									
Reference	14	0.8	0.9	0.2	0.2	2.5	2.8	0.6	0.6
50-ft buffer	13	6.8	7.2	1.6	1.7	36.2	52.5	8.3	12.1
Clear-cut	8	0.1	0.1	0.02	0.03	0.3	0.8	0.1	0.2
PIP buffer	3	13.3	11.0	3.1	2.5	105.5	128.1	24.2	29.4
2006-2008									
Reference	13	5.5	7.0	1.3	1.6	19.8	29.8	4.5	6.8
50-ft buffer	12	4.5	4.9	1.0	1.1	26.9	33.4	6.2	7.7
Clear-cut	7	0.1	0.2	0.02	0.04	0.1	0.2	0.02	0.05
PIP buffer	3	4.0	3.6	0.9	0.8	12.3	10.8	2.8	2.5
2003-2008									
Reference	14	2.9	2.8	0.7	0.6	9.1	12.0	2.1	2.7
50-ft buffer	13	5.5	5.3	1.3	1.2	30.0	35.2	6.9	8.1
Clear-cut	8	0.2	0.3	0.04	0.07	0.3	0.5	0.1	0.1
PIP buffer	3	9.6	6.0	2.2	1.4	68.2	72.6	15.7	16.7

[1] SD = standard deviation

LWD recruitment was higher in the 50-ft buffers than in the reference patches during the first three years after harvest (2003-2008), over 8 times higher in pieces/acre/yr and over 14 times higher in volume/acre/yr. In years 4-5 after harvest LWD recruitment decreased in the 50-ft buffers and increased in the reference patches, and the number of recruited LWD pieces/acre/yr was greater in the reference patches, although the volume of LWD recruited was greater in the 50-ft buffers. For the entire first 5 years after harvest, the 50-ft buffers recruited about twice number of LWD pieces recruited in the reference patches, and over 3 times the volume. There was little LWD recruitment in the clear-cut patches in the first 5 years following harvest.

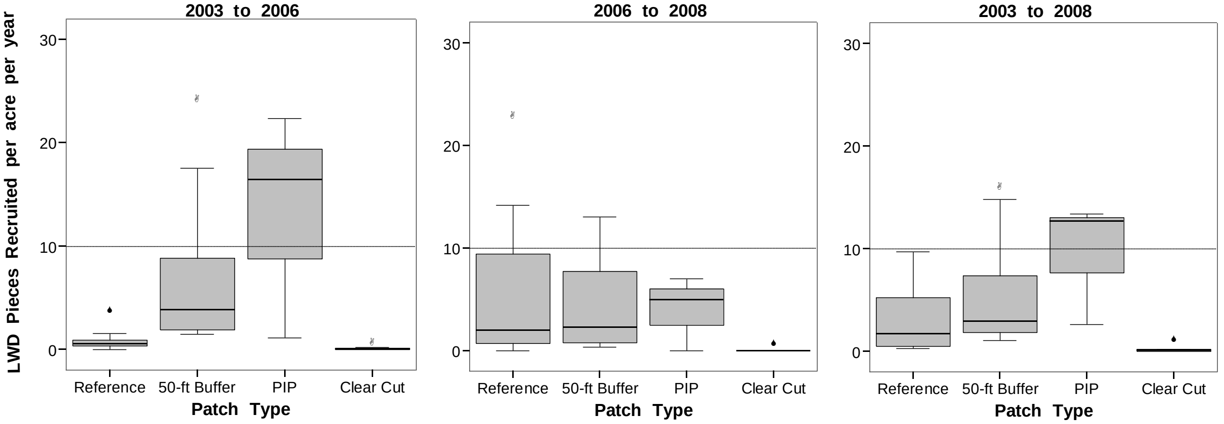

Figure 6. Distributions for annual rates of LWD recruitment in pieces/acre by patch type, for the 2003-2006, 2006-2008, and 2003-2008 time periods.

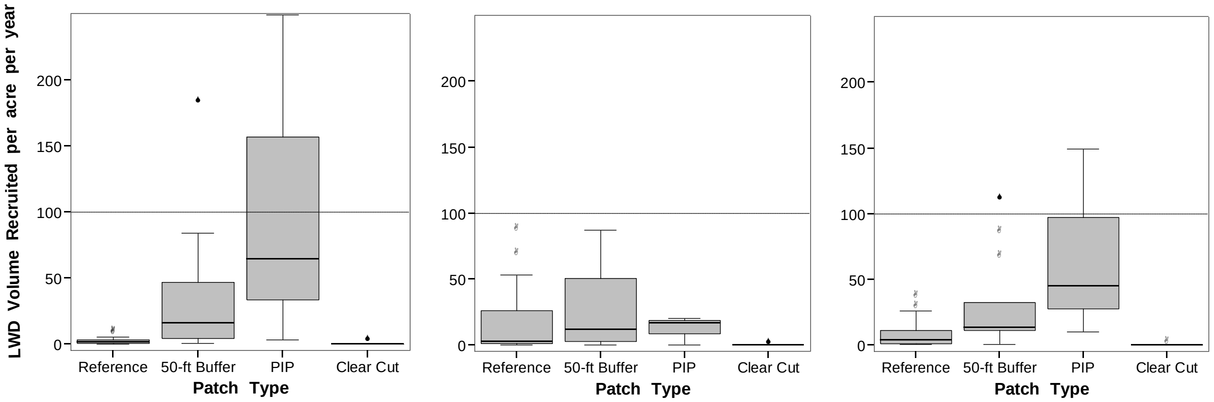

Figure 6. Distributions for annual rates of LWD recruitment in volume/acre by patch type, for the 2003-2006, 2006-2008, and 2003-2008 time periods.

Hypothesis Testing for Large Woody Debris Recruitment Metrics

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches in large woody debris recruitment rates (in pieces/acre/yr and volume/acre/yr) for each post-harvest time period. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. reference comparison

The clear-cut patches had low rates of LWD recruitment (both by count and by volume) for all time periods because there were few trees available to fall and recruit LWD in the clear-cut patches after harvest. The mean annual LWD recruitment rate in the clear-cut patches in both pieces/acre/yr and volume/acre/yr was only about one-tenth of the reference rates (Table 41). The differences between the clear-cut and the reference rates were significant for all periods ($P \leq 0.016$) so the null hypothesis was rejected.

50-ft buffer vs. reference comparison

During the first three years after harvest (2003-2006), the mean annual rates for LWD recruitment in the 50-ft buffers were higher for both mean LWD pieces/acre/yr and LWD volume/acre/yr (Table 42). The differences for both metrics were statistically significant so the null hypothesis was rejected and we conclude that the LWD recruitment rates in the 50-ft buffers were higher during the first three years after harvest. There was a seven-fold increase in the reference patch rates during the second time period (2006-2008) while the rates for the 50-ft buffers declined, and there was not a significant difference in either metric during this period. Over the entire five year period, the LWD recruitment rate for the 50-ft buffers was nearly twice the rate for the reference patches in pieces/acre/yr and over 3 times the reference rate in volume/acre/yr. The difference in LWD volume/acre/yr was significant ($P = 0.085$), while the difference in pieces/acre/yr was just above the threshold of significance ($P = 0.105$). Consequently, the evidence supports the conclusion that the LWD recruitment rates were higher in the 50-ft buffers over the entire five year period.

Table 42. 50-ft buffer prescription versus reference comparison for LWD recruitment rates in pieces/acre/year and volume in ft^3/acre/year with results of the Mann-Whitney test.

Sample Event	50-ft buffer Mean	Reference Mean	Difference (50-ft buffer–Reference)	*P*-value of the MW test[a]
LWD recruitment count in pieces/acre/year				
2003-2006	6.8	0.8	6.0	**<0.001**
2006-2008	4.5	5.5	-1.0	0.924
2003-2008	5.5	2.9	2.6	0.105
LWD recruitment volume in ft^3/acre/year				
2003-2006	36.2	2.5	33.7	**0.001**
2006-2008	26.9	19.8	7.1	0.314
2003-2008	30.0	9.1	20.9	**0.085**

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold.

PIP Buffer Observations

The data from the three PIP buffers indicate that LWD recruitment followed a similar pattern to the 50-ft buffers, with the highest recruitment rates during the first three years after harvest (2003-2006), and declining rates in years 4-5 after harvest (Table 41). However, mean LWD recruitment rates (by piece count and volume) in the PIP buffers during the first five years after harvest (2003-2006) were about twice as high as in the 50-ft buffers.

Characteristics of newly recruited large woody debris pieces

In-channel versus over-channel recruitment

LWD recruitment patterns in the buffers differed from the reference patches. Table 43 shows the in-channel, over-channel and total LWD volume/acre recruited over the first five years after harvest. Although the total volume of LWD reaching the channel in the 50-ft buffers was three times greater than the reference patches, the volume intruding into the bankfull channel was similar because only 2.4% of the total recruited volume for the 50-ft buffers intruded into the channel compared to 7.9% for the reference patches. Nearly half the recruited volume intruded into the channel in the PIP buffers.

Large Woody Debris Recruitment

Table 43. Comparison of in-channel versus over-channel recruited LWD volume by patch type.

Patch type	In-channel Volume/Acre (cu ft)	Over-channel Volume/Acre (cu ft)	Total LWD Volume/Acre (cu ft)	Percent In-channel Volume
Reference	3.6	41.9	45.5	7.9%
50-ft buffer	3.6	146.5	150.0	2.4%
Clear-cut	0.1	1.2	340.9	10.5%
PIP buffer	166.8	174.2		48.9%

Table 44 shows the percentage of LWD pieces by location relative to the bankfull channel. The bankfull piece count includes pieces that intrude into the channel below the height of the bankfull flow. Spanning pieces cross over the channel and touch on both sides. Suspended pieces hang over the channel but do not touch on one side. The majority of recruited LWD pieces in both the 50-ft buffer and reference patches were spanning, while suspended pieces comprised less than 30% of the total. Only about 15% of the total LWD pieces that reached the channel actually intruded below the height of bankfull flow for 50-ft buffers or references patches (Table 44). This finding is consistent with other studies that found the majority of newly recruited wood from buffers was spanning or suspended above the channel (Grizzel et al., 2000; Liquori, 2006).

Table 44. Distribution of LWD pieces by location relative to the channel.

Treatment	Bankfull pieces count (%)	Spanning pieces count (%)	Suspended pieces count (%)
Reference	14.1%	56.8%	29.1%
50-ft buffer	16.4%	55.1%	28.5%
Clear-cut	42.9%	42.9%	14.3%
PIP buffer	32.5%	42.5%	25.0%

Functions provided by newly recruited large woody debris

Few newly recruited LWD pieces provided in-channel functions because most did not intrude into the bankfull channel. Only 8% of all pieces provided sediment storage, 4% contributed to debris jam formation, 3% to step formation and 3% to pool formation (Figure 8).

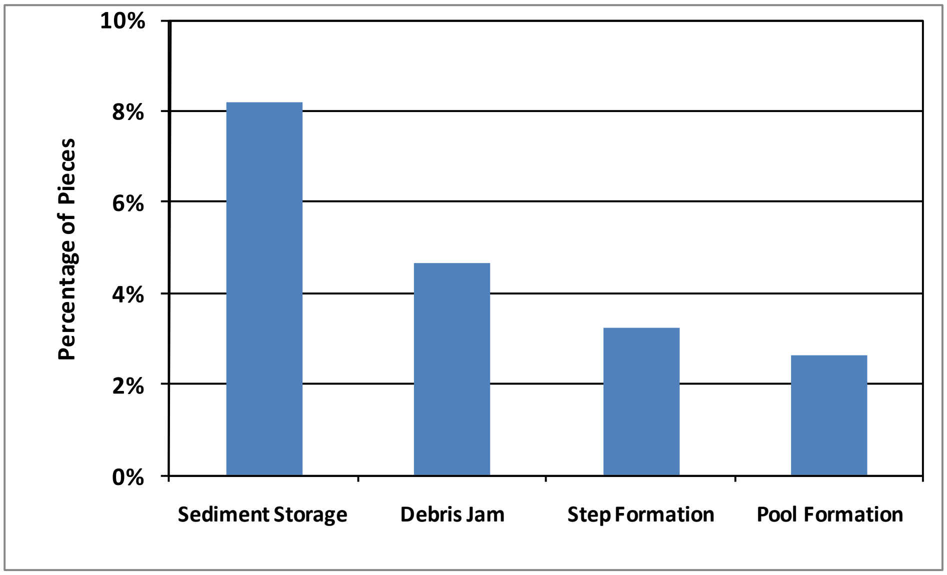

Figure 8. Percentage of recruited LWD pieces performing channel functions.

The mean volume of wood recruited (combined in- and over-channel) per LWD piece is shown in Table 45. On average, the mean recruited volume/piece for the 50-ft buffers and PIP buffers was larger than those for the reference and clear-cut patches.

Table 45. Mean recruited volume (cu ft) per LWD piece by patch type.

Prescription type	Mean Piece Volume (cu ft)
Reference	3.0
50-ft buffer	5.3
PIP buffer	7.0
Clear-cut	2.1

Figure 9 shows the relative proportion of LWD pieces that are conifer versus broad-leaf. Most riparian stands were dominated by conifers, and over 80% of the LWD piece count and volume came from conifers.

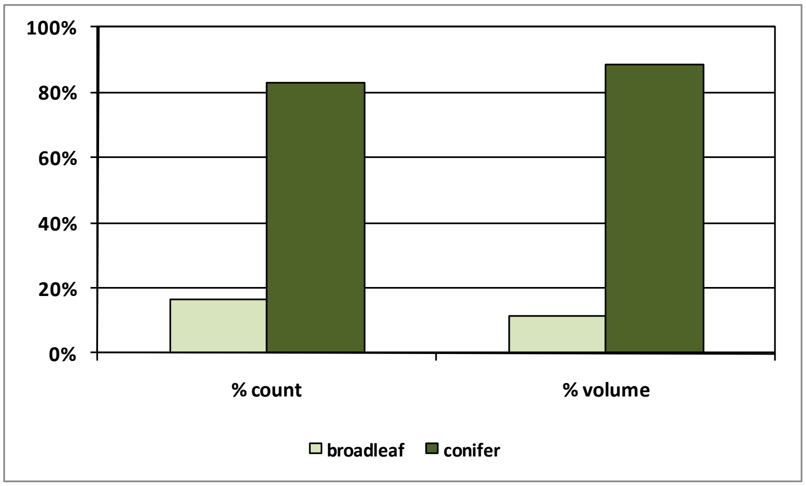

Figure 9. Percentages of conifer and broad-leaf LWD pieces recruited.

Discussion

Effect of the Prescriptions on LWD Recruitment Rates

The differences in LWD recruitment rates between patch types followed a similar pattern to the differences in tree mortality and tree fall rates. There was a strong correlation ($R^2 = 0.885$) between the tree fall in trees/acre/yr and LWD volume/acre/yr at the patch-scale (Figure 10). During the first three years after harvest, the mean LWD recruitment rates for the 50-ft buffers were higher than the reference rates, corresponding with the higher tree fall rates in the 50-ft buffers. LWD recruitment rates in the PIP buffers were higher than for the 50-ft buffers. Little LWD recruitment occurred in the clear-cut patches, where tree fall was minimal. The increase in LWD recruitment rates in the reference patches during years 4-5 after harvest correspond with the increase in tree fall rates in the reference patches due to the high magnitude wind-storms during the second time period.

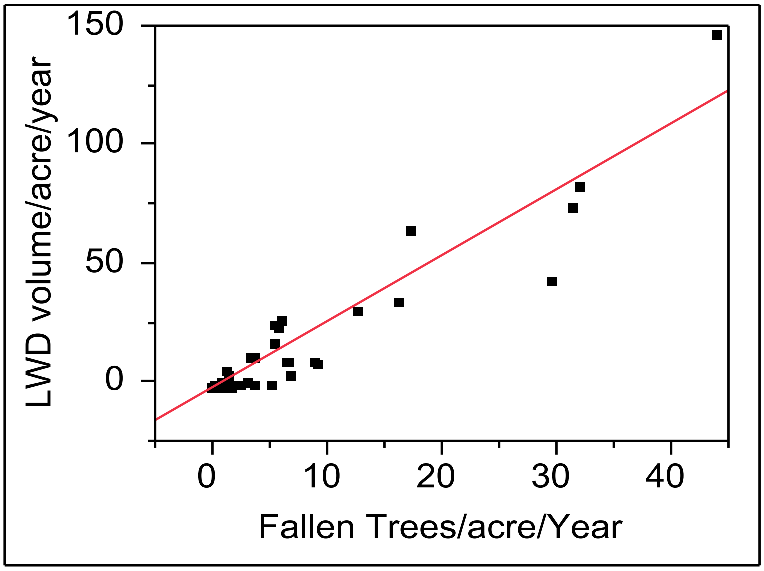

Figure 10. LWD recruitment volume/acre/yr (ft^3) vs. fallen trees/acre/yr.

Implications for the FFR LWD Recruitment Functional Objective

Schedule L-1 of the Forests and Fish Report has a functional objective for LWD/Organic Inputs to: "develop riparian conditions that provide complex habitats for recruiting large woody debris and litter", however there are currently no relevant performance targets in Schedule L-1 for Type Np streams. The following section discusses potential implications of differences in LWD recruitment rates and patterns on the functional objective for LWD recruitment.

The frequency distribution of patches by their cumulative LWD recruitment volume over the five year post-harvest period (Figure 11) follows a similar pattern to the frequency distribution for tree mortality (Figure 4). Reference patch volumes ranged from 2 - 181 ft^3/acre, and most were less than 100 ft^3/acre. The distribution of values for the 50-ft buffers is more variable than the reference patch distribution, ranging from 2 - 554 ft^3/acre. Although the majority of 50-ft buffer values were less than 100 ft^3/acre (similar to the reference patches), 20% had values greater than 300 ft^3/acre, well beyond the upper limits of the reference patch range. The distribution for the three PIP buffers shifts further to the right, and the highest value (747.5 ft^3/acre) is well beyond the range of the other patch types. Half of the clear-cut patches had no LWD recruitment in the first five years after harvest, and the remainder had low values, however wood input during the timber harvest operation was not documented.

The differences in tree fall and LWD recruitment rates are indicative of different wood input regimes. For the reference patches and most 50-ft buffers, LWD input into and over the channel was moderate and most trees remain standing five years after harvest, so there are many standing trees available to sustain LWD recruitment over time. A sub-set of the 50-ft and PIP buffers received a large pulse of wood input during the first few years following harvest due to high tree mortality and tree fall rates. However these LWD recruitment rates are unsustainable due to depletion of standing trees. Consequently, tree fall and LWD recruitment rates in buffers with high mortality should decline over the next few decades until regeneration and tree growth provide replacement trees, resulting in a discontinuous, cyclic LWD input pattern over time. LWD input in the clear-cut patches is intermittent and episodic. Wood input in the clear-cut patches during timber harvest was not quantified, however a large amount of broken pieces and tree tops were observed in the channel immediately after harvest, which is consistent with other studies that documented large inputs of debris and slash following clear-cut harvest on Type Np streams in western Washington (Jackson et al., 2001; Maxa, 2009). Since few trees are left standing in the clear-cut patches, the input of logging debris will be followed by a period with little wood recruitment while the stand re-grows.

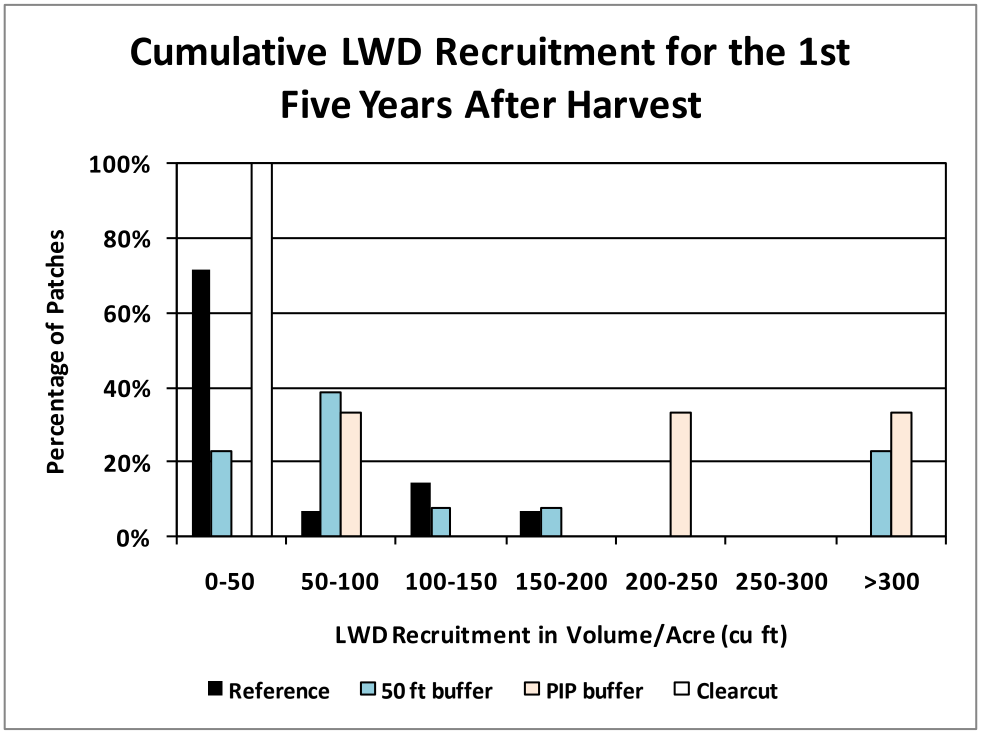

Figure 11. Cumulative LWD recruitment volume (ft^3/acre) five years after harvest by patch type.

The implications of these differences in LWD recruitment depend on the characteristics of the stream channel, because the functions of woody debris (and the amount and size of wood necessary to perform various functions) varies depending on factors such as channel width, gradient, stream power and morphology (Montgomery and Buffington, 1997; Gomi, 2001; Hassan et al., 2005). Smaller diameter wood that enters the stream as slash from clear-cut harvest and recruitment from young second-growth stands can persist and provide cover and functions such as sediment storage in narrow, low-gradient streams that are not vulnerable to debris flows (Gomi et al., 2001; Jackson et al., 2001; Maxa, 2009). However in larger streams with greater transport capacity and in steep channels prone to mass wasting and debris flow transport processes, small diameter wood is less stable than larger pieces. In these streams, large stable wood pieces increased roughness and create steps that dissipate energy, playing an important role in the accumulation and storage of sediment by forming stable sediment retention structures such as steps and jams that can are periodically evacuated during extreme events (O’Connor and Harr, 1994; Grizzel and Wolff, 1998; Gomi, 2001; May and Gresswell, 2003; Hassan et al., 2005). In headwater channels vulnerable to debris flow processes, large wood functions to reduce the velocity and run-out distance of debris flows (Lancaster et al., 2003). The trees remaining in the buffers will continue to grow over time, providing the opportunity to recruit large diameter wood in the future. In the clear-cut reaches, the window of opportunity for recruiting large diameter wood from the new stand is limited by the 40-60 year harvest cycle (Bisson et al., 1987; Andrus et al., 1988, McHenry et al, 1998; Beechie et al., 2000; Meleason et al., 2003). Mass wasting buffers are required along streams adjacent to unstable landforms, providing an additional source of wood recruitment to mass wasting prone headwater streams.

The majority of the wood recruited to the channel came from conifer trees because most of the stands were dominated by conifers. Conifer wood is typically more resistant to decay, breakage and degradation than broadleaf wood and persists longer in the channel (Andrus et al., 1988; Hyatt and Naiman, 2001). The functions potentially provided by LWD depend on its position relative to the channel. Pieces that intrude below the height of the bankfull flow (in-channel pieces) interact with flowing water during high discharge events and can store sediment; scour pools; form debris jams, channel steps or side channels; increase channel roughness and energy dissipation; and form habitat by sorting substrate, creating low velocity areas and providing in-channel cover (Jackson et al., 2001; May and Gresswell, 2003; Reeves et al., 2003). Most newly recruited wood was suspended over the channel, so the initial pulse of wood recruited from buffers will not result in a large increase in sediment storage, pool or step formation. Although spanning or suspended pieces do not initially perform in-channel functions, they provide shade and cover and often enter the stream channel over time as they settle, break apart or decay (Grizzel and Wolff, 1998, Bahuguna et al., 2010). Consequently, spanning and suspended pieces act as a reserve for future LWD input that will tend to moderate the intermittent pattern of tree fall in the buffers. Over a longer timeframe, LWD that accumulates in steep portions of the headwater stream network that are subject to debris flows can be transported downstream and contribute wood to fish-bearing streams lower in the drainage network (Gomi et al., 2001; May and Gresswell, 2003; Reeves et al., 2003).

CHANNEL DEBRIS

Type Np channels contain debris of various sizes that originates from sources including trees that fall into the channel, branch fall from adjacent standing trees, and debris from timber harvest. This section addresses uncertainty concerning the magnitude and duration of change in channel debris loading when the westside Type Np riparian prescriptions are applied.

Critical Questions

1. What amount of channel woody debris occurs in stream channels following application of the westside Type Np riparian prescriptions?
2. What is the magnitude and duration of change in channel debris following application of the westside Type Np riparian prescriptions compared to untreated reference sites?

Data Collection Procedures

Channel debris data were collected in 2006 (three years after harvest) and 2008 (five years after harvest). Data were collected along transects across the bankfull channel at 50-foot intervals along the stream. Percent total debris cover was visually estimated as a percentage of the bankfull channel surface area covered by woody debris looking down from above at an area extending two feet above and below each transect. Percent suspended debris cover is a subset of total debris cover that includes only the portions of woody debris suspended above the bankfull channel. If the channel is visible, the percentage of bankfull channel cross-sectional area obstructed by debris is visually estimated along the transect at each station. The in-channel functions provided by channel debris at each station were recorded.

Metrics, Hypotheses and Methods of Statistical Analysis

The objectives of the channel debris analyses were to: 1) characterize the channel debris conditions for each patch type at each sample event, 2) characterize the change in conditions for each patch type between sample events, and 3) compare channel debris conditions, and changes in conditions, for the westside Type Np prescriptions to the reference conditions.

Three metrics were used to evaluate debris loading and channel obstruction by debris. The mean value for each of these metrics was calculated for each individual patch using the data from the stations in the patch. The individual patch means were averaged to calculate the patch type mean.

Percent total woody debris cover (plan view). The mean percentage of the bankfull channel surface area obscured by woody debris; including debris above and within the bank full channel.

Percent suspended woody debris cover (plan view). The mean percentage of the bankfull channel surface area obscured by woody debris located entirely above the bankfull channel.

Percent channel cross-section filled with woody debris. The mean percentage of bankfull channel cross-sectional area obstructed by woody debris.

A one-tailed hypothesis test was used to compare percent total woody debris cover and percent suspended debris cover for the prescription patches to the reference patches, stated as:

> H_o: average condition for patches for a prescription ≤ average condition for the reference patches.

A two-tailed hypothesis was used to compare percentage of channel cross-section filled with debris. The two-tailed hypothesis was stated as:

> H_o: average conditions for patches from a prescription = average conditions for the reference patches.

As percentages, these metrics are bounded by 0.0 (or 0%) and 1.0 (or 100%). Examination of the data confirmed that these data should not be considered normally distributed. Therefore, the Mann-Whitney test was used to test for differences between the reference patches and the patches receiving one of the prescriptions. The level of significance was 0.10.

Results

Overview of Patterns in Channel Debris Metrics

Data on channel cover and obstruction by woody debris are shown in Table 46 for the 2006 and 2008 sample events. The first two columns show descriptive statistics for percent total woody debris cover (the percentage of the bankfull channel surface area obscured by woody debris of all sizes when viewed from above) for each sample event. The next two columns show percent suspended woody debris cover (a subset of the total consisting of debris suspended above the height of the bankfull channel). The last two columns show the percentage of the bankfull channel cross-section obstructed by woody debris, an indicator of flow obstruction by woody debris. Figure 12 shows the distribution of percent total woody debris cover by patch type.

Channel Debris

Table 46. Descriptive statistics for channel debris metrics by patch type three years (2006) and five years (2008) after harvest.

Patch Type	n	Total woody debris cover		Suspended woody debris cover		Channel cross-section obstructed by debris	
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]
2006							
Reference	13	27.8 %	15.0	10.4 %	7.3	18.3 %	11.4
50-ft buffer	12	24.7 %	13.6	11.1 %	6.6	12.8 %	10.5
Clear-cut	7	64.8 %	18.5	37.9 %	12.8	30.8 %	16.5
PIP buffer	3	25.3 %	17.0	20.7 %	17.0	12.8 %	19.3
2008							
Reference	14	28.0 %	14.6	13.8 %	10.6	19.3 %	11.7
50-ft buffer	13	23.2 %	17.1	16.0 %	14.6	11.1 %	9.6
Clear-cut	8	50.7 %	22.9	38.8 %	25.4	26.9 %	19.1
PIP buffer	3	42.5 %	10.9	40.8 %	12.8	7.5 %	6.6

[1] SD = standard deviation

The percentages of total and suspended woody debris cover were similar for the 50-ft buffer and reference patches in year 3 (2006) and year 5 (2008) after harvest. Total and suspended debris cover in the clear-cut patches was over twice as high as in the 50-ft buffer and reference patches three years after harvest. Total woody debris cover decreased by 15% between 2006 and 2008 in the clear-cut patches, but there was little change in suspended woody debris cover and both metrics were nearly twice the means for the reference and 50-ft buffer patches.

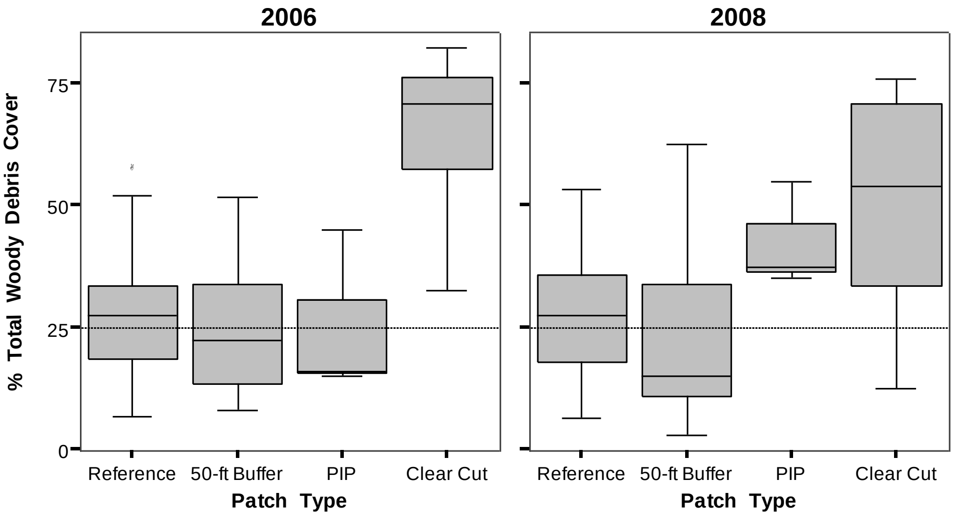

Figure 12. Distributions of patch means for percent total woody debris cover by patch type, three years after harvest (2006) and five years after harvest (2008).

Mean percent total woody debris cover was highest in the clear-cut patches, which averaged 65% three years after harvest (2006) and decreased to around 50% after five years (2008), about two times the reference patch means. The clear-cut patch values were highly variable in 2008 as the spread between high and low values increased (Figure 12). The percentage of channel cross-section obstructed by debris in the clear-cut channels was higher than in the reference and 50-ft buffer patches, and there was little change between 2006 and 2008.

Hypothesis Testing for Channel Debris Metrics

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches in the channel debris metrics at two post-harvest sample events. A second test was conducted to determine if the magnitude of change in values between sample events for each prescription were significantly different from the change observed in the reference patches. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut versus reference comparison

Percent total woody debris cover. Mean percent total woody debris cover for the clear-cut patches was 37.0% higher than the reference mean in 2006, and decreased in 2008 but was still 22.7% higher than the reference mean (Table 47). The differences were statistically significant for both sample events, so the null hypothesis was rejected and we concluded that total woody debris cover in the clear-cut patches was significantly higher. Levels in the clear-cut patches declined by 14.3% between 2006 and 2008. The magnitude of change (decrease) was statistically significant in comparison to the small amount of change in reference patches ($P = 0.034$).

Percent suspended woody debris cover. Mean percent suspended woody debris cover in the clear-cut patches was 3.5 times the mean reference value in 2006 and 2.8 times the reference value in 2008 (Table 47). The differences between the clear-cut and reference values were statistically significant for both sample events, so the null hypothesis was rejected and we conclude that suspended woody debris cover in the clear-cut patches was significantly higher. The mean values for suspended woody debris cover in the clear-cut patches were stable between 2006 and 2008 and the rate of change for the clear-cut patches was not significantly different than that of the reference patches.

Table 47. Clear-cut prescription versus reference comparison for channel debris loading and obstruction metrics with results of the Mann-Whitney test.

Sample Event	Clear-cut Mean	Reference Mean	Difference (Clear-cut–Reference)	*P*-value of the MW test[a]
Percent total debris cover				
2006	64.8 %	27.8 %	37.0 %	**0.001**
2008	50.7 %	28.0 %	22.7 %	**0.012**
Percent suspended debris cover				
2006	37.9 %	10.4 %	27.5 %	**<0.001**
2008	38.8 %	13.8 %	25.0 %	**0.008**
Percent of channel cross-section obstructed by debris				
2006	30.8 %	18.3 %	12.5 %	**0.097**
2008	26.9 %	19.3 %	7.6 %	0.482

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold.

Percentage of channel cross-section obstructed by woody debris. The mean percentage of channel cross-section obstructed by debris in the clear-cut patches was 12.5% greater than the reference mean in 2006, but decreased by 2008 and was only 7.6% greater than the reference value (Table 47). The difference was statistically significant in 2006, so the null hypothesis was rejected and we concluded that channel obstruction in the clear-cut patches was higher than in the reference patches. By 2008 the difference was no longer significant so the null hypothesis could not be rejected. It appears that there was a decreasing trend in mean clear-cut values between 2006 and 2008, however there was not a statistically significant difference in the mean change for the clear-cut and reference patches. The data likely underestimate mean channel obstruction in the clear-cut patches because data could not be collected at stations where the channel cross-section was buried under debris. Consequently, the differences between the clear-cut and reference mean values are likely to be greater than the data indicate.

50-ft buffer versus reference comparison

Percent total woody debris cover. Mean percent total debris cover values were somewhat higher for the reference patches than the 50-ft buffers at both sampling events, but the differences were less than 5% and were not significant for either sample event (Table 48). Mean values for both the 50-ft buffer and reference patches remained relatively consistent between the 2006 and 2008 sample events and there was not a significant difference in the rate of change.

Percent suspended woody debris cover. Mean percent suspended debris cover was similar for the reference and 50-ft buffer patches for both sample events and the differences were not significant (Table 48). Mean values in the reference and 50-ft buffer patches increased slightly between 2006 and 2008 but there was not a significant difference in the rate of change.

Percentage of channel cross-section obstructed by woody debris. Mean percent of channel cross-section obstructed by woody debris was lower in the 50-ft buffers than the reference patches in both 2006 and 2008. The difference increased over time and was significant for the 2008 sample event, so the null hypotheses was rejected and we concluded that mean channel obstruction was significantly lower for the 50-ft buffers in 2008 (Table 48). However, there was not a significant difference in the rate of change over time.

Table 48. 50-ft buffer prescription versus reference comparison for channel debris loading and obstruction metrics with results of the Mann-Whitney test.

Sample Event	50-ft buffer Mean	Reference Mean	Difference (50-ft buffer–Reference)	*P*-value of the MW test[a]
Percent total debris cover				
2006	24.7 %	27.8 %	-3.1 %	0.306
2008	23.2 %	28.0 %	-4.8 %	0.175
Percent suspended debris cover				
2006	11.1 %	10.4 %	0.7 %	0.282
2008	16.0 %	13.8 %	2.2 %	0.415
Percent of channel cross-section obstructed by debris				
2006	12.8 %	18.3 %	-5.5 %	0.205
2008	11.1 %	19.3 %	-8.2 %	**0.094**

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold.

PIP Buffer Observations

Mean total woody debris cover for the PIP buffers was similar to the 50-ft buffers in 2006, however suspended woody debris cover was nearly twice as high (Table 46). Both total and suspended debris cover increased by around 20% between 2006 and 2008 in the PIP buffers, while the levels in the 50-ft buffers remained stable. Mean percent channel obstruction by woody debris was similar in the PIP and 50-ft buffers in 2006 and decreased in 2008 (Table 46).

Discussion

Effect of Prescriptions on Channel Debris

Our ability to interpret the channel woody debris cover and obstruction data is limited by the absence of pre-treatment data and the fact that our first data point occurred three years after harvest. We did not observe evidence of noticeable input of logging debris slash in either the 50-ft buffers or the PIP buffers. This is consistent with Jackson et al. (2001), who observed that riparian buffer trees act as “fences” that prevent logging debris from the adjacent, upslope clear-cut areas from reaching the stream. Most changes in channel debris for the reference, 50-ft buffer and PIP buffer patches were due to wind-throw in the years following harvest. Total and suspended cover appeared to increase in the PIP buffers between the 2006 and 2008 sample events, apparently due to debris input as a result of accelerated tree fall in the PIP buffers.

The clear-cut treatment appeared to have the greatest effect on channel debris loading due to the input of logging debris including tree tops, branches and broken pieces of boles. Mean levels for all three channel debris metrics in the clear-cut patches were significantly higher than the reference patch means in 2006, and the differences for the two woody debris cover metrics were significant in 2008, indicating that the effect persisted through the first five years after harvest, although there was evidence of a decreasing trend in the clear-cut patches over time. Greater channel obstruction in the clear-cut patches relative to the other patch types appears to be due to the smaller size of cut tops and branches which allows them to settle down into the channel, while fallen trees tend to be suspended over the channel. Jackson et al. (2001) documented extensive burial of headwater stream channels with clear-cut timber harvest to the edge of the channel. They observed that debris depth and the percentage of channel covered decreased substantially two years after harvest, so it seems likely that debris coverage would have been greater in the clear-cut patches immediately after harvest than indicated by the data collected at our first sample event three years after harvest.

Implications of the Riparian Prescriptions on Channel Wood Debris

The frequency distributions for total woody debris cover by patch type are shown in Figure 13. Three years after harvest (left panel), most 50-ft buffer and reference patches had less than 40% total woody debris cover, while most clear-cut patches had over 60%. The distribution for the clear-cut patches shifted in 2008 (right panel), indicating that channel debris was decreasing in the clear-cut patches.

Channel debris from logging slash has been documented to have a number of channel effects, including accumulation and retention of fine sediment (Jackson et al., 2001; Maxa, 2009), with the proportion of fine sediment particles increasing as channel slope decreased (Maxa, 2009). Stream channels in the clear-cut patches are most likely to be affected, since it appears that the buffer prescriptions were largely effective in preventing initial input of slash during harvest. High tree fall rates elevated total suspended debris cover in some patches, but since much of the debris from fallen trees is suspended over the channel, it does not tend to obstruct the channel as readily as debris from timber harvest.

Channel Debris

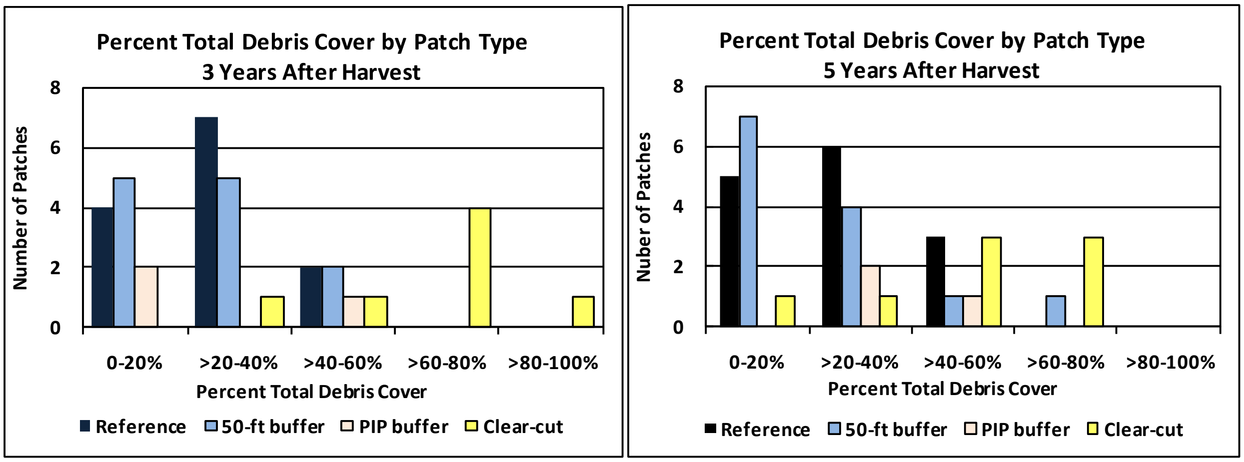

Figure 13. Frequency distribution for percent total woody debris cover by patch type, three years after harvest (left) and five years after harvest (right).

STREAM SHADE INDICATORS

This analysis addresses uncertainty about the amount of shade provided to stream channels following application of the westside Type Np riparian prescriptions, and how shade is affected by factors such as tree mortality following harvest. This analysis utilizes two indicators to evaluate different types of cover that potentially provide shade and thermal buffering of the stream channel. Shade from overhead cover documents obstruction of the view-to-sky by trees, shrubs and topography as viewed through a densiometer held at waist height in the stream channel. Shade from live understory plant cover documents the bankfull channel surface area obscured by live plants below the view of the densiometer.

Critical Questions

1. How much shade to the stream channel is provided by riparian stands following application of the westside Type Np riparian prescriptions?
2. What is the magnitude and duration of change in shade following application of the westside Type Np riparian prescriptions compared to untreated reference sites?

Data Collection Procedures

Shade indicator data were collected during the summer and early fall at three intervals, one year after harvest (2004), three years after harvest (2006) and five years after harvest (2008). Measurements were taken at a series of stations systematically located along the channel from a random starting point. The same measurement stations were used in subsequent years. We attempted to obtain 10 measurements per patch; however the number of stations varied due to patch length and accessibility. Because of the small size of the PIP buffer, stations were located at 50 ft intervals with a random starting point which resulted in 3 measurements per PIP buffer.

Shade from overhead cover was assessed by measuring percent canopy closure with a densiometer held at waist height (3.5 ft) using methods described in Pleus and Schuett-Hames (1998). Four measurements are 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 indicated.

Shade from understory plant cover immediately above the channel is not documented by densiometer readings. To document this component of cover, a visual estimate was made of the percentage of the bankfull channel surface area obscured from view by low growing plants in a section of the bankfull channel extending two feet upstream and downstream of each sampling station.

Metrics, Hypotheses and Methods of Statistical Analysis

The objectives of the shade analyses were to: 1) characterize stream shading for each patch type at each sample event, 2) characterize the change in stream shading between sample events, and 3) compare the Type Np prescriptions to the reference patches.

Two metrics are used to evaluate changes in shade conditions:

Percent overhead cover. Percent overhead cover viewed from the stream was calculated for each measuring station by averaging the four readings (upstream, downstream, left bank, right bank) and multiplying by 1.04 (Pleus and Schuett-Hames, 1998). The mean percent overhead cover for each patch is the average of the values for all stations within each patch. The mean for each patch type was calculated by averaging the mean patch values for each sample event.

Percent of channel obscured by live understory plant cover. The mean percent live understory plant cover for each patch is the average of the values for all stations within the patch. The mean for each patch type was calculated by averaging the mean patch values for each sample event.

A one-tailed hypothesis test was used to compare mean shade in the Type Np prescription patches to the reference patches because we were interested in determining if shade conditions decreased for the prescription patches in comparison to the reference patches. The one-tailed null hypothesis was stated as:

> H_o: average condition for patches for a Type Np prescription ≥ average condition for the reference patches.

A two-tailed hypothesis was used to compare changes in conditions between sample events. The two-tailed hypothesis was stated as:

> H_o: average change in conditions between sample events for patches from a Type Np prescription = average change in conditions for the reference patches.

As proportions, these metrics are bounded by 0.0 and 1.0 (100 %). Examination confirmed that these data should not be considered normally distributed. Therefore, the MW test was used to test for differences between the reference patches and patches receiving one of the prescriptions. The level of significance was 0.10.

Results

Overview of Patterns in Stream Shade Indicators

Table 49 shows shade indicator data (percent overhead cover and percent live understory plant cover) by patch type at year (2004), three years (2006) and five years (2008) after harvest.

Shade

Table 49. Descriptive statistics for stream shade metrics by patch type; one year (2004), three years (2006) and five years (2008) after harvest.

Patch Type	n	Overhead Cover (viewed from stream)		Percentage of Channel Obscured by Understory Plant Cover	
		Mean	SD[1]	Mean	SD[1]
2004					
Reference	14	89.3 %	4.4 %	14.3 %	8.3 %
50-ft buffer	13	75.9 %	15.7 %	28.9 %	16.8 %
Clear-cut	8	12.0 %	12.7 %	17.8 %	13.1 %
PIP buffer	3	54.9 %	21.2 %	37.3 %	26.4 %
2006					
Reference	13	93.3 %	4.9 %	13.3 %	4.7 %
50-ft buffer	12	80.8 %	19.9 %	31.3 %	20.2 %
Clear-cut	7	14.0 %	14.4 %	38.7 %	31.1 %
PIP buffer	3	65.0 %	13.2 %	29.4 %	14.6 %
2008					
Reference	14	90.2 %	4.6 %	16.0 %	16.8 %
50-ft buffer	13	80.6 %	15.7 %	34.7 %	21.0 %
Clear-cut	8	36.5 %	27.6 %	41.2 %	24.4 %
PIP buffer	3	61.7 %	21.4 %	47.4 %	38.1 %

[1] SD = standard deviation

Mean overhead cover was highest in the reference patches, lower in the 50-ft buffers and lowest in the clear-cut patches during the first five years after harvest (Table 49). Mean overhead cover remained stable over time in the reference and 50-ft buffers. The reference mean exceeded 89% at every sample event, and the 50-ft buffer mean ranged from 75.9-80.8%, about 10-13% lower than the reference patch mean. Overhead cover in the clear-cut patches was much lower than in the reference or 50-ft buffer patches, but increased from 12% to 37% during the first five years after harvest. There was less variability in the reference patches than the 50-ft buffers. Variability increased over time in the clear-cut patches (Figure 14) as values increased over time.

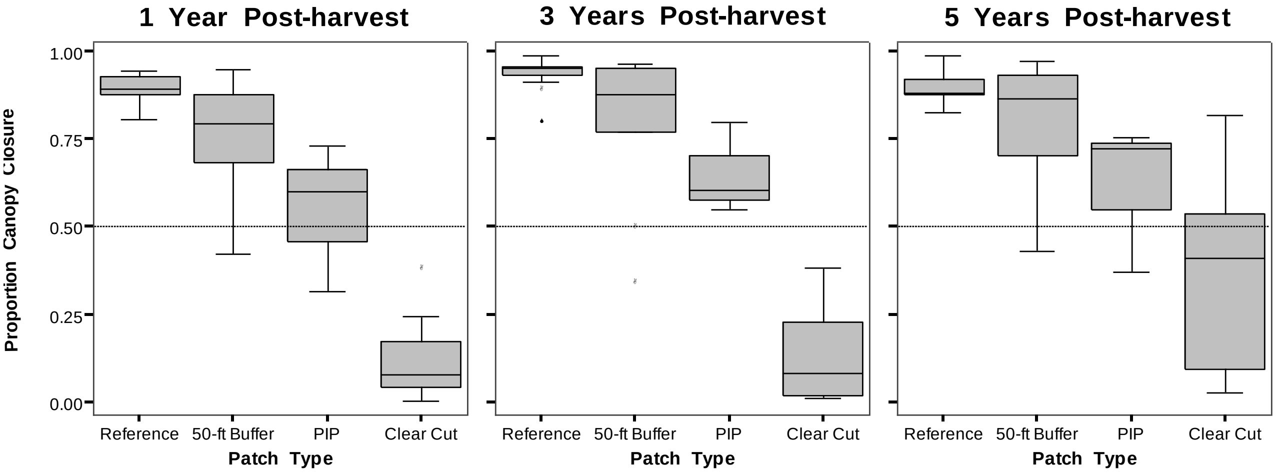

Figure 14. Distribution of mean overhead cover values by patch type by sample event.

In the first year after harvest, the mean percentage of channel obscured by live understory plant cover was lowest in the reference patches (14.3%), higher in the clear-cut patches (17.8%) and twice as high in the 50-ft buffers (28.9%); over twice the reference patch mean (Table 49). Live understory plant cover remained relatively consistent in the 50-ft buffer and reference patches over the five year period. The greatest change in live understory plant cover occurred in the clear-cut patches, which started with a mean of 17.8% at year one, increased to 38.7% at year three and to 41.2% at year five. Variability was lowest in the reference patches, and variability appeared to increase over time in all patch types (Figure 15).

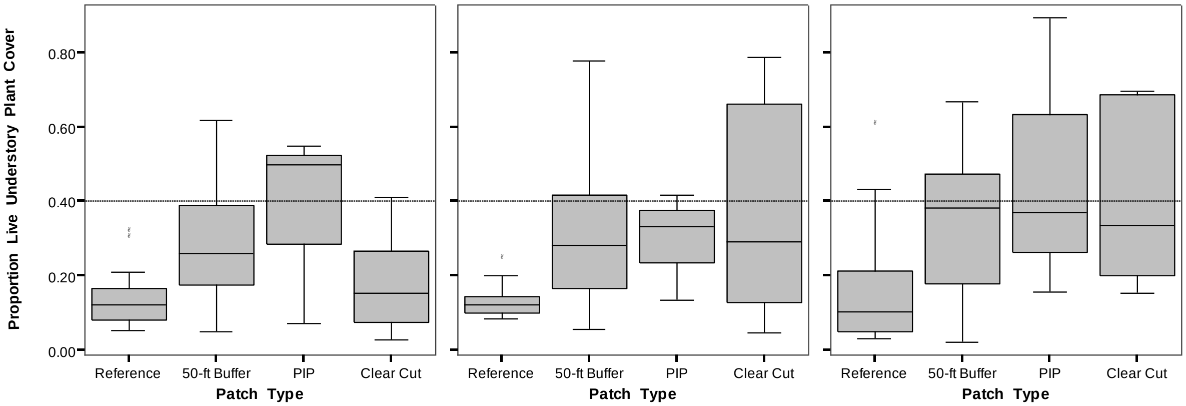

Figure 15. Distributions for percent of channel obscured by live understory plant cover by patch type, at one year (left), three years (middle) and five years (right) following timber harvest.

Hypothesis Testing for Stream Shade Indicators

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches in the stream shade indicators at three post-harvest sample events. A second test was conducted to determine if the magnitude of change in values between sample events for each patch type were significantly different from the change observed in the reference patches. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut vs. Reference Comparison

The clear-cut patches had the lowest mean overhead cover. The mean value for the clear-cut patches was 12.1% in 2004, 77% below the reference patch value. The clear-cut patch mean increased to 36.5% by 2008 and was 54% lower than the reference patch mean in 2008 (Table 50). The differences were significant for all sample events so the null hypothesis was rejected and we concluded that overhead cover was lower in the clear-cut patches. The difference in magnitude of change between 2004 and 2008 for the reference and clear-cut patches was statistically significant ($P = 0.006$) so we conclude there was a greater increase in mean percent overhead cover for the clear-cut patches.

The mean percentage of channel surface area obscured by live understory plant cover was similar for the clear-cut and reference patches in 2004. The clear-cut mean was 25% greater in 2006 and 2008 and the differences were significant (Table 50), so we rejected the null hypothesis and concluded that understory plant cover was greater in the clear-cut patches for the 2006 and 2008 sample events. The difference in the magnitude of change between 2004 and 2008 for the clear-cut and reference patches was statistically significant ($P = 0.002$) so we reject the null hypothesis and conclude there was a greater rate of change (increase) in mean percent of channel obscured by live understory plant cover in the clear-cut patches over the five year post-harvest period.

Shade

Table 50. Reference versus clear-cut comparison of shade indicator metrics by sample event with results of the Mann-Whitney test.

Sample Event	Clear-cut Mean	Reference Mean	Difference (Clear-cut–Reference)	*P*-value of the MW test[a]
Percent overhead cover (viewed from stream)				
2004	12.0 %	89.3 %	-77.3 %	**<0.001**
2006	14.0 %	93.3 %	-79.3 %	**<0.001**
2008	36.5 %	90.2 %	-53.7 %	**<0.001**
Percent of Channel Obscured by Live Understory Plant Cover				
2004	17.8 %	14.3 %	03.5 %	0.382
2006	38.7 %	13.3 %	25.4 %	**0.091**
2008	41.2 %	16.0 %	25.2 %	**0.001**

One-sided test of H_o: prescription ≥ reference. Tests significant with $P \leq 0.10$ are in bold.

50-ft buffer versus reference comparison

Mean overhead cover in the 50-ft buffers ranged from 75.9% to 80.8 over time, about 10 % lower than for reference patches. The differences were statistically significant for all sample events so the null hypothesis was rejected and we concluded that mean percent overhead cover was lower for the 50-ft buffers (Table 51). There was little change in either the 50-ft buffer or reference patch means between sampling events, so the differences in the magnitude of change between 2004 and 2008 was not statistically significant.

Table 51. Reference versus 50-ft buffer comparison for shade indicator metrics by sample event, with results of the Mann-Whitney test.

Sample Event	50-ft buffer Mean	Reference Mean	Difference (50-ft buffer–Reference)	*P*-value of the MW test[a]
Percent Overhead Cover				
2004	75.9 %	89.3%	-13.4 %	**0.007**
2006	80.8 %	93.3 %	-12.5 %	**0.030**
2008	80.6 %	90.2 %	-9.6 %	**0.058**
Percent of Channel Obscured by Live Understory Plant Cover				
2004	28.9 %	14.3 %	14.6 %	**0.005**
2006	31.3 %	13.3 %	18.0 %	**0.001**
2008	34.7 %	16.0 %	18.7 %	**0.010**

One-sided test of H_o: prescription ≥ reference. Tests significant with $P \leq 0.10$ are in bold.

The mean percentage of channel surface area obscured by live understory plant cover remained relatively consistent in the 50-ft buffer and reference patches throughout the study period, and was about 15% higher for the 50-ft buffers throughout the entire period (Table 51). The differences were significant at all sample events so the null hypothesis was rejected and we conclude that mean percent live understory plant cover was higher for the 50-ft buffers at all three sampling events, however understory cover may have been lower in the 50-ft buffers prior to harvest because of lower tree densities. The mean values for the 50-ft buffers increased from 28.9% to 34.7% between 2004 and 2008. The difference in the magnitude of change between 2004 and 2008 for the 50-ft buffer and reference patches was statistically significant (*P* = 0.043) so we reject the null hypothesis and there was a greater increase in mean percent of channel obscured by live understory plant cover for the 50-ft buffers over the five year post-harvest period.

PIP Buffer Observations

Mean overhead cover in the PIP buffers ranged between 55 and 65%, consistently 15-20% lower than the 50-ft buffers at all sample events (Table 49). Mean live understory plant cover for the PIP buffers was about 10% higher than the 50-ft buffers in 2004 and 2008 (Table 49), decreasing between 2004 and 2006, and then increased in 2008. High tree fall rates and associated disturbance appear to contribute to the variability and lack of a clear trend.

Trends in Shade Metrics Over Time

Figure 16 shows the distribution for mean percent overhead cover by patch type for the 2004 (left) and 2008 (right) sample events. All reference patches had over 75% overhead cover throughout the period. There was a slight shift to the right in the distributions for the 50-ft buffers as overhead cover increased over time at some patches. The clear-cut patches had the greatest increase over time. Only one clear-cut patch had over 25% overhead cover the first year after harvest, however by year five after harvest, 5 of 8 patches exceeded 25%.

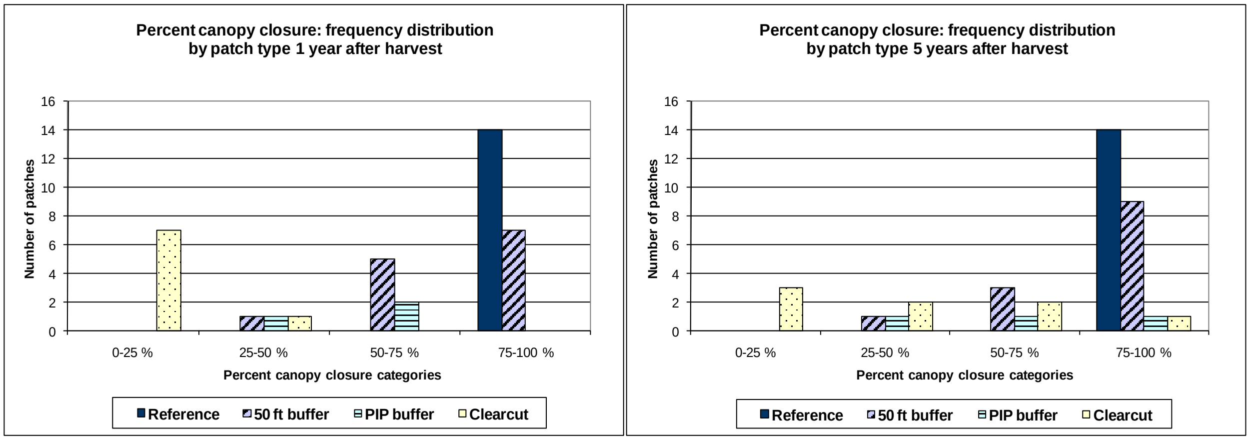

Figure 16. Frequency distribution of percent overhead cover values by patch type, one and five years after harvest.

Figure 17 shows the frequency distribution for mean percent of channel obscured by live understory plant cover for the 2004 (left panel) and 2008 (right panel) sample events. There was a shift in the distributions to the right over time for the reference, clear-cut and 50-ft buffer patches as live understory cover increased at some patches.

Shade

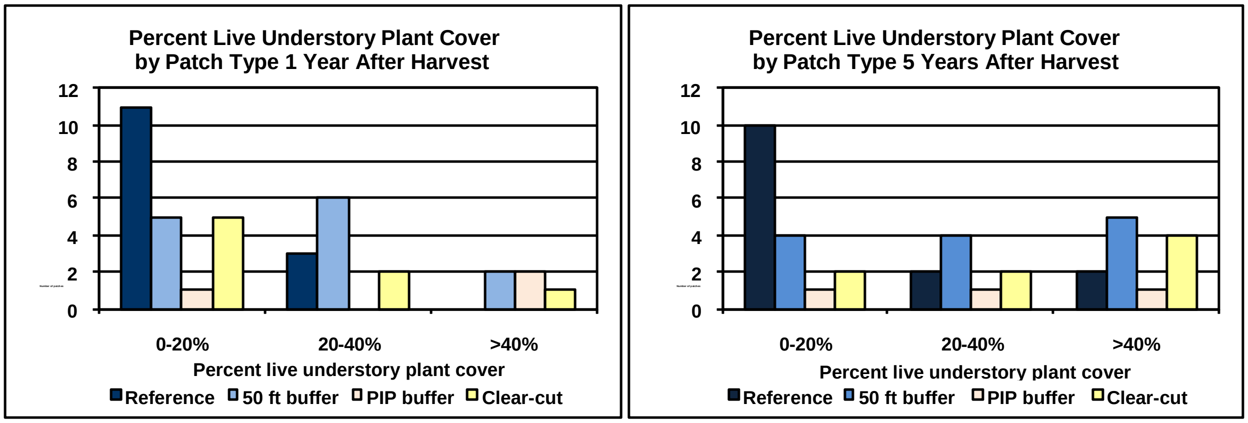

Figure 17. Distribution of mean percent live understory plant cover by patch type, for 2004 (left) and 2008 (right) sample events.

Characteristics of shade and factors affecting shade conditions

Sources of overhead cover

The relative importance of overhead cover from live trees, fallen trees, and shrubs varied by patch type and over time. Tree fall appears to be changing the sources of overhead cover in the reference, 50-ft buffer and PIP buffer patches. Live trees were the dominant source of overhead cover for the reference patches and the 50-ft buffers 1 year after harvest, but the percentage of stations where trees dominated declined over time, while shade from shrubs and fallen trees increased (Figure 18). Trees were the dominant source of overhead cover at all PIP buffer stations in year one, but by year five fallen trees were dominant at 44% of the PIP buffer stations. In the clear-cut patches, there was a decrease in the percentage of stations with no cover over time (from 28% to 10%) and an increase in the percentage of stations dominated by tall shrubs (from 16-51%) due to vigorous shrub growth in the clear-cut reaches following timber harvest.

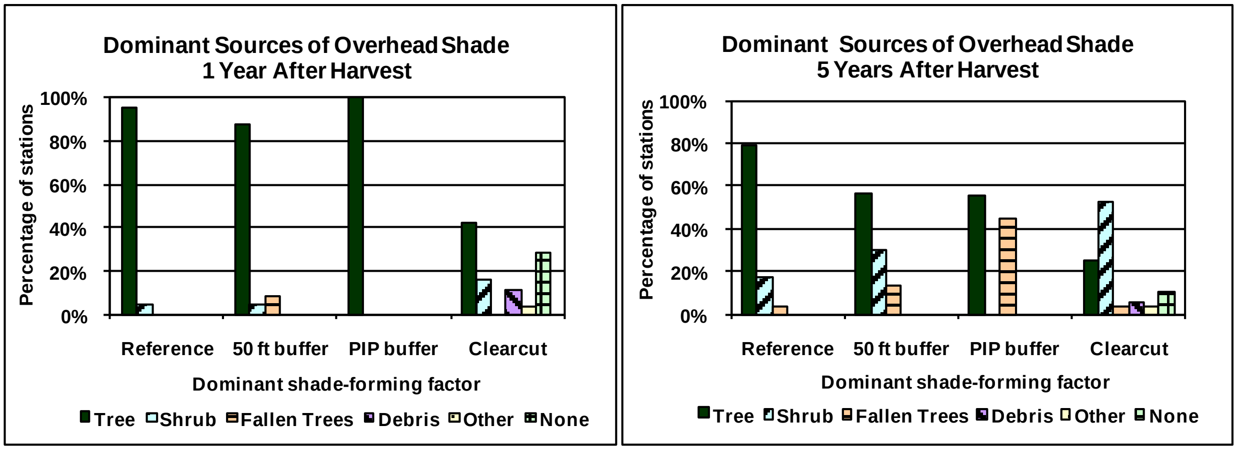

Figure 18. Dominant shade forming factors for individual patches by patch type, one year and five years after harvest.

Discussion

Comparison with the reference patches indicates a reduction in overhead cover associated with all three prescriptions during the first five years after harvest. Mean overhead cover was lowest in the clear-cut patches one year after harvest, but increased from 12% in year one to 37% year five after harvest due to rapid growth of shrubs and saplings. Mean overhead cover levels increased slightly in the 50-ft buffer patches between years one and five after harvest, despite post- harvest tree mortality that reduced stand density of some 50-ft buffer patches. In the 50-ft buffer patches where wind-throw occurred, there was an increase in the number of stations where shrubs and fallen trees provided the dominant source of overhead cover.

Since live trees were the dominant source of overhead cover at the majority of measurement stations, it is not surprising there is a relationship between canopy closure and riparian stand conditions. Linear regression analysis with mean patch values for percent canopy closure as the dependent variable showed positive relationships with live standing trees/acre ($R^2 = 0.573$) and live conifer trees/acre ($R^2 = 0.486$). The fact that these relationships were not stronger supports the conclusion that percent canopy closure is influenced by other factors such as tall shrubs and fallen trees.

Live understory plant cover was lowest for the reference patches at all sample events and higher (and more variable) for the 50-ft buffers and PIP buffers. Understory plant cover in the clear-cut patches was about 17% the first year after harvest, but doubled by 2006 and increased again in 2008. Linear regression analysis indicated a weak negative relationship between the mean percentage of live understory plant cover (dependent variable) and riparian stand condition metrics such as live standing trees/acre ($R^2 = 0.260$) or live conifer trees/acre ($R^2 = 0.240$). There was no evidence of a relationship ($R^2 = 0.044$) between percent understory plant cover (dependent variable) and percent canopy closure (independent variable), suggesting that understory plant cover responds to other factors in addition to overhead shade.

Combined overhead cover, understory plant cover and woody debris cover

Small streams are shaded by overhead tree and tall shrub canopy, low-growing understory plant cover and woody debris, so it is important to consider all sources in evaluating shade response to the westside Type Np prescriptions. Table 52 gives an indication of the relative importance of different cover types by patch type five years after harvest. Note that overhead cover is the percentage of the view to the sky that is obscured, while live understory plant cover and total woody debris cover are visual estimates of the percentage of the bankfull channel obscured when viewed from above, so the percentages are not directly comparable or additive.

Table 52. Comparison of channel shading from overhead cover, live understory plant cover and total woody debris cover by patch type five years after harvest.

	Overhead cover	**Live understory plant cover**	**Total woody debris cover**
Reference	90.2%	16.0%	28.0%
50-ft buffer	80.6%	34.7%	23.2%
Clear-cut	36.5%	41.2%	50.7%
PIP buffer	61.7%	47.4%	42.5%

The reference patches had the greatest overhead cover and the lowest live understory plant cover (Table 52). There was less overhead cover in the 50-ft buffers, however low-growing plant cover was more abundant, perhaps due to sunlight filtering in from the adjacent harvest unit or canopy gaps created by wind-throw (Table 52, Figure 19). Woody debris cover was similar in the 50-ft buffers and reference patches despite large numbers fallen trees in some 50-ft buffers. There was a slight increase in both overhead cover and live understory plant cover in the 50-ft buffers over time. The mean percentage of overhead shade in the PIP buffers was around 60%; lower than the 50-ft buffers. Five years after harvest low plant cover and suspended debris cover were higher in the PIP buffers than the 50-ft buffers (Table 52).

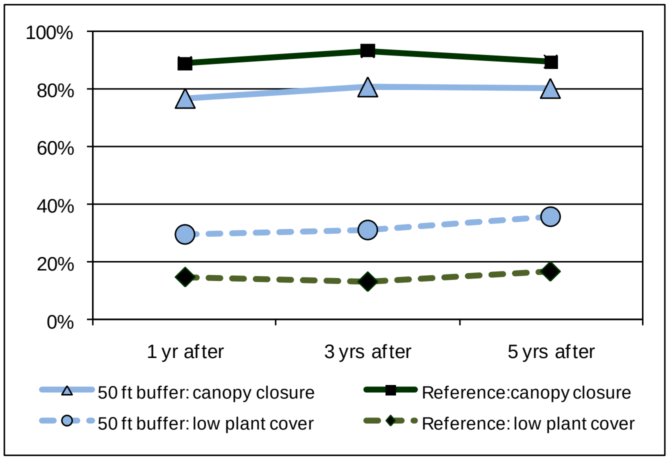

Figure 19. Comparison of mean canopy closure and mean understory plant cover for the 50-ft buffers versus reference patches at 1, 3 and 5 years after harvest.

There was a large difference in the mean percentage of overhead shade for the clear-cut and reference patches one year after harvest. Although there was a 30% increase in overhead shade for the clear-cut patches by year 5 due to rapid shrub and sapling growth, overhead shade the clear-cut patches was still much lower than in the reference patches (Table 52, Figure 20). The mean percentage of live understory plant cover was similar to the reference patch value in year 1, but it increased by about 20% by year 5 and was about 20% greater that the reference point mean (Figure 20). Woody debris cover was also higher in the clear-cut patches due to debris input into the channel (Table 52). Other studies have also documented the important role of low plant cover (Gavelle and Link, 2007) and logging debris (Jackson et al., 2001) in providing shade in small headwater streams running through clear-cuts. Consequently, it appears that as overhead shade from live trees decreases as a result of timber harvest or tree fall, there is an increase over time in cover from other sources such as shrubs, low-growing plants and woody debris from fallen trees (buffers) or logging debris (clear-cuts), however how long such cover will persist is unknown.

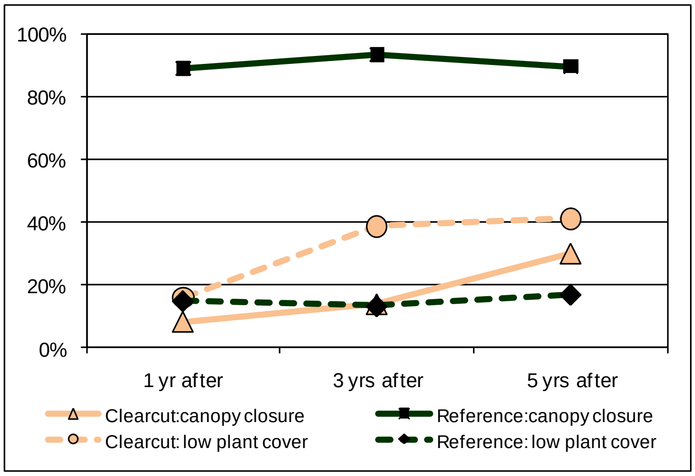

Figure 20. Comparison of mean canopy closure and mean low plant cover for clear-cut patches versus reference patches at 1, 3 and 5 years after harvest.

Implications for the FFR Heat/Water Temperature Functional Objective

Schedule L-1 of the Forests and Fish Report (USFWS and others, 1999) has a functional objective for heat/water temperature to “provide cool water by maintaining shade, groundwater temperature, flow and other watershed processes controlling stream temperature”. Schedule L-1 also sets performance targets. The performance target for Type Np streams is “shade available within 50 feet for at least 50% of stream length”. Interpreting this performance target is problematic because it does not specify a particular shade level and it is not clear if it refers to canopy shade, or shade from all sources. It appears that the performance standard is intended to be applied on the scale of each Type Np sub-basin, and that the intent is to maintain existing shade within 50 ft of the stream for at least 50% of the stream length in each sub-basin. Since the rules require that at least 50% of each sub-basin is buffered, it appears that if the buffers are effective in maintaining existing shade levels, the performance target will be met. Consequently, determining whether the performance target is met appears to be a compliance issue that must be addressed on the scale of an entire Type Np sub-basin, which was outside the scope of this harvest unit-scale study.

The sensitivity of headwater streams to changes in the amount of incoming solar radiation blocked by trees, shrubs and other cover varies depend on a suite of site-specific factors, including stream size (volume), channel geometry (width/depth), rate of flow, groundwater exchange (input or outflow), and hyporheic exchange rate (Poole and Berman, 2001; Moore et al, 2005). High rates of hyporheic exchange (often associated with permeable alluvial streambeds beds and the presence of debris jams and sediment wedges); influx of cool groundwater; rapid flow rates; large volumes and deep channels are factors that reduce the response of stream temperature to solar energy input. Conversely, factors such as low rates of hyporheic exchange (bedrock channels or channels with little alluvium or sediment storage), high channel width:depth ratios, low volume and flow rates; and loss of stream flow to groundwater increase sensitivity of streams to changes in solar radiation input (Adams and Sullivan, 1989; Constantz, 1998; Johnson, 2004; Cristea and Janisch, 2007; Dent el al., 2008; Hunter and Quinn, 2009).

Differences in these factors appear to explain many discrepancies in stream temperature response to changes in riparian vegetation (Johnson, 2004). For example, Veldhuisen and Couvelier (2006) identified two temperature regimes for headwater streams in the Skagit river basin, 1) stream reaches that maintained consistently cool temperatures due to cool water input from springs or groundwater, and 2) surface-flux driven reaches where water temperature responded to changes in surface energy inputs. Summer stream temperatures in the surface-flux reaches were sensitive to changes in riparian vegetation. Jackson et al. (2001) also noted a range of temperature responses to changes in overhead cover that were assumed to be due to differences in groundwater input. Consequently, we conclude that the implications of the changes in shade from in overhead canopy cover, understory plant cover and debris will vary depending on the temperature sensitivity of individual stream reaches. The small changes in shade and cover observed in the intact buffers are expected to have little effect on stream temperature unless streams are highly temperature sensitive. The larger changes in cover associated with greater levels of disturbance would be expected to have a greater effect on stream temperatures, except in streams less sensitive to solar input or if the loss of canopy shade is compensated by corresponding increases in shrub cover or woody debris.

HARVEST-RELATED SOIL DISTURBANCE

This component addresses uncertainty concerning the effectiveness of the westside Type Np prescriptions in meeting performance targets for soil disturbance and stream bank integrity. The Type Np prescriptions restrict activities with the potential to cause soil disturbance within the 30 foot wide equipment limitation zone (ELZ) on both sides of Type Np streams to protect stream-banks and prevent sediment delivery to stream channels. Schedule L-1 (USFWS et al., 1999) establishes performance targets for the level of disturbance of stream-banks adjacent to harvest units and for disturbance of soil within riparian areas. This analysis will help address uncertainty about the effectiveness of the equipment limitation zones in preventing soil disturbance and sediment delivery.

Critical Questions

1. What levels of harvest-related soil and stream-bank disturbance are observed where the westside Type Np riparian prescriptions have been applied?
2. What proportion of prescription patches achieves the FFR soil/stream-bank disturbance performance targets?

Data Collection Procedures

Data on soil disturbance associated with timber harvest activities were collected at treatment sites in the first year following timber harvest. A complete inventory (census) was made of harvest-related stream-bank erosion and soil disturbance features within 30 feet horizontal distance of the channel edge (the ELZ). The inventory was conducted by a two person crew, one person walking down the center of the ELZ 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 square feet; 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.

Metrics, Hypotheses and Methods of Statistical Analysis

The objective of this analysis was to: 1) characterize harvest-related soil disturbance for each patch type after timber harvest, 2) compare harvest-related soil disturbance for the three Type Np prescriptions, and 3) determine if soil disturbance targets were achieved.

The following metrics are used to evaluate harvest-related soil disturbance:

Number of harvest-related stream-bank disturbance features per 100 ft of stream length. This metric was calculated by tallying the harvest-related stream-bank disturbance features within the ELZ throughout the patch following harvest, dividing by the stream length of the patch, and multiplying by 100.

Number of harvest-related soil disturbance features per 100 ft of stream length. This metric was calculated by tallying the harvest-related soil-disturbance features within the ELZ throughout the patch following harvest, dividing by the stream length of the patch, and multiplying by 100.

Number of harvest-related soil disturbance features that deliver sediment per 100 ft of stream length. This metric was calculated by tallying the harvest-related soil disturbance features with evidence of sediment deliver to the stream channel within the patch and dividing by the stream length of the patch times 100.

Percentage of equipment limitation zone (ELZ) with harvest-related soil disturbance. The surface area of each individual harvest-related soil disturbance feature was calculated by multiplying the mean width by the length. Total surface area of harvest-related soil disturbance within the ELZ was calculated for each patch by summing the areas of the individual features. The percentage of ELZ with soil disturbance was calculated by dividing the total area of soil disturbance features by the total area of the ELZ for the patch.

Percentage of patches exceeding the soil disturbance performance target. Patches with more than 10% soil disturbance in the equipment limitation zone were considered to exceed the performance target. The percentage of patches exceeding the performance target was calculated by dividing number of patches that exceed the target by the total number of patches for each treatment type.

A two-tailed hypothesis test was used to compare the first four soil and stream-bank disturbance condition metrics because we were interested in determining whether there was a difference between the two prescriptions. The null hypothesis was stated as:

> H_o: average condition for patches for 50-ft buffer patches = average condition for the clear-cut patches.

Examination of the data for the first four metrics confirmed that the data should not be considered normally distributed. Therefore, the non-parametric, two-sample Mann-Whitney test was used to test for differences among the prescriptions. The level of significance was 0.10.

A two-tailed hypothesis test was used to compare the percentage of patches exceeding the soil disturbance performance target (more than 10% of the ELZ area disturbed by management-related activities). The null hypothesis was stated as:

> H_o: the relative frequency of patches exceeding the performance target for the 50-ft buffer prescription = the relative frequency of patches exceeding the performance target for the clear-cut prescription.

The data for the performance target metric was a proportion with a high frequency of zeros. Therefore, Fisher’s Exact test was used to compare the frequency of patches exceeding the performance target in the 50-ft buffer and clear-cut patches. The level of significance was 0.10.

Results

Overview of Patterns in Soil and Stream-bank Disturbance Metrics

Harvest-related soil and stream-bank disturbance features within the ELZ occurred more frequently in the clear-cut patches than in the 50-ft buffers or PIP buffers (Table 53). The mean frequency of harvest-related soil disturbance features for the clear-cut patches was over 10 times greater than the 50-ft buffers. No harvest-related soil disturbance was observed in PIP buffers.

Table 53. Harvest-related soil and stream-bank disturbance metrics by patch type.

Metrics	Clear-cut	50-ft buffer	PIP buffer
Harvest-related soil disturbance features per 100 ft of stream length	1.3	0.09	0
Harvest-related soil disturbance features that deliver sediment per 100 ft of stream length	0.5	0.06	0
Mean percent of Equipment Limitation Zone with soil disturbance	6.2%	0.29%	0%

A similar pattern was observed for the sub-set of features that delivered sediment, where the frequency for the clear-cut patches was 8 times greater than for the 50-ft buffers. On average, soil disturbance features occupied 0.29% of the equipment limitation zone (ELZ) in the 50-ft buffers compared with 6.2% in the clear-cut patches. The higher mean value for the clear-cut patches was heavily influenced by one patch with large soil disturbance features.

Hypothesis Testing for Soil and Stream bank Disturbance Metrics

The differences between the mean values for clear-cut patches and the 50-ft buffers were significant for all four metrics ($P \leq 0.082$), so we concluded there was more harvest-related soil disturbance following harvest in the clear-cut patches than the 50-ft buffers.

Soil Disturbance Performance Target

Table 54 shows the percentage of patches exceeding the soil disturbance performance target (over 10% of the ELZ with harvest-related soil disturbance) for each prescription type. All of the 50-ft buffer and PIP buffer patches met the performance target. One clear-cut patch exceeded the target. Fisher’s Exact test comparing the percentages of 50-ft buffer and clear-cut patches exceeding the target was significant ($P = 0.007$).

Table 54. Percentage of patches exceeding the soil disturbance performance target following harvest by prescription type.

Prescription	Sample Size	Percent Exceeding Target
50-ft buffer	13	0.0%
Clear-cut	8	12.5%
PIP buffer	3	0.0%

Characteristics of Soil Disturbance Features

Table 55 summarizes information on the frequency and size of harvest-related soil disturbance features. Most of the soil disturbance features observed appeared to be associated with the falling or yarding of individual trees However, the clear-cut patch 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. The disturbance extended for 300 feet along the stream channel.

Table 55. Size of harvest-related soil disturbance features.

Soil Disturbance Feature	Number of features	Surface area (ft2)		
		Average	Minimum	Maximum
Soil disturbances with sediment delivery	25	752	31	9060
Soil disturbances without sediment delivery	36	65	13	214
All soil disturbances	61	347	13	9060

Factors affecting sediment delivery from harvest-related soil disturbance

Factors affecting whether a soil disturbance feature associated with timber falling and yarding delivered sediment to the stream channel were analyzed using data collected shortly after harvest in 2003. Delivery of sediment to streams was best predicted by the horizontal distance between the soil disturbance and the stream channel ($P < 0.0001$). The average distance to the stream for soil disturbance features that delivered sediment was 1 ft (max. = 7.7), while the average distance for non-delivering soil disturbance features was 14 ft (min 3.3). Using distance-to-stream alone, 96% of the observations were correctly predicted based on whether the horizontal distance to the stream was greater or less than 5.4 ft (Rsquare U[4] = 0.80).

Discussion

Implications for the FFR Soil Disturbance Performance Target

Soil disturbance from timber felling and yarding within the ELZ was minimal in the patches harvested under the 50-ft buffer and PIP buffer prescriptions. Soil disturbance was less than 10% of the ELZ for all buffer patches and all met the soil disturbance target. All of the 50-ft buffers had less than 0.1 soil disturbance feature per 100 feet of stream. This appears to be due to the limitation on harvest within 50 ft of the stream, since few trees felled outside the buffers fall into the buffers and cause disturbance in the ELZ. Soil disturbance was more frequent in the clear-cut patches. One patch exceeded the 10% target, and the mean rate was about 1.3 features per 100 ft of stream. With the exception of the one patch with extensive soil disturbance from yarding, the number of features that delivered sediment in the clear-cut patches was low (0.5 features/100 ft).

Rsquare U is the proportion of total uncertainty attributed to the model fit. The difference between the log-likelihood from the fitted model versus from horizontal lines is a test statistic to examine the hypothesis that the factor variable has no effect on the response. The ratio of this test statistic to the background log-likelihood is subtracted from 1 to calculate R^2.[4]

SOIL DISTURBANCE ASSOCIATED WITH UPROOTED TREES

Soil disturbance occurs when trees topple over and the roots are pulled from the ground. The depressions left in the ground after a tree has been uprooted by wind or other disturbances are referred to as root-pits. Soil disturbance from root-pits and associated mounds has the potential to deliver sediment to stream channels. This analysis is designed to address uncertainty concerning the magnitude of uprooted tree soil disturbance processes and associated sediment delivery in riparian buffers on westside Type Np streams relative to reference conditions.

Critical Questions

1. How much soil disturbance and sediment delivery are associated with uprooted trees in stream channels following application of the westside Type Np riparian prescriptions?
2. What is the magnitude and duration of change in soil disturbance and sediment delivery associated with uprooted trees following application of the westside Type Np riparian prescriptions compared to untreated reference sites?

Data Collection Procedures

Data were collected on soil disturbance associated with each new (post-harvest) root-pit observed within 50 ft of the stream channel. The width of the pit (parallel to the channel) was measured, 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.

Metrics, Hypotheses and Methods of Statistical Analysis

The objectives of these analyses were to: 1) characterize the annual rates of root-pit formation for each patch type for the 2003-2006 period, 2006-2008 period, and for the entire 2003-2008 period, and 2) compare these annual rates for each prescription to the reference patch rate.

Four metrics were used to evaluate soil disturbance associated with uprooted trees:

Root-pits per acre. Root-pits/acre was calculated by tallying the number of root-pits in each patch and dividing by the patch acreage.

Root-pits per 100 ft of stream length. Root-pits/100 ft of stream length was calculated by tallying the number of root-pits in each patch (both sides of the stream), dividing by the stream length, and multiplying by 100.

Root-pits with sediment delivery per acre. Root-pits/acre with evidence of sediment delivery to the channel was calculated by tallying the number of root-pits where evidence of sediment delivery to the stream channel is observed in each patch and dividing by the patch acreage.

Root-pits with sediment delivery per 100 ft of stream length. Root-pits with sediment delivery/100 ft of stream length were calculated by tallying the number of root-pits with evidence of sediment delivery in each patch (both sides of the stream), dividing by the stream length, and multiplying by 100.

A two-tailed hypothesis was used to compare the standardized annual rates at each sample event (and for the entire five year period). The two-tailed hypothesis was stated as:

H_o: average annual rate of change between sample events for patches from a Type Np prescription = average annual rate of change for the reference patches.

The distribution was typically weighted toward rates at or near zero and had an extended right tail to the distribution. Examination confirmed that these data should not be considered normally distributed. Therefore, the Mann-Whitney (MW) test was used to test for differences between the reference patches and patches receiving one of the Type Np prescriptions. The MW test did not require a data normality assumption or a transformation of the data. The level of significance was 0.10. The PIP buffer prescription was not included in these analyses due to the small sample size.

Additional analysis was done to identify and analyze factors affecting whether sediment originating in root pits was delivered to stream channels. Logistic regression was conducted to evaluate the influence of distance-to-stream, root-pit size, and slope on sediment delivery.

Results

Overview of Patterns of Soil Disturbance from Uprooted Trees

Mean rates for root-pit formation (total root-pits and root-pits that deliver sediment) are shown in Table 56 for three time periods, the first three years after harvest (2003-2006), years 4-5 after harvest (2006-2008) and for the entire first five years (2003-2008). In the first three years after harvest, the mean annual rate of total root-pit formation (all root-pits) in the 50-ft buffers was over 10 times higher than the reference rate. The mean total root-pit formation rate in the clear-cut patches was much lower than the reference rate, because there were few trees left to topple over. The results for the subset of root-pits that delivered sediment were similar to those for total root-pits.

During the second time period (years 4-5 after harvest) the greatest change in the root-pit formation rates was a large increase in the rate for the reference patches and a decrease in rates for the 50-ft buffers (Table 56). The clear-cut patches continued to have the lowest rate. Over the entire first five years, the rate of total root-pit formation for the 50-ft buffers was nearly double the reference rate. The pattern was similar for root-pits with sediment delivery, however the difference between the reference and buffer patches was less pronounced due to the higher percentage of root-pits delivering sediment in the reference patches. The percentage of root-pits with evidence of sediment delivery was much higher in the clear-cut patches than in the 50-ft buffers (20.1%) and the reference (26.0%) patches.

Table 56. Descriptive statistics for root-pit soil disturbance metrics by patch type for years 1-3 (2003-2008), years 4-5 (2006-2008) and the entire first five years (2003-2008) after harvest.

Patch Type	**n**	**Total root-pits/acre/yr**		**Root-pits w/sediment delivery/acre/yr**		**Total root-pits/100ft of stream/yr**		**Root-pits w/sediment delivery/100 ft of stream/yr**		**Percent root-pits w/sediment delivery**
		Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean	SD[1]	Mean
2003-2006										
Reference	14	0.5	0.4	0.1	0.2	0.1	0.1	0.03	0.04	24.0%
50-ft buffer	13	5.7	6.9	0.9	1.1	1.3	1.6	0.2	0.3	19.7%
Clear-cut	8	0.03	0.08	0.03	0.08	0.01	0.02	0.01	0.02	100.0%
PIP buffer	3	14.5	12.6	3.2	3.6	3.3	2.9	0.7	0.8	22.2%
2006-2008										
Reference	13	4.9	6.8	1.4	2.0	1.1	1.6	0.3	0.5	26.9%
50-ft buffer	12	3.9	3.8	0.8	1.5	0.9	0.9	0.2	0.4	21.2%
Clear-cut	7	0.07	0.18	0.07	0.18	0.02	0.04	0.02	0.04	100.0%
PIP buffer	3	9.0	7.8	0.6	1.0	2.1	1.8	0.1	0.2	6.7%
2003-2008										
Reference	14	2.4	2.6	0.6	0.8	0.5	0.6	0.1	0.2	26.0%
50-ft buffer	13	4.6	5.1	0.8	1.1	1.1	1.2	0.2	0.3	20.1%
Clear-cut	8	0.07	0.1	0.04	0.07	0.02	0.02	0.01	0.02	66.7%
PIP buffer	3	12.3	10.2	2.2	2.0	2.8	2.4	0.5	0.5	17.6%

[1] SD = standard deviation

Hypothesis Testing for Soil Disturbance Associated with Uprooted Trees

This section presents results of the Mann-Whitney (MW) test conducted to determine if there were significant differences between the reference and 50-ft buffer or clear-cut patches in rates of soil disturbance from uprooted trees for each post-harvest time period. Statistical tests were not conducted on the PIP buffers due to the small sample size, but observations are presented in a separate section.

Clear-cut versus reference comparison

The rates of root-pit formation for the clear-cut patches (both total and root-pits with sediment delivery) were very low for all time periods because there were few trees to fall and create root-pits in the clear-cut patches (Table 56). The differences between the clear-cut rates and the reference rates for total root-pits were statistically significant for all time periods ($\mathrm{P} \leq 0.001$) so the null hypothesis was rejected. The differences for root-pits with sediment delivery did not reach the threshold of significant for the 2003-2006 period ($P = 0.174$), but were significantly lower in the clear-cut patches 2006-2008 period and over the entire five years ($P \leq 0.008$).

50-ft buffer versus reference comparison

During the first three years after harvest (2003-2006), the mean annual rates for root-pit formation were about 10 times higher in the 50-ft buffer patches than in the references patches for both total root-pits and root-pits with sediment delivery (Table 57). These differences were significant so the null hypothesis was rejected and we conclude that root-pit formation rates were higher in the 50-ft buffers during the 2003 to 2006 period.

Root-pit formation rates were higher for the reference patches than the 50-ft buffers during the second time period (2006-2008), due to tenfold increase in root-pit formation rates for the reference patches combined with a decrease in rates for the 50-ft buffers, but the differences were not significant. Over the entire five year period total root-pit formation in the 50-ft buffers was about twice the rate for the reference patches and the rates for root-pits with sediment delivery was 1.3 times the reference rate, however these differences were not statistically significant so the null hypothesis was not rejected.

Table 57. 50-ft buffer prescription versus reference comparison for annual rates of root-pit formation by time period with results of the Mann-Whitney test.

Sample Event	**50-ft buffer Mean**	**Reference Mean**	**Difference (50-ft buffer–Reference)**	***P*-value of the MW test**[a]
Total roots pits formed per acre per year				
2003-2006	5.7	0.5	5.2	**0.002**
2006-2008	3.9	4.9	-1.0	0.781
2003-2008	4.6	2.4	2.2	0.308
Roots pits delivering sediment formed per acre per year				
2003-2006	0.9	0.1	0.8	**0.027**
2006-2008	0.8	1.4	-0.6	0.203
2003-2008	0.8	0.6	0.2	0.953

[a] Two-sided test of H_o: prescription = reference; tests significant with $P \leq 0.10$ are in bold.

PIP Buffer Observations

Root-pit formation in the PIP buffers followed a similar pattern to the 50-ft buffers, with the highest rates in the 2003-2006 period, and lower rates in the 2006-2008 period (Table 56). However, the mean rate of total root-pit formation in the PIP buffers was over twice the rate in the 50-ft buffers in both periods. The mean rate for root-pits with evidence of sediment delivery was higher in the PIP buffers in the 2003-2008 period, but dropped sharply in the 2006-2008 period and was less than half the rate for the 50-ft buffers. Over the entire 5 year period, the percentage of root-pits with evidence of sediment delivery in the PIP buffers (17.6%) was similar to the percentage for the 50-ft buffers (19.8%).

Factors affecting sediment delivery from root-pit soil disturbance

Factors affecting whether sediment originating in root pits delivered to streams were analyzed using data from 2006 and 2008. In both years, sediment delivery to streams was best predicted by the distance of the root-pit from the stream ($P < 0.0001$). Mean horizontal distance to the stream for root-pits that delivered sediment was 8.2 ft compared to 28.0 ft for those that did not deliver (Figure 21). Root-pits that delivered to streams had larger pit widths as well, although the inclusion of pit width in statistical models did little to improve the predictive capability with respect to sediment delivery. Using horizontal distance to stream, the proportion of the total uncertainty that is attributed to the model fit (Rsquare U) was 0.39, and 80% of the observations were correctly predicted based on whether the horizontal distance to stream was greater or less than 12.5 ft. The inclusion of pit width increased the model certainty (Rsquare U = 0.42) but did not significantly change the predictive capability of the model. Hill slope gradient was expected to have a significant effect on sediment delivery. That metric was only collected in 2006 and analysis of those data revealed no significant difference in slope gradients between those root-pits that delivered and those that did not. This was probably due to overriding importance of proximity to the stream channel.

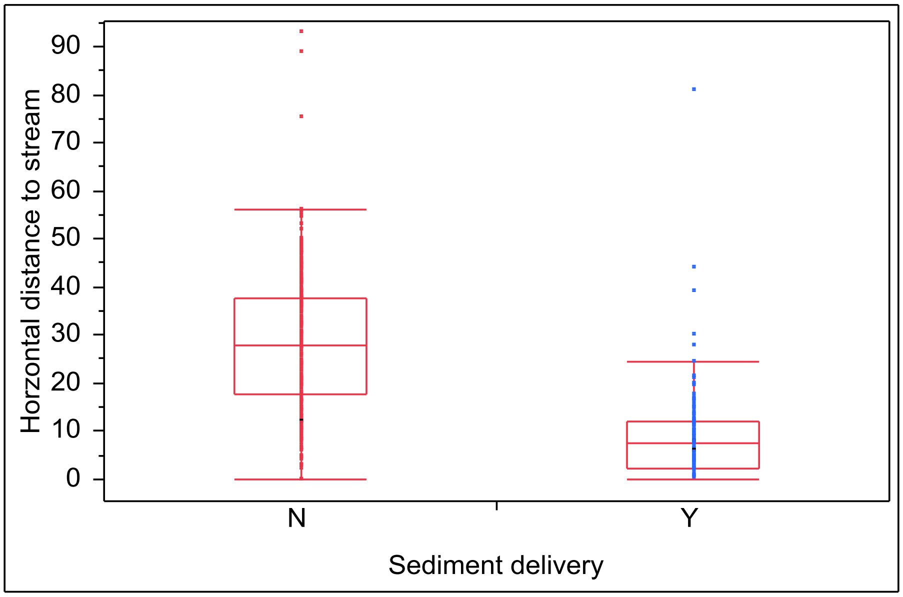

Figure 21. Box and whisker plot for distance-to-stream for root-pits that delivered sediment (right) versus those that did not deliver sediment (left).

Discussion

Effect of Wind-Events and Tree Fall Rates on Root-pit Formation

Approximately 68% of fallen trees were uprooted rather than broken along the stem, so it is not surprising that there is a strong correlation between tree fall rates in fallen trees/acre/yr and soil disturbance rates from uprooted trees in root-pits/acre/yr ($R^2 = .912$). It appears likely that the higher root-pit soil disturbance rate observed in the 50-ft buffers relative to the reference patches during in the 2003-2006 period was due to higher tree fall rates resulting from wind-throw. The increase in tree fall rates in the reference patches during the 2006-2008 period (associated with the stronger wind-storms during this period) resulted in smaller differences between the reference and 50-ft buffer patches during that period.

Implications of Soil Disturbance from Uprooted Trees

Sediment delivery from soil disturbance features from uprooted trees has potential implications for water quality, stream channel conditions and aquatic life. Our data indicate that about 20% of the root-pits in the 50-ft buffers delivered sediment which was similar to the estimate of 17% by Grizzel and Wolff (1998), and that most sediment delivery was associated with root-pits immediately adjacent or in close proximity to the stream channel.

Soil Disturbance Associated with Uprooted Trees

The mean frequency of root-pits that deliver sediment is low for the 50-ft buffers (0.2 root-pits/100ft or stream/yr) and PIP buffers (0.5 root-pits/100ft of stream/yr). The quantity of sediment typically delivered to the channel from root-pits appears to be small unless the pit is immediately adjacent to the stream channel and is over-run or eroded during high flows. Consequently, it appears that sediment delivery from root-pits would be limited at most sites. Grizzel and Wolff (1998) concluded that sediment delivery from wind-throw was generally not a significant source of sediment delivery and was relatively small compared to the volume of sediment stored in the channel. Andrus and Froehlich (1986) concluded that in most cases sediment delivery from uprooted trees was small compared to overall sediment yield. However, highly disturbed buffers with many uprooted trees can generate significant sediment (Gomi et al., 2005). For example, Andrus and Froehlich (1986) estimated short-term increases in sediment yield of 12% and 21% at two sites on small streams with large amounts of wind damage. Consequently, short-term increases in sediment yield may have occurred at the sub-set of 50-ft buffer and PIP buffer sites with high rates of tree fall and root-pit formation. How long these features will remain un-vegetated, and whether they will continue to provide sediment delivery over time is not known.

Soil disturbance from uprooted trees also has implications for soil development and the productivity of riparian forests. Soil disturbance from uprooted trees can affect the forest floor in riparian areas, creating uneven, hummock pit and mound terrain that can persist for long periods (Schaetzl et al., 1990). Uprooting of deeply rooted trees causes churning and disturbance of soil deep in the ground. This disturbance may increase soil productivity by mixing organic and mineral horizons, breaking up impermeable soil layer, and releasing nutrients that accumulated in certain soil horizons (Nowacki and Kramer, 1998; Gabet et al., 2003). The average area of soil disturbance per root-pit was 62.6 ft^2 so a large amount of bare soil can be created in areas where multiple trees are uprooted.

SYNTHESIS

Summary of Prescription Effects

There were two categories of effects from the westside Type Np riparian prescriptions on riparian stands and adjacent stream channels: 1) direct, immediate effects due to harvest activity, and 2) indirect effects that result from changes in the rates of riparian processes over time following timber harvest.

Direct effects of timber harvest

Examples of potential direct effects of timber harvest on riparian stand and stream channel conditions include: loss of shade to the stream due to felling of trees; input of debris (logging slash) to the channel from felling, limbing, bucking and yarding; and sediment input from soil disturbance associated with felling and yarding of trees.

The greatest direct effects of timber harvest occurred in the clear-cut patches. Removal of most riparian trees resulted in extensive loss of overhead canopy cover. Mean canopy closure for the clear-cut patches one year after harvest was 12%, 77% less than the reference mean. Large amounts of logging slash and debris were present in the channel following harvest in the clear-cut patches. The clear-cut patches had higher rates of soil disturbance from timber harvest than the buffer patches. Retention of all trees in the 50-ft buffers and PIP buffers prevented most direct effects from timber harvest. Little direct mortality from timber harvest was observed in either the 50-ft or PIP buffers. The buffers prevented harvest-related soil disturbance near the stream, and prevented logging debris from the adjacent harvest unit from reaching the stream channel. The 50-ft buffers were more effective than the PIP buffers in maintaining overhead shade immediately following harvest. One year after harvest, mean overhead cover for the 50-ft buffers was about 10% below reference levels while the PIP buffers were 35% lower.

Changes in processes over time following timber harvest

The indirect effects of harvest occurred over the 5 year post-harvest period as disturbance and recovery processes resulted in changes in riparian stands, riparian processes and adjacent stream channels. Disturbance processes such as wind-throw elevated tree mortality and tree fall rates in the buffers, reducing stand density and decreasing overhead shade. Tree fall in the buffers also increased rates of woody debris recruitment and soil disturbance from uprooting of trees. Regeneration of trees and shrubs and growth of suppressed trees increased shade, stabilized disturbed soil, and re-initiated riparian stand development, particularly in the clear-cut patches.

Wind was the dominant disturbance process that affected riparian buffers by causing tree mortality and tree fall. In general, the percentage of tree fall was higher in the newly established buffers than the reference patches during the first three years after harvest, a period with three wind-storms of moderate intensity. However, as a result of high intensity wind-storms during years 4 and 5, tree mortality rates increased in the reference patches, demonstrating that riparian stands embedded in continuous forests are susceptible to wind damage during high intensity wind-storms. Rates for LWD recruitment to stream channels and soil disturbance from uprooted trees followed a similar pattern. Overhead shade also responded to tree mortality and tree fall rates, tending to be lower in patches with high mortality. Since few trees were left in the clear-cut patches following harvest, post-harvest rates of LWD recruitment and soil disturbance from uprooted trees were low. In the clear-cut patches, rapid growth of shrubs and saplings in the five years after harvest resulted in an increase in overhead and understory shading of streams. There was also a decrease in channel debris in the clear-cut reaches by year five after harvest.

Summary of Implications for FFR Resource Objectives

The Forest and Fish Report (USFWS et al., 1999) identifies overall performance goals for protection of aquatic resources including fish, stream associated amphibians and water quality with functional objectives for watershed functions and processes potentially affected by forest practices. The functional objectives include:

- LWD/Organic Inputs: Develop riparian conditions that provide complex aquatic habitats by 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 maximum extent practicable, the delivery of management-induced coarse and fine sediment (including timing and quantity) by protecting stream bank integrity, providing vegetative filtering, protecting unstable slopes, and preventing the routing of sediment to streams.

To evaluate the potential implications of the Type Np prescriptions for the FFR resource objectives, we identified three distinct riparian disturbance and recovery scenarios based on differences in direct harvest effects and subsequent disturbance following timber harvest (primarily tree mortality due to wind-throw). Clear-cut harvest of the riparian trees produced an immediate change in riparian stand and channel conditions with a pattern of disturbance and recovery different from that of the buffers. Although buffer mortality rates occur along a continuum, our sample had a somewhat bi-modal distribution. The majority (10 of 13) of the 50-ft buffers (10 of 13) had tree mortality rates less than 33% over the five year post-harvest period. Mortality rates were over 50% at the remaining three 50-ft buffers (no buffers had mortality rates between 33% and 50%). Consequently, we grouped the 50-ft buffer patches into two categories (those with mortality rates less than 33% and those with rates greater than 50%) and contrast the resource response and implications. The implications of the three disturbance scenarios for riparian stand conditions and FFR functional objectives are discussed in the following sections.

Riparian Stand Conditions

The westside Type Np riparian prescriptions are typically applied during harvest of young (40-60 year old) stands that have regenerated following the previous timber harvest. Clear-cut harvest of riparian stands is allowed on up to 50% of the stream length of each Type Np stream network, so the prescriptions clearly envision a variety of future riparian stand conditions on Type Np streams. The following sections discuss the implications of the three disturbance scenarios on riparian stand conditions over time.

Clear-cut scenario: The portion of the stream network where the clear-cut prescription is applied is managed in a cycle of clear-cut harvest. Under this scenario, riparian stands and processes are directly affected by harvest on a 40-60 year rotation. Nearly all trees were removed when the clear-cut prescription was applied at our study sites. The mean density after harvest in the clear-cut patches was 12.5 trees/acre, and nearly 50% of the remaining trees died within the first five years after harvest. After harvest, the riparian area was replanted with conifers which will grow over time and eventually be re-harvested.

<u>Buffers with greater than 50% mortality</u>: The mean percentage of standing trees that died in this group over the five year period was 68.2%, and one 50-ft buffer patch had mortality rates in excess of 90%. The primary mortality agent was wind-throw. The mean density of surviving live trees for this group was 62.8 trees/acre five years after harvest (range 8.7-134.1). Often the surviving trees occurred in patches interspersed among openings created by tree fall. Natural regeneration of conifers is likely to result in development of a patchy, multi-cohort stand with a younger age class of trees in disturbed patches interspersed among older surviving trees. However competition from shrubs and broad-leafs may limit conifer regeneration in some cases, resulting a shrub or broad-leaf component that increases variability of future stand conditions.

<u>Buffers with less than 33% mortality:</u> The average percentage of standing trees that died in the buffers with less than 33% mortality was 15.0%, and the mean density of standing trees was 140.0 trees/acre five years after harvest (range 58.8-247.2 trees/acre). These buffers appear likely to continue to progress through the stem exclusion stage as well-stocked, single-aged stands.

Large Woody Debris/Organic Input

The characteristics of woody debris recruited to the stream depend upon the condition of the adjacent riparian stand (e.g. tree density, size and species composition). The pre-harvest data indicate that the study sites typically had dense riparian stands dominated by conifers, providing a potential pool of trees for wood recruitment. The timing and amount of wood recruitment depends on the frequency and magnitude of various disturbance and mortality processes. The amount and characteristics of woody debris in the channel is a function of the current wood loading, and the rates of input and depletion (loss of wood due to decay, breakage and transport downstream) over time (Lienkaemper and Swanson, 1987, Martin and Benda, 2001). The following sections discuss the implications of the three disturbance scenarios on wood recruitment rates over time.

<u>Clear-cut scenario</u>: The timing of wood input is intermittent and cyclic in riparian areas managed for clear-cut harvest. Clear-cut streams typically receive a large amount of logging debris at the time of harvest, minimal wood recruitment for several decades as a new stand of young trees becomes reestablished, followed by another pulse of wood during the next harvest cycle (Murphy and Koski, 1989; Beechie et al., 2000; Meleason et al., 2003). The logging debris entering the channel from felling, bucking, limbing and yarding during timber harvest consists of branches, tops and broken pieces of stems of un-merchantable trees. Although logging debris is typically smaller in size than wood recruited from a whole tree, Jackson et al. (2001) observed that it provided functions in headwater streams including increased channel obstruction and roughness, creation of steps and storage of sediment. However the quantity of logging debris in the channel is expected to decrease over time because most logging debris consists of small pieces that decay more rapidly than larger pieces and are transported downstream over time in channels with high stream power (Murphy and Koski, 1989; Gomi et al., 2001; Maxa, 2009). Some wood is typically recruited from young trees as the stand grows, however large diameter

wood does not accumulate as rapidly as it is depleted for most of the harvest rotation cycle, so a net loss of large diameter pieces over time is predicted to occur in clear-cut reaches (Beechie et al., 2000; Meleason et al., 2003).

The implications of wood input patterns under the clear-cut scenario are expected to vary depending on the characteristics of the stream channel. In channels with low stream-power, small diameter debris from logging slash and young trees recruited from the replacement stand would be expected to provide cover, habitat formation, and sediment retention functions (Gomi et al., 2001; Jackson et al. 2001). Channels with greater stream power require larger diameter wood to provide stable sediment retention structures (steps and debris jams) that persist over time so a reduction in large wood input can result in release of stored sediment over time (O'Connor and Harr, 1994; May and Gresswell, 2003).

Buffers with greater than 50% mortality: Channels adjacent to these buffers received a large pulse of LWD input (mean of 436.8 ft^3/acre) from fallen trees over the first five years after harvest; nearly 10 times the rate for the reference patches. However most of the volume remained suspended or spanning over the channel. Consequently, in the short term, LWD input in this group of buffers will provide a limited increase in sediment retention, step formation and pool formation functions. Suspended and spanning pieces will continue to drop into the channel in the future, although the timing is unknown. Accelerated rates of tree mortality and tree fall in the high mortality buffers has reduced the density of standing trees available to provide future LWD recruitment. However, the surviving trees may grow to larger size more quickly due to reduced competition. Over the long term, the success of natural stand regeneration processes will determine the availability of new trees to provide future wood recruitment.

Buffers with less than 33% mortality: The LWD recruitment rate for buffers with less than 33% mortality was 64.0 ft^3/acre, less than one sixth the rate for the buffers with over 50% mortality but about 40% higher than the reference rate for the five years after harvest, with the majority suspended or spanning over the channel. Since past management practices have often decreased LWD loading levels (Ralph et al., 1994), moderate inputs of LWD may increase LWD loading and functions over time. Many live standing trees remain in these buffers to provide potential LWD input in the future and the size of LWD recruited should increase as trees continue to grow over time. The rate of LWD recruitment begins to substantially exceed the rate of LWD depletion after a stand age of about 50 years according to model predictions (Beechie et al., 2000), so accumulation of large diameter wood is expected to increase over time in adjacent streams in the absence of harvest or channel disturbance events such as debris flows.

Shade and heat/water temperature response

Thermal loading in headwater streams is affected by many factors including the amount of shade and cover available to block incoming solar radiation, the temperature of the surrounding air, the depth, volume and velocity of the water, the quantity and temperature of groundwater inputs, and cooling due to hyporheic flow (Johnson and Jones, 2000; Johnson, 2004; Gavelle and Link, 2007). Shade can be provided by a variety of sources, including standing trees, fallen trees, shrubs and low-growing plants, woody debris and surrounding topography (Johnson and Jones, 2000; Johnson, 2004; Gavelle and Link, 2007). The amount of shade provided by riparian buffer trees depends on the density of trees, the height of the trees and the width of the buffer (DeWalle, 2010). The following sections discuss the implications of the three disturbance scenarios on shade over time.

Clear-cut scenario: Most overhead shade is removed as a result of tree harvest in the clear-cut patches. Mean overhead shade immediately after harvest in the clear-cut patches was 12%, compared to about 90% in the reference stands. However, input of logging debris during harvest created substantial channel cover, and cover from shrubs and understory vegetation increased rapidly in the five years after harvest in the clear-cut reaches. Overhead shade should increase as the adjacent stand of trees becomes established. When the tree canopy closes over the stream, overhead shade should be high until the next harvest cycle.

A variety of responses in thermal loading have been documented in headwater streams following clear-cut harvest. Veldhuisen and Couvelier (2006) observed higher maximum water temperatures in clear-cut reaches of Type Np streams in the Skagit basin compared to forested reaches, and some clear-cut streams exceeded water quality standards. On the other hand, Jackson et al. (2001) observed little change in maximum temperatures in headwater streams in the Willapa Hills following clear-cut harvest, which they attributed to the extensive cover provided by logging slash. Johnson and Jones (2000) observed increases in maximum stream temperature and diurnal temperature range, and a shift in the timing of the summer maxima in a small western Oregon stream following clear-cut harvest. Consequently, it appears that the stream temperature response to clear-cut harvest is likely to vary, depending on site-specific factors such as debris loading, shade from shrubs and factors such as ground-water input, substrate, hyporheic flow, and hydrologic regime that affect temperature sensitivity (Johnson and Jones, 2000; Johnson, 2004; Gavelle and Link, 2007).

Buffers with greater than 50% mortality: Mean overhead shade for this group of buffers five years after harvest was 59.3%, about 30% less than the reference patch mean. Fallen trees suspended above the channel were the dominant source of shade at 37.8% of the stations and shrubs dominated at another 20%. Increases in understory plant cover and in-channel debris provided additional cover to channels adjacent to these buffers, which may off-set to some extent the loss of shade due to decreased density of live standing trees. Loss of shade in Type Np buffers because of wind-throw can result in increased stream temperature in temperature sensitive streams. Veldhuisen and Couvelier (2006) found that Type Np streams adjacent to buffers with reduced shade due to wind-throw had higher maximum summer temperatures than intact buffers. This finding is consistent with modeling done by DeWalle (2010) which indicated that density of trees is an important factor (along with tree height) on the amount of shade provided by buffers. However, at sites where the loss of shade from live trees is off-set by a corresponding increased shade from shrubs and fallen trees, or where the stream is not temperature sensitive because of physical or hydrologic factors, little or no change in stream temperature may occur.

Buffers with less than 33% mortality: Our data indicate that 50-ft buffers with less than 33% mortality provided similar overhead shade as the reference patches five years after harvest. (86.9%, compared to 90.2% for the reference stands). These buffers should continue to provide high levels of overhead shade over time, unless mortality rates increase. Veldhuisen and Couvelier (2006) developed a regression describing the relationship between average shade and average buffer width for their sample of headwater streams in the Skagit basin that predicts that 50 foot wide two sided buffers would provide 80% shade, similar to mean values for the 50-ft buffers in this study. They documented that maximum stream temperatures in the buffered sites were not significantly different than in the forested streams, so the buffers effectively prevented increases in maximum temperature although the range of daily fluctuation in temperature was greater in the buffered reaches. Consequently, little change in stream temperature would be expected in this group of buffers, except in highly sensitive stream reaches.

Sediment Input

Headwater streams can receive sediment input from a variety of sources including mass wasting, bank erosion, soil creep, forest roads, and soil disturbance from uprooted trees or timber harvest activity (McDonald and Ritland, 1989; Gomi et al., 2005). Some of the sediment entering the headwater stream network is transported downstream, while some is stored behind obstructions such as boulders, wood pieces and debris accumulations (O'Connor and Harr, 1994). This study only addresses riparian soil disturbance from uprooting of riparian trees and timber harvest activities. The following sections discuss the implications of the three disturbance scenarios on sediment input from riparian areas over time.

Clear-cut scenario: We documented some sediment delivery from soil disturbance during timber harvest in most clear-cut patches; however the soil disturbance targets were met at all but one site. Since most trees were removed, there was little soil disturbance from uprooted trees in the clear-cut patches in the five years following harvest. Initially after harvest, an increase in fine sediment accumulations in association with logging debris accumulations would be expected based on the results of other studies (Gomi et al. 2001, Jackson et al., 2001; Maxa, 2009). O'Connor and Harr (1994) documented the important role of large woody debris jams in storing sediment in headwater channels. Their model predicts that sediment behind these obstructions will be released and transported downstream as the debris jams decay and fail over time in channel unless new wood is recruited to form replacement jams. Given the low number of residual trees in the clear-cut patches, it is expected that much of the sediment stored in these channels will be released over time.

Buffers with greater than 50% mortality: These buffers had the largest amount of soil disturbance from uprooted trees in the first five years after harvest of the adjacent stands; 14.7 root-pits/100 feet of stream, over five times the rate for the reference patches. However, only 2.6 root-pits/100 feet delivered sediment. Other research indicates trees uprooted by wind-throw are usually not a significant source of sediment delivery to streams (Grizzel and Wolff, 1998), however a short-term increase in sediment yield can occur when there is widespread wind-throw of buffer trees growing in close proximity to the channel (Andrus and Froehlich, 1986).

Buffers with less than 33% mortality: These buffers had little soil disturbance during harvest, and minimal soil disturbance from uprooted trees in the first five years after harvest. The total rate of root-pit formation (2.5 root-pits/100 feet of stream) was slightly lower than the reference rate, and only 0.4 root-pits/100 feet of stream had evidence of sediment delivery.

Site and Regional Variation

Although we observed differences between the prescription treatment groups, there was substantial variability among sites within the treatment groups. This variation is indicative of the extent to which stand conditions, and processes such as tree mortality and LWD recruitment, are affected by differences in climate, environmental conditions, and geomorphology and vegetation among sites, as well as differences in past management and disturbance history. The variability among sites we observed is consistent with literature indicating that both riparian stands and their adjacent stream channels typically exhibit extensive variability on both local (site) and regional scale.

The characteristics of the riparian stands (age, size, density and species composition) are influenced by physical, climatic, environmental factors that affect stand establishment, stand development, and disturbance. Riparian vegetation is highly variable in space and time, often expressed as a mosaic of patches consisting of different plant communities (Naiman et al, 1998). This variability has been attributed to many factors including differences in the type and frequency of disturbance processes, differences in regeneration and successional processes, and differences in growing conditions (Gregory et al., 1991; Naiman et al., 1998; Naiman et al., 2000). The factors that contribute to variability in riparian stand conditions operate at various scales, from the regional or landscape scale to the local site scale (Pabst and Spies, 1999; Sarr, 2004).

At the regional or landscape scale, differences in climate (e.g. precipitation and temperature), terrain and geology contribute to regional differences environmental conditions, competition and disturbance processes that result in differences in riparian vegetation (Sarr, 2004). Regional variation in growing conditions contributes to differences in the distribution of tree and shrub species, as well as differences in hydrology and the type and frequency of disturbance processes that affect riparian vegetation. At a finer scale, differences in watershed position and drainage area contribute to differences in geomorphology and process regimes that contribute to variability in riparian stands (Gregory et al., 1991, Montgomery. and Buffington, 1997; Pabst and Spies, 1999; Acker et al., 2003). For example, riparian stands along small, steep first-order headwater streams situated in narrow valleys are typically similar to adjacent upslope stands and the disturbance regimes are dominated by mass wasting processes such as debris flows, debris slides and snow avalanches and as well as fire and timber harvest. Streams further downstream are typically situated in wider valleys with floodplains where hydrologic disturbance processes such as flooding, bank erosion and channel migration result in soils and growing conditions that differ from the adjacent uplands (reference) resulting in development of riparian vegetation which differs from upland stands. In these settings, fine-scale differences in growing conditions and riparian vegetation occur due to differences in soils, geomorphology, and micro-climate associated with differences in geomorphic landforms (Rot et al., 2000).

Disturbance from natural processes or human activities also contribute to variation in riparian stands. Riparian stands are subject to disturbance from many natural processes such as debris flows, avalanches, floods, channel migration, fire and wind in addition to widespread human disturbance from logging and other land use activities (Naiman et al., 1998). These disturbances trigger tree regeneration and successional processes as stands are re-established and grow over time. The variable nature and patchy distribution of disturbance in space and time, and differences between natural and silvicultural regeneration leads to a patchwork of stands of different age, structure and composition on a landscape scale.

The number of sites in this study is not large enough to document the full range of riparian stand and site conditions present on Type Np harvest units on state and private forest lands in western Washington. While it is likely that both regional and local differences contributed to the variability we observed in riparian stand conditions, mortality and tree fall rates, and riparian processes and functions we observed within treatment groups, the sample size is not sufficient to conduct a robust analysis of the influence of site conditions. Further research would be useful in determining how the physical or biological characteristics of Type Np sites in western Washington affect riparian stand composition and structure, the type and magnitude of disturbance processes and the sensitivity of riparian stands and functions to harvest.

STUDY LIMITATIONS

This study had a number of limitations related to sample size, availability of reference sites, lack of pre-harvest data, limited duration and site-scale scope.

Sample size

Sample size is an important constraint to consider in interpreting and extrapolating the results of the study. The sample size was limited to 14 reference patches, 13 50-ft buffers, 8 clear-cut patches and 3 PIP buffers. There was substantial variability among sites for many metrics and the limited sample may not have documented the full range of site and regional variability or provided a precise estimate of the distribution of values for the metrics we examined. This is particularly problematic for the PIP buffers because the sample was quite small (three patches) and the geographic distribution was limited. Consequently, the PIP buffer sample provides an indication of the response to the prescriptions but does not provide a robust characterization of response across the range of conditions across state and private forest land in western Washington. Consequently, the PIP buffer results should be used with caution. Although the sample of 50-ft buffer, clear-cut and reference patches was large enough to detect statistically significant differences in response for some metrics, a larger sample size would provide greater power to detect differences between the treatment and reference patches, reducing the likelihood of Type II errors and providing a more precise estimate of the distribution of conditions across western Washington FFR lands. A larger sample would allow a more robust analysis of the role of regional and site conditions on riparian stand conditions and their response to the treatments.

Reference Conditions

Finding suitable reference sites that were not scheduled to be harvested within the five year period of the study was a challenge in commercial timber land. In many cases the reference stands had greater density and smaller mean and quadratic mean diameters, and limited sampling of tree ages indicated that the reference stands were often younger. Nonetheless, we believe that stand conditions were similar enough to provide a reasonable basis for comparison of the reference and treatment sites. However, the study design did not specifically include selection of reference sites with perennial initiation points to provide a basis for comparison with the PIP buffer patches. Consequently, direct comparison between the PIP buffer and the reference patches has been avoided.

Pre-Harvest Sampling

Because the sites for this study were selected from approved forest practices applications, there was no opportunity for pre-harvest sampling of conditions. Consequently, there was no pre-harvest baseline, and results are limited to examining post-harvest changes. Lack of opportunity for pre-harvest sampling also made it infeasible to collect and interpret some types of data on aquatic resource conditions (e.g. stream temperature).

Timeframe

The duration of sampling was limited to the first five years following harvest. This provides information on the short-term response to the treatments, however many important disturbance and recovery processes continue over a longer timeframe (such as buffer tree mortality, tree regeneration, large wood recruitment, and changes in channel debris and shading). Sampling over a longer timeframe will be necessary to document the duration of disturbance and the trajectory of recovery processes.

Spatial Scale

The study was limited to evaluating response on a site or harvest-unit scale. Study at this scale provided useful insights on changes in riparian processes in the immediate vicinity of the treatment, but did not provide the ability to interpret effects on the scale of a Type Np basin or to evaluate downstream effects on the fish-bearing portion of the stream network.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study documented the magnitude of change in riparian stand conditions and riparian processes, the first link in the pathway of potential resource effects. These effects were examined over a short-term time scale (5 years) and at a reach or harvest unit scale. The study results provided insights on the reach-scale response of riparian conditions and processes over a five year time horizon. While this study reduced scientific uncertainty about the effect of the westside Type N prescriptions within these constraints, additional questions outside the scope of this study remain to be answered, particularly related to disturbance and recovery processes in the clear-cut and highly disturbed buffer reaches. Disturbance under these scenarios may limit the ability of the prescriptions to meet the functional objectives for heat/temperature, LWD/litter fall and sediment on a reach-scale in some cases. These findings raise additional questions concerning:

- the distribution of Type Np riparian stand conditions across the landscape,
- the duration of disturbance and the timeframe for recovery in Np streams following harvest, particularly in clear-cut reaches and buffers with high mortality;
- the effectiveness of PIP buffers in meeting FFR resource objectives
- the effect of site conditions on the sensitivity of riparian stands to the Type Np prescriptions, particularly factors affecting the susceptibility to wind-throw,
- the response of aquatic resources to changes in riparian stands and processes associated with the westside Type Np riparian prescriptions on a sub-basin scale
- the need for performance targets for the westside Type Np riparian prescriptions

The following sections discuss areas of scientific uncertainty that can be addressed by additional research effort. Appendix C contains a detailed list of potential follow-up research questions.

Distribution of Type Np riparian stand conditions and disturbance

The current study provides some indication of possible regional patterns in disturbance. Research that provides a better understanding of riparian stand conditions and disturbance patterns over time across state and private forest lands in western Washington would be useful in assessing riparian prescription effectiveness over time, and identifying regional issues or sensitivities that could result in more effective management practices. This could be addressed by designing and implementing a riparian stand assessment component to CMER's extensive riparian temperature monitoring project.

Duration of disturbance and recovery in clear-cut and highly disturbed buffers

The five year timeframe of the current sampling effort is too short to fully document the duration of disturbance and subsequent recovery in riparian stands and processes following application of the westside Type Np prescriptions. The study raises questions concerning the duration of disturbance following harvest and the timeframe for recovery processes. In the clear-cut reaches, there is uncertainty about the persistence and function of channel debris, and the role of debris, shrubs and trees in providing shade over time. There are also questions concerning the fate of the riparian buffers with high levels of wind-throw mortality, including how these stands will respond and develop over time, as well as the fate of fallen trees spanning or suspended over the channels. Extending the timeframe of the Type N BCIF study to undertake additional sampling of the existing study sites at 5 year intervals would provide additional information that would reduce these uncertainties.

The effectiveness of PIP buffers in meeting FFR resource objectives

The study provided an indication of high levels of tree mortality and disturbance in the PIP buffers. However, we are uncertain how representative this small sample is of the overall population of PIP buffers, and have additional questions about whether the aquatic resources that PIP buffers are designed to protect are adversely affected by high tree mortality and tree fall. These uncertainties will be addressed to some extent by additional data on PIP buffer response from the Type N experimental buffer study, which is currently being analyzed. If this data is not adequate to address this uncertainty, CMER could undertake a separate project to obtain a larger sample of PIP buffers and more detailed information on their effectiveness in meeting FFR resource objectives.

The effect of site condition

Because of extensive variability in site conditions in western Washington, it is important to understand how local site conditions affect sensitivity to the prescriptions. This and other studies indicate that there is substantial variation in riparian vegetation, functions and disturbance processes between sites (Gregory et al., 1991; Naiman et al. 1998; Sarr, 2004) but the sample size was not large enough for a robust evaluation of the influence of site conditions. A project to collect additional data at a larger number of sites would increase our understanding of how site conditions affect riparian stand conditions, disturbance processes and riparian functions.

Additional information on how site conditions affect the susceptibility of riparian stands to wind-throw disturbance or the sensitivity of stream temperature to changes in shade would be useful for adaptive management and in designing more effective research and monitoring studies.

Aquatic resource response to riparian management and disturbance

The westside Type Np prescription package is designed to be applied on a sub-basin scale and is intended to protect aquatic resources in headwater streams while providing the opportunity to harvest some riparian trees and flexibility in the layout of harvest and yarding operations. There was an expectation that buffering sensitive portions of the Np network would limit the magnitude and extent of the harvest-related impacts to aquatic resources and allow for recovery of stream temperature before the water reached downstream fish-bearing stream reaches. This study documented reach-scale disturbances associated with the clear-cut harvest prescription and buffers with high tree mortality from wind-throw, however it did not address how changes in riparian stands and processes affected channel habitat, water quality or amphibian populations, or the effects on fish or water quality in downstream Type F waters. CMER has two studies that are evaluating the effects of Type Np riparian prescriptions on aquatic resources when the prescriptions are applied at the scale of a Type Np basin (the Westside Type N experimental treatment studies). These studies will provide a more complete assessment of the effects on water quality and stream associated amphibians. However the uncertainty related to downstream effects may require a cumulative effects study on the scale of a Type F basin.

Performance targets for the Westside Type Np riparian prescriptions

The current performance targets for westside Type Np streams are of limited use in evaluating the effectiveness of the westside Type Np prescriptions. There is currently no performance target for riparian stand condition on Type Np streams. The shade and litter fall performance targets are confusing and repeat the prescriptions, apparently based on the assumption that if the prescriptions are followed the functional objectives will be met. It is unclear if the LWD performance targets for pool frequency, in-stream LWD and residual pool depth are meant to be applied to Type Np streams. The performance targets would benefit from an effort to review the Type Np prescriptions, clarify confusing wording, and incorporate headwater stream research that has occurred over the past decade.

CONCLUSIONS

The key findings of the study area summarized below:

- The clear-cut prescription resulted in the greatest change in riparian stand conditions and functions. Few trees remained after clear-cut harvest (mean density =12.5 trees/acre). LWD recruitment rates were low (0.1 ft^3/100 ft/yr), but total channel debris cover was abundant (50.7%) due to slash input from logging. There was little overhead cover immediately after harvest (12%), but overhead cover and cover from understory plants and shrubs increased following harvest.
- Of the treatments, the 50-ft buffer prescription resulted in the least change in riparian stands and functions. Over the 5 year post-harvest period, the rate of change (reduction) in stand density was similar in the 50-ft buffer and reference patches, although the reference patches

retained more trees/acre. Mean overhead shade was 10-13% lower than in the reference reaches over the 5 year post-harvest period. LWD recruitment was about double the reference rate.

- Wind was the dominant cause of tree mortality in the 50-ft buffers. Wind was also the dominant mortality agent in the small sample of PIP buffers. The data suggest that the mortality rate for the PIP buffers was higher than for the 50-ft buffers.
- Mortality from wind varied by harvest treatment and storm intensity. During the first three years after harvest there were four windstorms of moderate intensity (peak winds 40-60 mph) and mortality in the newly established buffers was significantly greater than in the reference patches. During years 4-5 there were two powerful storms (peak winds greater than 60 mph) and mortality in the 50-ft buffers was not significantly different from mortality in the reference patches.
- There was substantial variation in tree mortality rates among the 50-ft buffer group, which resulted in corresponding differences in stand condition and riparian functions. Mortality rates had a bi-modal distribution. Ten 50-ft buffer patches had less than 33% morality over the 5 year post harvest period, while three patches had mortality in excess of 50%. In the group with higher mortality rates, stand density was greatly reduced, overhead shade decreased and LWD recruitment rates were higher.
- It is uncertain how these riparian stands will respond over a longer timeframe, and whether the subset of 50-ft (and PIP) buffers with high mortality will meet FFR resource objectives for heat/water temperature and LWD recruitment.
- The soil disturbance performance target was met at all 50-ft and PIP buffer patches, and at seven of eight clear-cut patches.
- It was difficult to evaluate the effectiveness of the westside Type N streams using some performance targets. Some appear to re-state the prescriptions (e.g. the shade target), and it was unclear whether others applied to Type N streams (e.g. stand condition and LWD recruitment). Consequently, the study evaluated prescription effectiveness by comparing the treatments with unharvested reference sites of similar age.
- Further research on wind damage in westside buffers is needed. The results indicate that there is variation in wind mortality, with the heaviest damage occurring in a limited number of sites. Additional research on regional patterns and the effect of site conditions on mortality rates could be useful in designing prescriptions to reduce wind mortality.
- Long-term monitoring of tree mortality, shade levels, channel debris loading and LWD recruitment associated with the westside Type N prescriptions is needed. These processes operate over long time frames, so five years is not enough time to fully evaluate the effects of the prescriptions.
- Since many of the FFR resource objectives for Type Np streams are related to protection of downstream resources, the results of this harvest-unit scale study do not provide a complete story of prescription effectiveness. Combining the results of this study with sub-basin scale studies that examine the effects of the prescription on aquatic organisms within Type N basins and exports of heat, sediment and nutrients to fish-bearing streams will provide a more complete assessment of prescription effectiveness.

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APPENDIX A. MEAN TEMPERATURE AND PRECIPITATION FOR WESTERN WASHINGTON AS PERCENTAGE OF LONG-TERM AVERAGES

Table A-1. Mean summer (June-August) temperature and precipitation as percentages of the long-term average (Western Regional Climate Center, 2009).

	2003	**2004**	**2005**	**2006**	**2007**	**2008**
Percentage of mean summer temperature						
Puget Lowlands	101.6%	103.1%	99.4%	100.0%	98.8%	97.1%
Coastal Olympics	101.0%	103.2%	100.1%	99.6%	99.8%	96.3%
Cascades-west	103.3%	102.8%	97.9%	100.8%	97.7%	97.4%
Percentage of mean summer precipitation						
Puget Lowlands	35.5%	132.6%	110.6%	60.6%	115.7%	145.1%
Coastal Olympics	30.3%	133.2%	93.5%	62.5%	134.3%	146.2%
Cascades-west	25.0%	174.4%	100.3%	69.4%	85.7%	145.2%

Table A-2. Mean winter (November-February) temperature and precipitation as percentages of the long-term average (Western Regional Climate Center, 2009).

	2003-4	2004-5	2005-6	2006-7	2007-8
Percentage of mean winter temperature					
Puget Lowlands	102.7%	103.0%	103.4%	100.3%	98.8%
Coastal Olympics	101.6%	103.3%	102.1%	100.5%	97.4%
Cascades-west	100.2%	107.5%	100.2%	99.1%	95.1%
Percentage of mean winter precipitation					
Puget Lowlands	90.9%	73.0%	137.7%	106.5%	106.4%
Coastal Olympics	93.4%	79.1%	136.1%	110.1%	104.5%
Cascades-west	91.4%	66.0%	138.1%	107.0%	102.1%

APPENDIX B. STAND RECONSTRUCTION PROCEDURES

Estimates of the pre-harvest and immediate post harvest stand conditions were necessary to determine changes in riparian stand condition following harvest and to estimate tree mortality rates. The study plan called for collection of riparian stand and mortality data immediately after the harvest in 2003 using low altitude photography. Those data were to be used to reconstruct pre-harvest stand conditions. The low altitude photography method was not successful and the limited number of ground validation plots was not adequate to reliably estimate stand conditions. Consequently, it was necessary to reconstruct pre-harvest and immediate post-harvest stand conditions from the 2006 data (most sites) or 2008 data (for 2 sites not visited in 2006 due to access problems). The stand reconstruction was guided by the following assumptions:

Standing trees

- Trees standing (live or dead) in 2006 were standing in the pre-harvest and immediate post-harvest periods.
- Standing live trees in 2006 were standing live trees in the pre-harvest and immediate post-harvest periods. However in-growth may have occurred between 2003 and 2006 because trees too small to count in 2003 may have grown to threshold size (4” dbh) by 2006.
- Standing dead trees may have been alive or dead in the pre-harvest and immediate post-harvest time periods.

Fallen trees

- All fallen trees in 2006 were standing trees in the pre-harvest time period (we did not collect data on trees that we thought fell before the harvest). However some 2006 fallen trees were tops from standing trees that should not be counted as separate trees in the reconstruction.
- Fallen live trees in 2006 were alive in the pre-harvest and immediate post-harvest periods.
- Fallen dead trees in 2006 may have been alive or dead in the pre-harvest or immediate post-harvest periods.
- Trees that were recorded as fallen (live or dead) in 2006 may have fallen during the harvest.

Stumps

- Fresh stumps were trees cut during harvest and were standing live trees prior to harvest.
- Older relic stumps were cut or already dead prior to harvest.

Based on these assumptions, the primary questions in the stand reconstruction then were:

1. Was a dead tree (standing or fallen in 2006) alive in the pre-harvest and immediate post-harvest periods?
2. Did a fallen tree fall during the harvest or after the harvest?
3. Would a 2006 live tree have been too small to be counted as a tree in the pre-harvest or immediate post-harvest periods (in-growth)?

Several sources of data were used to answer question 1. For sites reconstructed using 2006 data, the 2006 data collection protocols included assessing and recording whether a standing dead tree died pre-harvest or post-harvest. These data were used to determine if a 2006 standing tree was alive or dead in the pre-harvest time period. In addition, all fresh stumps were assumed to be standing live trees in the pre-harvest time period but not in the immediate post-harvest period.

For dead standing or fallen trees recorded for the first time in 2008. For sites reconstructed using 2008 data, the pre-harvest condition was inferred from the decay class recorded for the tree (based on the assumption that a tree with few signs of decay indicated more recent mortality than a tree with more advanced signs of decay). Dead trees with a decay class of 1 were assumed to have been alive in the pre-harvest and immediate post-harvest time-periods. Dead trees with decay class of 3, 4 or 5 were assumed to have been dead in the pre-harvest and immediate post-harvest time period. Trees with a decay class of 2 were given a tree condition of ‘unknown’ in the pre harvest and immediate post-harvest time periods because this decay class does not convey specific enough information on the timing of the tree’s death.

To address question 2, direct observation of the tree’s condition and felling process were used to determine whether a tree fell during the harvest. Trees that were recorded as fresh stumps were assumed to have been cut down during the harvest and included in the immediate post-harvest stump table. Trees which had ‘yarding’ recorded as the cause of falling were assumed to have fallen during the harvest and included in the immediate post-harvest fallen tree table.

To address question 3, we subtracted the estimated diameter growth estimated to have occurred since 2003 using a diameter growth rate of 0.1 inches/yr, based on values in the literature (McArdle et al., 1961, Wiley, 1978) and tree cores from a sample of young trees in several of our study sites. Any trees with diameters ≤ 4.3 inches in 2006 (or ≤4.5 inches in 2008) were assumed to be in-growth and were not included in the pre- or immediate-post harvest stand tables.

Once all the pre-harvest and immediate post-harvest tree conditions had been assessed, the fallen trees were ‘stood’ back up to create separate pre-harvest and immediate post-harvest standing tree tables. These stand tables were used to calculate BAPA, TPA etc. by condition (live, dead), tree type (conifer vs. broadleaf), species, etc. for each of the time periods. Table B-1 lists and describes the codes assigned to each standing and fallen tree record when preparing the stand tables for the pre-harvest and immediate post-harvest reconstruction. Table B-2 describes how the assumptions and individual tree data were combined as criteria to create the pre-harvest, immediate post harvest, mortality, and fallen tree stand tables.

Table B-1. Codes used to create pre-harvest and immediate post-harvest stand tables.

Code	**Pre-harvest stand reconstruction**
SL	Pre-harvest live standing tree
SD	Pre-harvest dead standing tree (snag)
RS	Pre-harvest relic stump
SU	Unknown whether tree alive or dead pre-harvest
Z	Broken fallen tree already counted in standing tree table (to prevent double counting of trees)
Code	**Immediate post-harvest stand reconstruction**
SL	Post-harvest live standing tree
SD	Post-harvest dead standing tree (snag)
RS	Post-harvest relic stump
SU	Unknown whether tree alive or dead immediately post-harvest
ST	Buffer tree cut down during harvest
Y	Tree knocked down during harvest
Z	Broken fallen tree already counted in standing tree table (to prevent double counting of trees)

Table B-2. Data used to create the pre-harvest and immediate post-harvest stand tables.

A) Pre-harvest stand reconstruct ion

1. Pre-harvest live standing trees
    a. Standing trees, condition = L
    b. Standing trees, condition = D, mortality timing = POST
    c. Standing trees, condition = ST
    d. Standing trees, condition = D, mortality timing = null, Decay = 1,2 ***(2008 trees only, site 47 & 56)***
    e. Fallen trees, type = B, condition = L, no associated standing tree
    f. Fallen trees, type = B, condition = D, decay class = 1, no associated standing tree
    g. Fallen trees, type = U, condition = L
    h. Fallen trees, type = U, condition = D, decay class = 1

2. Pre-harvest dead standing trees
    a. Standing trees, condition = D, mortality timing = PRE
    b. Standing trees, condition = D, mortality timing = null, decay class = 3, 4, 5 ***(2008 trees only, site 47 & 56)***
    c. Fallen trees, type = U, condition = D, decay class = 3, 4, 5
    d. Fallen trees, type = B, condition = D, decay class = 3, 4, 5, no associated standing tree

3. Pre-harvest relic stumps
    a. Standing trees, condition = RS

4. Pre-harvest tree condition ‘unknown’
    a. Standing trees, condition = D, mortality timing = U
    b. Fallen trees, type = U, condition = D, decay class = 2
    c. Fallen trees, type = B, condition = D, decay class = 2, no associated standing tree

B) Immediate Post harvest stand conditions

5. Post-harvest live standing trees
    a. Standing trees, condition = L
    b. Standing trees, condition = D, mortality timing = POST
    c. Standing trees, condition = D, mortality timing = null, decay class = 1, 2 ***(2008 trees only, site 47 & 56)***
    d. Fallen trees, type = B, condition = L, no associated standing tree
    e. Fallen trees, type = B, condition = D, decay class = 1, no associated standing tree
    f. Fallen trees, type = U, condition = L
    g. Fallen trees, type = U, condition = D, decay class = 1

6. Post-harvest dead standing trees
    a. Standing trees, condition = D, mortality timing = PRE
    b. Standing trees, condition = D, mortality timing = null, decay class = 3, 4, 5 ***(2008 trees only, site 47 & 56)***
    c. Fallen trees, type = U, condition = D, decay class = 3, 4, 5
    d. Fallen trees, type = B, condition = D, decay class = 3, 4, 5, no associated standing tree

7. Post-harvest relic stumps
    a. Standing trees, condition = RS

8. Post-harvest tree condition ‘unknown’
    a. Standing trees, condition = D, mortality timing = U
    b. Fallen trees, type = U, condition = D, decay class = 2
    c. Fallen trees, type = B, condition = D, decay class = 2, no associated standing tree

9. Buffer trees cut during harvest
    a. Standing Trees, condition = ST

10. Trees knocked down during harvest
    a. Fallen Trees, felling process = Y

APPENDIX C. LIST OF SPECIFIC FOLLOW-UP RESEARCH QUESTIONS

Following is a list of potential future research questions related to effectiveness of the westside Type Np riparian prescriptions.

Riparian stand response

- How successful is natural tree regeneration in buffers that are subject to high mortality rates and disturbance due to wind? What are the characteristics of tree stands that regenerate following these disturbances? Does competition from shrubs and low-growing plants delay or prevent tree regeneration in highly disturbed riparian areas?
- How do riparian processes and channel conditions respond to changes in riparian stand conditions beyond five years following disturbance in the buffers and clear-cut areas? (E.g. LWD recruitment and channel wood, shade and stream temperature).

Heat/water temperature response

- How does thermal loading change when overhead shade is reduced due to high rates of tree mortality or clear-cut timber harvest?
- To what extent does cover from fallen trees, logging slash, shrubs and understory plants compensate for loss of tree canopy shade due to tree mortality or clear-cut timber harvest?
- Is it feasible to differentiate headwater streams in western Washington based on sensitivity to changes in stream temperature due to loss of shade?

Woody debris response

- What are the effects of episodic input of a large amount of woody debris from large wind-throw events on channel functions such as sediment storage?
- What is the fate of spanning and suspended fallen trees? How much of this wood ultimately enters the channel and provides channel functions and over what time frame?
- What are the effects of large inputs of logging slash from clear-cut timber harvest on channel morphology, channel cover, stream temperature and sediment storage/routing? How long does logging debris persist in the channel and how is debris loading and function affected by decay and transport processes? Do the functions provided by small diameter wood and slash differ from those provided by large diameter wood in headwater stream channels?
- How do LWD and litter fall rates change over time as riparian stands recover from disturbance due to large wind-throw events or clear-cut timber harvest?
- Under what conditions do headwater streams transport LWD downstream to fish-bearing waters, and how important is the contribution of headwater streams to the wood budget of western Washington streams?

Sediment response

- Does sediment delivered by soil disturbance from clear-cut harvest or trees uprooted during large wind-storms result in changes in substrate characteristics or suspended sediment and turbidity levels, and for how long do these effects persist?
- How are sediment storage and routing affected by changes in the amount and type of debris inputs to headwaters streams, and the frequency and persistence of debris jams that retain sediment?

Wind-throw response

- Are the impacts to aquatic resources associated with the current rate of wind-throw in Type Np riparian buffers acceptable?
- Can areas of high wind-throw risk be identified, and if so, what are appropriate riparian management strategies for wind-throw prone areas?

Perennial initiation point (PIP) buffer response

- How representative is this small sample of PIP buffers of the distribution of conditions in the overall population of PIP buffers?

Are the aquatic resources that PIP buffers are designed to protect adversely affected by high tree mortality and tree fall

Sub-basin-scale response

- Is the 300-500 ft no-cut buffer located at the downstream end of the Type Np basin effective in ameliorating potential effects of clear-cut harvest or buffer mortality further upstream in the basin on exports from the Type Np basin and downstream fish habitat?
- Does clear-cut harvest of up to 50% of the Type Np stream length provide an appropriate level of protection for aquatic resources to meet FFR resource objectives? Under what conditions would be appropriate to increase or decrease the percentage of stream length with clear-cut harvest?
- What is the effect of high rates of buffer tree mortality on aquatic resources? Is the amount of disturbance in buffers acceptable on a landscape scale, or is it desirable to reduce the occurrence of high mortality in buffers?