Appendix C – Annotated Bibliography of Literature Describing the Effects of Riparian Management on Stream Shade and Stream Temperature

Peter Leinenbach – USEPA Region 10

1.1 - Variable Buffer Widths and Water Quality – Ripstream Project - 1

Groom J. D., L. Dent, L. and Madsen. 2011a. Stream temperature change detection for state and private forests in the Oregon Coast Range. *Water Resources Research* 47

Location: Western Oregon coast range (45^{o} Latitude)

Abstract: Oregon's forested coastal watersheds support important cold-water fisheries of salmon and steelhead (Oncorhynchus spp.) as well as forestry-dependent local economies. Riparian timber harvest restrictions in Oregon and elsewhere are designed to protect stream habitat characteristics while enabling upland timber harvest. We present an assessment of riparian leave tree rule effectiveness at protecting streams from temperature increases in the Oregon Coast Range. We evaluated temperature responses to timber harvest at 33 privately owned and state forest sites with Oregon's water quality temperature antidegradation standard, the Protecting Cold Water (PCW) criterion. At each site we evaluated stream temperature patterns before and after harvest upstream, within, and downstream of harvest units. We developed a method for detecting stream temperature change between years that adhered as closely as possible to Oregon's water quality rule language. The procedure provided an exceedance history across sites that allowed us to quantify background and treatment (timber harvest) PCW exceedance rates. For streams adjacent to harvested areas on privately owned lands, preharvest to postharvest year comparisons exhibited a 40% probability of exceedance. Sites managed according to the more stringent state forest riparian standards did not exhibit exceedance rates that differed from preharvest, control, or downstream rates (5%). These results will inform policy discussion regarding the sufficiency of Oregon's forest practices regulation at protecting stream temperature. The analysis process itself may assist other states and countries in developing and evaluating their forest management and water quality antidegradation regulations.

Riparian Stand and Harvest Conditions:

Sites: Thirty three (33) first and third order streams on 18 private sites and on 15 State forest sites.

Stand Conditions: Dominated by Douglas fir and red alder. Forest stands were 50-70 years old and were fire- or harvest regenerated. Mean measured tree height was 25.7 m. Sites with evidence of debris torrent or beaver disturbance were excluded. Pre-treatment buffer basal area (m^2/ha) was 41 and 43 for state and private sites, respectively.

Stream Conditions: First to third order streams. Average BFW was 4.6 and 4.1 meters for state and private sites, respectively. Average wetted width was 2.3 and 2.0 meters for state and private sites, respectively.

Harvest conditions: There was an upstream control reach for each sample reach (average length of 684 m). There was also a downstream "recovery" reach for many of these sites. Average "no touch" buffer width for the private sites was 26 m (85 ft), and ranged from 14 to 36 m (The reported mean distance was 31m and was defined as "the perpendicular distance from the stream bank to the first stump encountered within 10 m of the observer, measured every 60 m along the treatment reach." It was assumed that, on average, that the perpendicular distance of the stump to the stream will be 5 meters further from the stream than the observer (i.e., 31 m – 5 m = 26 m).). Using a similar calculation, the average "no touch" buffer width for the state sites was 46.8 m (154 ft), and ranged from 20 to 56 m. Thirteen (13) of the 15 State sites had harvest on only one bank of the river, and 4 of the 18 private sites had harvest on only one bank of the river.

Stream Length Logged: Average treatment length was 800 and 600 meters for state and private sites, respectively. Minimum treatment length target was 300m.
Time line: 2002 through 2008 - Two years of preharvest data and five years of post harvest data. Temperature analysis was limited to all of the pre-harvest data (two years for most sites and more at others) and two years of post-harvest data.

Summary of Results:

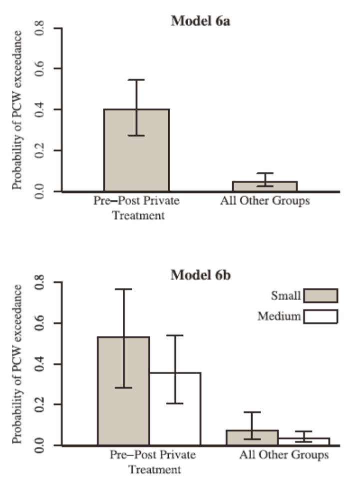

Figure 5. Point estimates for the two best supported mixed effects logistic regression models (±95% CI). Point estimates represent the probability of each comparison type exceeding the PCW. Model 6a allowed preharvest to post-harvest year-pair comparisons for private treatment reaches (PPPT) to differ from all other comparison types combined (all other groups). Model 6b is similar in formulation to model 6a except that it additionally allowed small streams to differ from medium streams.

This is the initial article in 2011 from Groom et al which describes the results associated with the Ripstream project. The project determined that timber harvested along medium or small fish-bearing streams on private lands resulted in a 40.1% probability that a preharvest to postharvest comparison of 2 years of data will detect a temperature increase of >0.3 C (i.e., violate the **Protecting Cold Water (PCW) criterion**: The PCW criteria is defined as "Anthropogenic activities are not permitted to increase stream temperature by more than 0.3 C above its ambient temperature."). State forest riparian stands did not exhibit exceedance rates that differed from preharvest, control, or downstream rates (i.e., 5%).

The authors did not report on temperature recovery.

Groom J. D., L. Dent, L. Madsen, J. Fleuret. 2011b. Response of western Oregon (USA) stream temperatures to contemporary forest management. *Forest Ecology and Management* 262(8):1618–1629.

Location: Western Oregon coast range (45^{o} Latitude)

Abstract: A replicated before–after-control-impact study was used to test effectiveness of Oregon's (USA) riparian protection measures at minimizing increases in summer stream temperature associated with timber harvest. Sites were located on private and state forest land. Practices on private forests require riparian management areas around fish-bearing streams; state forest's prescriptions are similar but wider. Overall we found no change in maximum temperatures for state forest streams while private sites increased pre-harvest to post-harvest on average by 0.7 °C with an observed range of response from −0.9 to 2.5 °C. The observed increases are less than changes observed with historic management practices. The observed changes in stream temperature were most strongly correlated with shade levels measured before and after harvest. Treatment reach length, stream gradient, and changes in the upstream reach stream temperature were additionally useful in explaining treatment reach temperature change. Our models indicated that maximum, mean, minimum, and diel fluctuations in summer stream temperature increased with a reduction in shade, longer treatment reaches, and low gradient. Shade was best predicted by riparian basal area and tree height. Findings suggest that riparian protection measures that maintain higher shade such as the state forests were more likely to maintain stream temperatures similar to control conditions.

Riparian Stand and Harvest Conditions:

Sites: Thirty three (33) first and third order streams on 18 private sites and on 15 State forest sites.

Stand Conditions: Dominated by Douglas fir and red alder. Forest stands were 50-70 years old and were fire- or harvest regenerated. Mean measured tree height was 25.7 m. Sites with evidence of debris torrent or beaver disturbance were excluded. Pre-treatment buffer basal area (m^2/ha) was 41 and 43 for state and private sites, respectively.

Stream Conditions: First and third order streams. Average BFW was 4.6 and 4.1 meters for state and private sites, respectively. Average wetted width was 2.3 and 2.0 meters for state and private sites, respectively.

Harvest conditions: There was an upstream control reach for each sample reach (average length of 684 m). There was also a downstream "recovery" reach for many of these sites. Average "no touch" buffer width for the private sites was 26 m (85 ft), and ranged from 14 to 36 m (The reported mean distance was 31m and was defined as "the perpendicular distance from the stream bank to the first stump encountered within 10 m of the observer, measured every 60 m along the treatment reach." It was assumed that, on average, that the perpendicular distance of the stump to the stream will be 5 meters further from the stream than the observer (i.e., 31 m – 5 m = 26 m).). Using a similar calculation, the average "no touch" buffer width for the state sites was 46.8 m (154 ft), and ranged from 20 to 56 m. Thirteen (13) of the 15 State sites had harvest on only one bank of the river, and 4 of the 18 private sites had harvest on only one bank of the river.

Stream Length Logged: Average treatment length was 800 and 600 meters for state and private sites, respectively. Minimum treatment length target was 300m.

Time line: 2002 through 2008 - Two years of preharvest data and five years of post harvest data. Temperature analysis was limited to all of the pre-harvest data (two years for most sites and more at others) and two years of post-harvest data.

Summary of Results:

Table 5

Mean and range values for State and Private independent variables and site characteristics. Values are calculated from 15 State sites and 18 Private sites. Pre and Post refer to measurements taken preharvest or postharvest. For Shade ranges see Fig. 4; basal area and trees per hectare are BAPH and TPH, respectively.

Variable	State		Private	
	Mean	Range	Mean	Range
Gradient (%)	6.5	1.5–13.2	6.4	1.0–17.5
treatment Length (km)	0.8	0.3–1.5	0.6	0.3–1.8
Elevation (m)	350	160–570	300	3–900
Watershed area (ha)	222	72–593	208	27–626
Crown ratio	0.43	0.30–0.56	0.40	0.26–0.57
Buffer width (m)[a]	51.8	25–61	31	19–41
Bankfull width (m)	4.6	2.7–7.9	4.1	2.2–7
Wetted width (m)	2.3	1.3–3.7	2.0	1.0–3.0
Thalweg (cm)	17	9–30	15	8–24
Basal area (m /ha)				
Pre-harvest	41	19–74	43	23–73
Post-harvest	42	25–73	25	11–40
Trees per ha				
TPH pre	368	147–665	465	196–664
TPH post	387	128–645	270	111–429
Tree height (m)	26	17–37	25	18–31

[a] Means reported in Groom et al. (2011); 95% CI for State sites = 45.6 m, 58.0 m; 95% CI for Private sites = 26.7 m, 35.3 m.

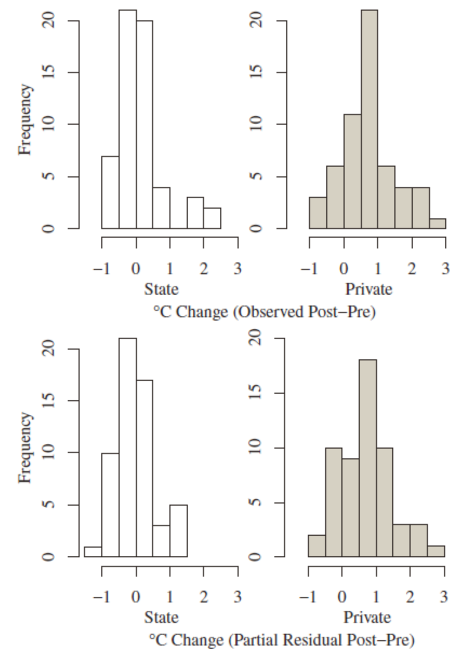

Fig. 6. Within-site pairwise differences in temperature change between post-harvest and pre-harvest values for Maximum observed data and partial residuals. Observed values are presented individually in Fig. 3. Partial-residual values represent observed values but control for site treatment reach length, upstream control temperature change, and stream gradient.

Vegetation Response - Average post-treatment buffer **basal area** (m^2/ha) for state sites was 42, which is an increase over pre-harvest levels (i.e., Pre-harvest levels were 41 m^2/ha). This result was most likely a result of two factors: 1) the “no-touch” buffer associated with state sites was 51.8 m, and 2) Only limited selective harvest occurred outside of this zone at many of these sites. Average private site post-harvest basal area were reduced by around half (i.e., Pre-harvest levels were 43 m^2/ha and post-harvest levels were 25 m^2/ha). Reductions at private sites may be occurring for two reasons: 1) The average “no-touch” buffer zone width was 26 m; and 2) Harvest activities outside of this zone were all “clearcut”. Thus, basal area reductions following harvest is primarily a result of vegetation removal in the outer zone of the riparian zone (The riparian area was defined in this study as a 170 ft (53 m) distance from the stream, which corresponds to the riparian management area (RMA)).

Stream Shade Response - Private site post-harvest **stream shade** values differed significantly from pre-harvest values (mean change in Shade from 85% to 78%); however, only a small difference was observed for state site stream shade values (mean change in Shade from 90% to 89%). The shade model BasalXHeight which included parameters for basal area per hectare (BAPH), tree height, and their interaction was best-supported: Its model weight (ω = 1.00) indicated strong relative support for this model and virtually no support for the remaining models. (BAPH and Height variables were calculated by using vegetation plot data from the edge of the bank to a perpendicular distance of 30 m, a distance at which they surmise that tree canopies have likely ceased to influence stream shade during daily periods of the greatest radiation intensity (mean measured tree height = 25.7 m).) Accordingly, stream shade conditions were shown to be a function of tree height and stand density (i.e., basal area - BAPH). Between 68% and 75% of variability in post-harvest shade may be accounted for by basal area within 30 m of the stream, tree height, and possibly blowdown. Sites with wider uncut buffers, or fewer stream banks harvested had greater basal area (i.e., BAPH). Sites with higher basal area within 30 m of the stream resulted in higher post-harvest shade.

<u>Stream Temperature Response -</u> The authors determined that maximum, Average, Minimum, and Diel Fluctuation **stream temperatures** increased as a consequence of timber harvest. Particularly, ranking models determined that by far the most critical driver for stream temperature change was shade. In addition, they generally observed an increase in maximum temperature pre-harvest to post-harvest for sites that exhibited an absolute change in shade of > 6%; otherwise, directionality appears to fluctuate.

A comparison of within-site changes in ***maximum temperatures*** from pre-harvest to post-harvest indicated an overall increase in Private site temperatures while observed changes at State sites were as frequently positive as negative: The average observed maximum change at State sites was 0.0 °C (range = −0.89 to 2.27 °C); and the average observed maximum temperature change at Private sites averaged 0.73 °C (range = −0.87 to 2.50 °C), and Private sites exhibited a greater frequency of post-harvest increases from 0.5 to 2.5 °C compared to State sites. They repeated this comparison while controlling for the effects of control reach temperature change, treatment reach length, and gradient by plotting differences in partial residuals from the Maximum temperature model Grad_Shade (each datum = model residuals + predicted effect of Shade). They found that State site differences became less extreme for positive increases (<1.5 °C) while private comparisons appeared to occupy the same range of responses. Using a linear mixed effects model ("HarvestPrivate") the authors determined that maximum temperatures at Private sites increased ***relative to State sites*** on average by 0.71 C, mean temperatures increased by 0.37 C, Minimum temperatures by 0.13 C, and Diel Fluctuation increased by 0.58 C.

The authors did not report on temperature recovery.

1.3 - Vegetation Buffers and Water Quality – Coast Range of Washington Study

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Jackson, C.R., C.A. Sturm, and J.M. Ward. 2001. Timber harvest impacts on small headwater stream channels in the Coast Ranges of Washington. *JAWRA* 37(6):1533–1549.

Location: Coast Range, Washington

Abstract: We evaluated changes in channel habitat distributions, particle-size distributions of bed material, and stream temperatures in a total of 15 first-or second-order streams within and nearby four planned commercial timber harvest units prior to and following timber harvest. Four of the 15 stream basins were not harvested, and these streams served as references. Three streams were cut with unthinned riparian buffers; one was cut with a partial buffer; one was cut with a buffer of non-merchantable trees; and the remaining six basins were clearcut to the channel edge. In the clearcut streams, logging debris covered or buried 98 percent of the channel length to an average depth of 0.94 meters. The slash trapped fine sediment in the channel by inhibiting fluvial transport, and the average percentage of fines increased from 12 percent to 44 percent. The trees along buffered streams served as a fence to keep out logging debris during the first summer following timber harvest. Particle size distributions and habitat distributions in the buffered and reference streams were largely unchanged from the pre-harvest to post-harvest surveys. The debris that buried the clearcut streams effectively shaded most of these streams and protected them from temperature increases. These surveys have documented immediate channel changes due to timber harvest, but channel conditions will evolve over time as the slash decays and becomes redistributed and as new vegetation develops on the channel margins.

Riparian Stand and Harvest Conditions:

Sites: fifteen first and second order streams in the coast range of Western Washington. Four of the 15 streams basins were not harvested, and these streams served as references. Four for each harvest type (“Reference”, clearcut, full buffer, and non-merchantable buffer)

Stand Conditions: Not described

Stream Conditions: 1^{st} and 2^{nd} order streams

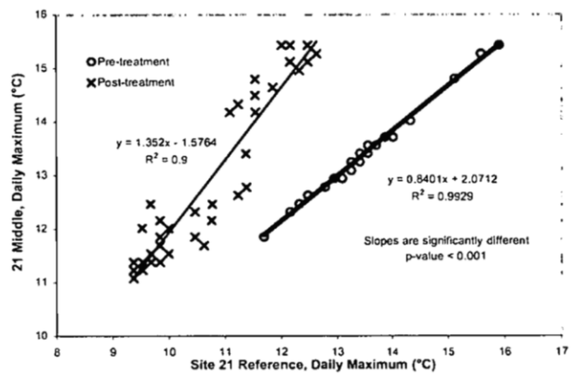
Harvest conditions: No adjacent harvest (reference stream), standard clearcut, full riparian buffer and a non-merchantable harvest (There was very little non-merchantable vegetation so these effectively became clearcut harvest.). Widths of buffers applied to the buffered streams were dictated by operational considerations, and the buffer widths were around 8 to 10 meters on each side of the stream.

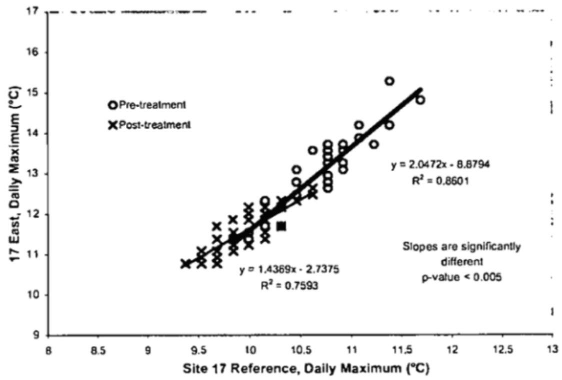
Stream Length Logged: Not described

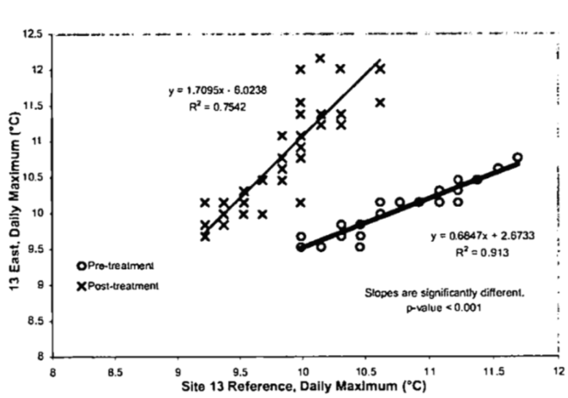
Time line: Two years of water temperature data – one pre and one post-harvest

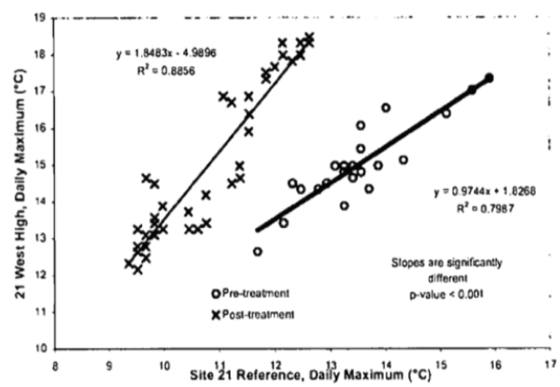
Summary of Results:

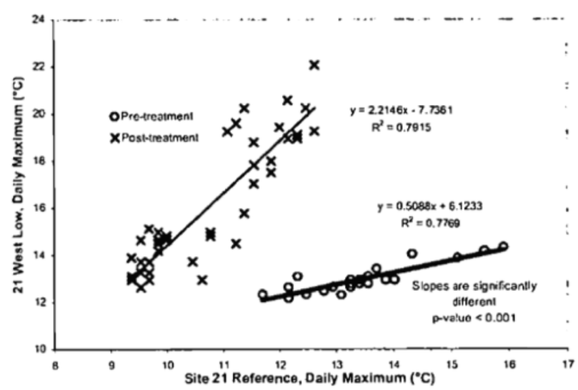
Streams with no buffer did not have a statistically significant temperature response as a result of the streams being buried by a layer of slash that was deposited over these streams. Four of the five buffered streams became warmer (+2.0, 2.6, 2.8 and 4.9 C), and one became slightly cooler (-0.5 C) (Site 17E). The year following harvest at Site 17E had blowdown of some of the riparian vegetation, which buried 29% of the sample reach. This covering up of the stream channel confounded the temperature response for this sample reach (added additional shade), and thus it could be expected that the response temperature may have been warmer without the blowdown vegetation lying on top of 29% of the stream reach length.











Temperature recovery is not observable because there was only one year of post harvest data. However, “significant” blowdown was observed in the year following this study period (2000), indicating that temperatures may have increased due to potentially elevated solar loading from the low shade levels following blowdown of the riparian vegetation. In a follow-up study, Jackson et al 2007 reported that blowdown ranged from 33 to 64% of buffered trees with attendant effects on canopy cover.

1.4 - Variable Buffer Widths and Water Quality – Malcolm Knapp Research Forest Study - 1

Kiffney, P. M., J. S. Richardson, J. P. Bull. 2003. Responses of periphyton and insect consumers to experimental manipulation of riparian buffer width along headwater streams. *Journal of the American Water Resources Association* 40:1060-1076.

Location: Coastal British Columbia (49^{o} Latitude)

Abstract: Riparian trees regulate aquatic ecosystem processes, such as inputs of light, organic matter and nutrients, that can be altered dramatically when these trees are harvested. Riparian buffers (uncut strips of vegetation) are widely used to mitigate the impact of clear-cut logging on aquatic ecosystems but there have been few experimental assessments of their effectiveness. Forests along 13 headwater stream reaches in south-western British Columbia, Canada, were clear-cut in 1998, creating three riparian buffer treatments (30-m buffer, 10-m buffer and clear-cut to the stream edge), or left as uncut controls, each treatment having three or four replicates. We predicted that periphyton biomass and insect consumers would increase as buffer width decreased, because of increased solar flux. We used two complementary studies to test this prediction. In one study, we compared benthic communities before and after logging in all 13 streams; a second study focused on periphyton and insect colonization dynamics over 6-week periods in each of four seasons in four streams, one in each treatment. Photosynthetically active radiation, and mean and maximum water temperature, increased as buffer width narrowed. Periphyton biomass, periphyton inorganic mass and Chironomidae abundance also increased as buffer width narrowed, with the largest differences occurring in the clear-cut and 10-m buffer treatments. Photosynthetically active radiation, water temperature, periphyton biomass and periphyton inorganic mass were significantly greater in the 30-m buffer treatment than in controls during some seasons. We have shown that a gradient of riparian buffer widths created a gradient in light and temperature that led to non-linear increases in periphyton biomass and insect abundance. For example, Chironomidae abundance was generally greater in the 10-m and 30-m buffer treatments than in controls, whereas this was not always the case in the clear-cut treatment. This pattern may be due to the high sediment content of the periphyton mat in the clear-cut treatment, which potentially limited the response of some insects to increased food resources. Overall, our results indicate that uncut riparian buffers of 30-m or more on both sides of the stream were needed to limit biotic and abiotic changes associated with clear-cut logging in headwater, forested watersheds.

Riparian Stand and Harvest Conditions:

Sites: 13 headwater streams in South-Western British Columbia, Canada.

Stand Conditions: 550-650 trees/ha, average dbh 40 cm, average height 45 m, average age 70 years, and western hemlock, western red cedar, and Douglas-fir were the dominate species.

Stream Conditions: headwater streams

Harvest conditions: Riparian no-touch buffer widths of 10m and 30m, zero m, and control (unharvested).

Stream Length Logged: Ranged from 215 to 650 meters

Time line: Pre-harvest data and one year of post-harvest data collection.

Summary of Results:

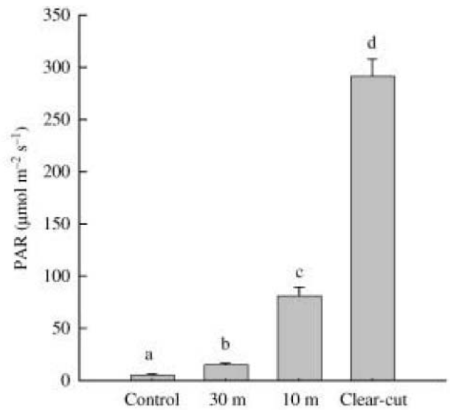


Fig. 2. Mean (1 SD) annual PAR (400–700 nm) measured in each treatment the first year after logging. Means with the same letter were not statistically different based on the within-season comparison.

Mean solar flux (Photosynthetically active radiation – PAR) reaching streams with clear-cut (zero meters), 10-m, and 30-m buffers was 58, 16, and 5 times greater, respectively compared to the control sites. This corresponds with an approximate reduction of 2.6 and 25.9 units of shade associated with the 30 m and 10 m buffers, respectively, as compared to the control. Authors concluded that "our observations suggest that additional light penetration comes through the sides of the buffer" and that there was a significant relationship between light levels and buffer width along small streams. Compared with controls, mean daily maximum summer water temperatures increased by 1.6, 3.0, and 4.8 degrees Celsius for the 30 m, 10 m and zero meter (clearcut) harvest treatments, respectively.

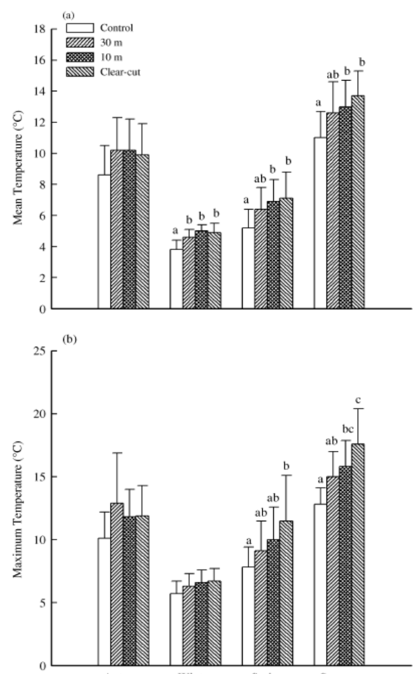


Fig. 3. Mean (1 SD) (a) daily and (b) maximum daily water temperature in each riparian treatment in each season the first year after logging. Means with the same letter were not statistically different based on the within-season comparison.

1.5 - Variable Buffer Widths and Water Quality – Malcolm Knapp Research Forest Study - 2

Gomi T., D. Moore, and A.S. Dhakal. 2006. Headwater stream temperature response to clear-cut harvesting with different riparian treatments, coastal British Columbia. *Water Resour. Res.* 42:W08437.

Location: Coastal British Columbia (49° Latitude)

Abstract: A 6-year study document the effects of clear-cut harvesting with and without riparian buffers (10m and 30m wide) on headwater stream temperature in coastal British Columbia. The experiment involved a replicated paired catchment design. Pretreatment calibration relations between treatment and control streams were fitted using theme series of daily minimum, mean, and maximum temperature. Generalized least squares (GLS) regression was used to account for auto correlation in the residuals. While water temperature in streams with 10 and 30 m buffers did not exhibit marked warming, daily maximum temperature in summer increased by up to 2 – 8 C in the streams with no buffer. The effectiveness of the buffers may have been maximized by the north-south orientation of the streams, which meant that the streams would be well shaded from late morning to early afternoon by the overhead canopy, even under the 10 m buffer. The variation in response for the no-buffer treatments is consistent with the differences in channel morphology that influence their exposure to solar radiation and their depth. Relations between treatment effect and daily maximum air temperature suggested that recovery toward pre-harvest temperature conditions occurring, with rates appearing to vary with stream and by season

Riparian Stand and Harvest Conditions:

Sites: Ten locations: Three control sites, four sites at zero buffer, one site at 10m buffer, and two sites at 30m buffer.

Stand Conditions: Not presented (from Kiffney et al., 2003 - 550-650 trees/ha, average dbh 40 cm, average height 45 m, average age 70 years, and western hemlock, western red cedar, and Douglas-fir were the dominate species.)

Stream Conditions: BFW ranged from 0.5 to 4.0 meters

Harvest conditions: Riparian buffer width 10m, 30m (No logging in riparian buffers.) and zero meter buffers.

Stream Length Logged: 215 to 650 meters

Time line: Six Years: Two years pre- harvest, and post-harvest was four years.

Summary of Results:

The sites used in this analysis were similar to that of Kiffney et al., 2003. They had to remove two 10m and one 30m treatment streams in the study because these sites had less than one year of pre-treatment stream temperature data. This left only one 10 m, and two 30m buffered streams for this study. Treatment effects from harvesting were most strongly expressed for daily maximum temperature, particularly in summer. The summer daily maximum temperature increased 4.1 C for the 10m buffer, which indicated a significant treatment effect. The 30 m buffers resulted in a 1.1 and 1.8 C increase of the daily maximum temperatures: 1.8 C treatment effect was statistically significant, but the 1.1 C treatment effect was not.

Temperature recovery rates were not presented for the riparian buffered streams.

1.6 - Variable Buffer Widths and Water Quality – Westside Type N Buffer Study – CEMR

Schuett-Hames., D., A. Roorbach, and R. Conrad. 2011. Results of the Westside Type N Buffer Characteristics, Integrity and Function Study – CEMR Final Report. December 14, 2011

Location: Western Washington

Executive Summary 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. The study evaluated 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 prescription on aquatic organisms and exports of heat, sediment and nutrients to fish-bearing streams will provide a more complete assessment of prescription effectiveness.

Riparian Stand and Harvest Conditions:

Sites: 24 non-fish bearing headwater streams in the western hemlock zone of western Washington

Stand Conditions: Randomly selected sites 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. Mean common tree height was 95 feet, and ranged from 60 to 128 feet. The mean site index was 122.

Stream Conditions: Mean bankfull width was 6 feet, and ranged from 3.1 to 11.4 feet.

Harvest conditions: 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 (not within 100 feet of the treatment site).

Stream Length Logged: 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.

Time line: Data were collected one year after harvest (2004), again in 2006 (three years after harvest), and in 2008 (five years after harvest).

Summary of Results:

The first year following harvest stream shade decreased 13.4 units of shade for the 13 sites with a 50-ft buffer.

In the years following harvest, tree mortality rates exceeded 50% at three of the 50-ft buffer sites. 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. The 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 units of shade 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.

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). Overhead shade in this group of buffers was reported 10-13 units of shade less than the reference reaches. These buffers had minimal soil disturbance from uprooted trees in the first five years after harvest.

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

1.7 - Variable Buffer Widths and Water Quality – Rogue River Siskiyou National Forest Study

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Park., C., C. McCammon, and J. Brazier. 2008. Draft Report - Changes to Angular Canopy Density from Thinning with Varying No Treatment Widths in a Riparian Area as Measured Using Digital Photography and Light Histograms.

Location: Rogue River Siskiyou National Forest, Oregon

Abstract: A study was conducted on the Rogue River Siskiyou National Forest measuring changes in Angular Canopy Density (ACD) as a result of thinning in a riparian stand. The study established varying widths of no treatment riparian buffers and measured ACD before and after thinning. The intent of the study was to add to the 1972 Brazier and Brown ACD data set and to apply the specified no-treatment widths defined by Table 3 of the Northwest Forest Plan Temperature Strategy (NFPTS) to verify that ACD remains unchanged after thinning. Digital photography was used to generate light histograms to measure ACD. The study site was clearcut in the early 1960s and was planted with Douglas-fir. The trees were 40 years old, 95 feet tall on a slope less than 30 percent and the trees were over dense and in need of overstory thinning. Thinning to the stream without a no-treatment buffer reduced ACD by 14% to 24%. As expected as the width of the no-treatment buffer increased, the loss of ACD was reduced. There was no change in ACD before and after the thinning treatment with a no treatment buffer of 50 feet. This validates the specified no-treatment width recommended in Table 3 of the NFPTS for the tree height and percent hill slope of the study site.

Riparian Stand and Harvest Conditions:

Sites: One stream with various stream buffer management scenarios applied at different locations

Stand Conditions: The study site, clearcut in the early 1960s and planted with Douglas-fir, had trees 40 years old, 95 feet tall on a slope less than 10 percent. The trees were 220 stems per acre. The stand was 98% Douglas-fir with a small mix of alder and cedar.

Stream Conditions: Not directly described in the draft report, however an image in the report indicate that the bankfull width is narrow (≈< 3 feet).

Harvest conditions: Thinning maintained the dominate trees and removed 80 to 100 stems per acre. Various “no-touch” buffer widths were maintained (i.e., 20, 40, 60, and 80 feet) with thinning occurring outside of this zone to distance of 180 ft from the stream.

Stream Length Logged: One hundred feet

Time line: Not specified

Summary of Results:

Thinning the stand from 220 stems per acre to around 120 to 140 stems per acre increased the Angular Canopy Density (ACD) over the stream by 14% in one plot and 24% in another plot (Each treatment had two reported plot values). ACD reductions were observed for at least one plot at each of the “no-touch” buffer widths (up to 80 feet). The magnitude of decrease was lower as the “no-touch” buffer width increased, with average reductions in ACD near zero with a “no-touch buffer” of 60 feet.

1.8 - Variable Buffer Widths/Thinnings and Water Quality – Stuart-Takla Study

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Macdonald, J.S., E.A. MacIsaac, and H.E. Herunter. 2003. The effect of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. *Can. J. For. Res*. 33(8): 1371–1382.

Location: Interior sub-boreal forests of northern British Columbia (55^{o} Latitude)

Abstract: Stream temperature impacts resulting from forest harvesting in riparian areas have been documented in a number of locations in North America. As part of the Stuart–Takla Fisheries–Forestry Interaction Project, we have investigated the influence of three variable-retention riparian harvesting prescriptions on temperatures in first-order streams in the interior sub-boreal forests of northern British Columbia. Prescriptions were designed to represent a range of possible harvesting options outlined by the Forest Practices Code of B.C., or associated best management practice guidelines. Five years after the completion of harvesting treatments, temperatures remained four to six degrees warmer, and diurnal temperature variation remained higher than in the control streams regardless of treatment. Initially, the high-retention treatment acted to mitigate the temperature effects of the harvesting, but 3 successive years of windthrow was antecedent to reduced canopy density and equivalent temperature impacts. We speculate that late autumn reversals in the impacts of forest harvesting also occur. Temperature impacts in this study remained within the tolerance limits of local biota. However, even modest temperature changes could alter insect production, egg incubation, fish rearing, migration timing, and susceptibility to disease, and the effects of large changes to daily temperature range are not well understood.

Riparian Stand and Harvest Conditions:

Sites: Eight first order streams in British Columbia Canada. Five harvested streams were compared to 3 control streams

Stand Conditions: Sub-Boreal Spruce biogeoclimatic zone (Engelmann Spruce Subalpine Fir zone at high elevations)

Stream Conditions: BFW range 0.6 to 3.2 meters

Harvest conditions: Three harvest conditions: 1) Low Retention Buffer – remove all merchantable timber (>15 cm and >20 cm dbh for pine and spruce-pine respectively) within 20 m of stream, 2) High Retention Buffer – Remove all large merchantable timber > 30 cm dbh within the 20-30m zone and 3) Patch cut – a high-retention along the lower 60% of the stream and removal of all riparian vegetation in the upper 40% of the watershed. Forest harvest actions outside of these buffer areas were not presented.

Stream Length Logged: 185 m to 810 m

Time line: 1.5 years before and 5 years after harvest

Summary of Results:

The authors concluded that summer stream temperatures clearly increased following forest harvesting and found that water temperatures were still elevated 5 years following treatment for all riparian buffers used in the analysis.

Canopy density conditions over the stream were shown to decrease following harvest activities, from an average condition of 76 in the control group, to 17 and 9 percent canopy density for “High” Retention buffer (B3) and “Low” Retention buffer (B5), respectively.

Summer maximum mean weekly temperature increased by an average of 2.4*C and 5 *C for the “low” retention buffers. For the “high” retention buffers, summer maximum mean weekly temperature increased by an average of 0.3*C and 1.7 *C. Several years of blowdown associated with the second listed high retention buffer and patch retention buffer increased the temperature response from this treatment. Before the blowdown event, this buffer had a temperature increase of over 1 C for the weekly average temperature condition, and it increased to near 2 C following the blowdown events. The other high retention buffer in this study had around a 0.5 C temperature increase following harvest: This reach was the largest stream, and had very little stream length exposed to cutblocks (375 m).

No temperature recover was observed after five years and windthrow in the years following harvest had resulted in higher stream temperatures.

1.9 - Variable Buffer Widths/Thinnings and Water Quality – Western Maine Project

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Wilkerson E., J.M. Hagan, D. Siegel, and A.A. Whitman. 2006. The Effectiveness of Different Buffer Widths for Protecting Headwater Stream Temperature in Maine. *Forest Science* 52(3):221–231.

Location: Western Maine (45^{o} Latitude)

Abstract: We evaluated the effect of timber harvesting on summer water temperature in first-order headwater streams in western Maine. Fifteen streams were assigned to one of five treatments: (1) clearcutting with no stream buffer; (2) clearcutting with 11-m, partially harvest buffers, both sides; (3) clearcutting with 23-m, partially harvested buffers; (4) partial cuts with no designated buffer; and (5) un-harvested controls. Over a 3-year period we measured summer water temperature hourly before and after harvesting, above and below the harvest zone. Streams without a buffer showed the greatest increase in mean weekly maximum temperatures following harvesting (1.4-4.4 C). Stream with an 11-m buffer showed minor, but not significant, increases (1.0-1.4 C). Streams with a 23-m buffer, partial harvest treatment, and control streams showed no changes following harvest. The mean weekly maximum temperatures never exceeded the thermal stress limit for brook trout (25 C) in any treatment group. The mean daily temperature fluctuations for streams without buffers increased from 1.5 C/day to 3.8 C/day, while with 11-m buffers fluctuations increased nonsignificantly by 0.5-0.7 C/day. Water temperatures 100 m below the harvest zone in the no-buffer treatment were elevated above pre-harvest levels. We concluded that water temperature in small headwater streams is protected from the effects of clearcutting by an 11-m buffer (with >60% canopy retention).

Riparian Stand and Harvest Conditions:

Sites: 15 Study Streams

Stand Conditions: No harvest within the last 20 years. Trees at least 15 m tall and mature closed-canopy cover (>85%).

Stream Conditions: Headwater streams draining small watersheds. Mean BFW – 1.9 to 4.2 m.

Harvest conditions: Fifteen streams were assigned to one of five treatments: (1) clearcut with no stream buffer (less than 6.8 m^2/ha residual basal area); (2) a thinned 11-m buffer (thinning target of 13.7 m^2/ha) and clearcut outside of this zone; (3) a thinned 23-m buffer (thinning target of 13.7 m^2/ha) and clearcut outside of this zone; (4) partial cuts with no designated buffer (retaining at least 13.7 m^2/ha residual basal area in the harvest zone); and (5) un-harvested controls. There were three replicates of each treatment.

Stream Length Logged: 300m and was on both sides of the stream

Time line: 3 years – 2001 (Pre-harvest) and Postharvest (2002 and 2003)

Summary of Results:

Vegetation Response - Basal area values associated with "Clearcut harvest" stands in this study were reduced to levels well below the minimum target (retain at least 6.9 m^2/ha). The basal associated with the partial-harvest treatment ranged from 14.0 to 18.9 m^2/ha. Thinning targets associated with the buffered streams (11 m and 23-m) exceeded the 13.8^2/ha target in 5 of the 6 streams (only one was slightly below 13.5^2/ha).

Stream Shade Response - Canopy cover measured in the middle of the stream channel was reduced following harvesting efforts for the 11m thinned buffers (Average canopy cover was 94 before treatment and 84 following treatment.) Canopy closure reduced by 4 units following harvesting efforts for the 23m thinned buffers (Average canopy cover was 94 before treatment and 90 following treatment.)

Stream Temperature Response - The temperature increase associated with the 11m buffer ranged from 1.0 to 1.4 C. They did not report a temperature increase associated with the 23 m and partial harvest buffers. They speculated that t high subsurface groundwater flow significantly mitigated the effects of canopy removal by slowing temperature increases.

No apparent temperature recovery was observed after 3 years.

Table 3. Average (minimum, maximum) basal area and canopy closure for preharvest year (2001) and the first postharvest year (2002) for each of the 15 study streams

		Cut block basal area Mean (min, max) m^2/ha		Riparian buffer basal area Mean (min, max) m^2/ha		% Canopy closure Mean (min, max)	
Stream	Treatment	Preharvest 2001	Postharvest 2002	Preharvest 2001	Postharvest 2002	Preharvest 2001	Postharvest 2002
Kibby	0 m	23.9 (7.8, 46.8)	1.5 (0.0, 6.2)	30.1 (26.5, 32.7)	0.0 (0.0, 0.0)	95 (81, 99)	1 (0, 4)
Pierce 1	0 m	28.6 (6.2, 49.9)	1.3 (0.0, 12.5)	22.9 (9.4, 37.4)	3.6 (1.6, 6.2)	97 (90, 99)	37 (4, 80)
Skinner 1	0 m	25.9 (10.9, 40.0)	2.1 (0.0, 9.4)	22.3 (17.2, 28.1)	3.1 (0.0, 6.2)	95 (88, 98)	27 (2,88)
Bald Mt.	11 m	22.0 (6.2, 35.9)	0.0 (0.0, 0.0)	24.9 (15.6, 39.0)	15.1 (10.9, 18.7)	98 (86, 99)	84 (60, 93)
Caratunk	11 m	33.9 (20.3, 51.5)	1.7 (0.0, 9.4)	19.2 (10.9, 34.3)	13.5 (9.4, 18.7)	91 (53, 99)	92 (68, 98)
Skinner 2	11 m	26.0 (10.9, 39.0)	1.9 (0.0, 9.4)	21.8 (17.2, 28.1)	16.6 (0.0, 31.2)	93 (2, 99)	75 (3, 97)
Mass 2	23 m	32.7 (12.5, 54.6)	0.7 (0.0, 3.1)	29.6 (18.7, 42.1)	24.9 (15.6, 34.3)	95 (89, 98)	91 (83, 95)
Roxbury	23 m	21.8 (0.0, 34.3)	1.1 (0.0, 6.2)	21.3 (15.6, 28.1)	19.2 (15.6, 21.8)	96 (92, 99)	94 (89, 98)
Sanderson	23 m	20.4 (3.1, 42.1)	1.0 (0.0, 9.4)	24.9 (18.7, 29.6)	15.6 (9.4, 18.7)	91 (79, 98)	86 (58, 98)
Mass 1	Partial	24.3 (3.1, 48.3)	18.9 (3.1, 37.4)	17.2 (9.4, 24.9)	14.0 (6.2, 21.8)	96 (86, 99)	96 (88, 99)
Pierce 2	Partial	25.1 (12.5, 40.5)	14.9 (3.1, 37.4)	24.9 (17.2, 29.6)	16.1 (14.0, 18.7)	96 (93, 99)	91 (71, 98)
UpCup	Partial	33.8 (14.0, 59.3)	16.1 (3.1, 51.5)	22.3 (17.2, 29.6)	17.2 (12.5, 21.8)	87 (59, 98)	82 (49, 98)
Appleton	Control	22.3 (6.2, 37.4)	21.3 (6.2, 34.3)	14.6 (3.1, 21.8)	15.1 (3.1, 21.8)	93 (66, 99)	90 (68, 99)
Bryant	Control	23.1 (10.9, 32.7)	24.1 (14.0, 37.4)	19.2 (18.7, 20.3)	19.2 (15.6, 21.8)	97 (90, 99)	96 (94, 97)
Dud	Control	24.5 (12.5, 37.4)	23.8 (6.2, 34.3)	18.7 (14.0, 24.9)	19.8 (15.6, 28.1)	94 (76, 100)	92 (50, 100)

1.10 - Vegetation Buffers and Water Quality – Washington Headwater Stream Study

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

Location: Western Washington (46.5° Latitude)

Abstract: We examined stream temperature response to forest harvest in small (<9 ha) forested headwater catchments in western Washington, USA over a seven year period (2002–2008). These streams have very low discharge in late summer (mean≈ 0.3 L s^{-1}) and many become spatially intermittent. We used a before–after, control-impacted (BACI) study design to contrast the effect of clearcut logging with two riparian buffer designs, a continuous buffer and a patch buffer. We focused on maximum daily temperature throughout July and August, expecting to see large temperature increases in the clearcut streams (n = 5), much smaller increases in the continuously buffered streams (n = 6), with the patch-buffered streams (n = 5) intermediate. Statistical analyses indicated that all treatments resulted in significant (α= 0.05) increases in stream temperature. In the first year after logging, daily maximum temperatures during July and August increased in clearcut catchments by an average of 1.5 °C (range 0.2–3.6 °C), in patch-buffered catchments by 0.6 C (range 0.1–1.2 °C), and in continuously-buffered catchments by 1.1 °C (range 0.0–2.8 °C). Temperature responses were highly variable within treatments and, contrary to our expectations, stream temperature increases were small and did not follow expected trends among the treatment types. We conducted further analyses in an attempt to identify variables controlling the magnitude of post-harvest treatment responses. These analyses showed that the amount of canopy cover retained in the riparian buffer was not a strong explanatory variable. Instead, spatially intermittent streams with short surface-flowing extent above the monitoring station and usually characterized by coarse-textured streambed sediment tended to be thermally unresponsive. In contrast, streams with longer surface-flowing extent above the monitoring station and streams with substantial stream-adjacent wetlands, both of which were usually characterized by fine-textured streambed sediment, were thermally responsive. Overall, the area of surface water exposed to the ambient environment seemed to best explain our aggregate results. Results from our study suggest that very small headwater streams may be fundamentally different than many larger streams because factors other than shade from the overstory tree canopy can have sufficient influence on stream energy budgets to strongly moderate stream temperatures even following complete removal of the overstory canopy.

Riparian Stand and Harvest Conditions:

Sites**:** Five streams with clearcut harvest, six streams with continuously buffer streams, and five stream with patch-buffered streams.

Stand Conditions: Even aged stands ranging from 50 to 100 years, dominated by Douglas-fir and western hemlock. Conifers in all catchments were approximately 40 m tall. The forest canopy was closed, and was "providing dense shade throughout the catchment before logging". Red alder was the dominant hardwood species, and was more common in riparian areas.

Stream Conditions: Headwater streams draining small watersheds (average of 4.9 hectare size for continuous buffered streams). Mean BFW for the continuous buffered streams was 0.6 m, and the flow rate was around 0.01 cfs (i.e., 0.3 Ls^{-1}) in the late summer. The valley floor associated with these sites was generally only a few meters wide and often the bankfull stream channel occupied the fully width of the valley floor.

Harvest conditions: In small forested watershed (< 9 ha) the following three treatments were applied: (1) clearcut (n=5); (2) continuous buffered (n= 6); and (3) patch-buffered streams (n=5). In all three treatments, the upland portions of the catchments were clearcut harvested so that these treatments differed only in the way the riparian zone was harvested. The continuous riparian buffers reported in this study range from 10 to 15 meters on each side of the stream. Correspondences with the lead author of this study clarified the following widths of the continuous "no-touch" buffer: The no-touch buffer widths were variable, but on average the continuously buffered streams were around 20 meters on each side of the stream (estimated by the lead author through the use of aerial imagery). For patch buffers, portions of the riparian forest approximately 50-110 m long were retained in distinct patches along some portions of the headwater stream channel, with the remaining riparian area clearcut harvest. There was substantial variation in the locations of the patch treatments. For clearcut treatments, overstory trees were harvested from the catchment, including the entire riparian zone.

Stream Length Logged: The mean stream length of continuous buffered treatment streams was 279 meters, however only 43% of the stream length (on average) was observed to be flowing in the first post harvest year.

Time line: A seven year monitoring period (2002-2008), with three years of post harvest temperature data collection activities.

Summary of Results:

Stream Shade Response – Stream shade was calculated from hemispherical photography, and included both canopy and topography. Shade averaged 94% over the stream channel before logging and measured shade did not differ significantly between reference and treatment reaches. Stream shade in reference sites did not change substantially (average = 94%) after logging activities. Stream shade decrease on average to 86% for the continuous buffer treatment reaches. This corresponds to an average reduction of 8 units of stream "shade" associated with this treatment.

Stream Temperature Response – The temperature statistic used in this analysis was maximum daily temperature averaged over July and August. For continuous buffered catchments, temperature changes were significantly greater than zero ($\alpha = 0.05$) in the first two post-treatment years. In the third post-treatment year, the magnitude of the temperature change estimated from the statistical model was significantly different for most of the monitoring period but not significantly different from zero after Julian day 228 (≈15th August). However, the absolute temperature response is still greater than zero during the last two weeks of the monitoring period. The July –August average temperature change for the three post-treatment years for the continuous buffered streams was 0.8 °C (i.e., (1.06+0.89+0.38)/3 = 0.8 °C). Temperature response was highest at the start of the evaluation period (i.e., July) and decreased in latter parts of the summer (i.e., July 1st average temperature response was approximately 1.3 °C, 1.1 °C and 0.8 °C in post-treatment year one, two and three, respectively). Accordingly, the estimated average July 1st temperature change for the three post-treatment years was 1.1 °C.

Table 2
Mean response of each treatment group in each post-logging year. A debris flow removed all riparian understory vegetation from one patch-buffered catchment between Years 2 and 3, leading to large temperature increases, so we also present treatment group means for patch-buffered catchments with that outlier removed from the calculation of temperature response in all three post-treatment years.

Treatment	Temperature response (°C)		
	Year 1	Year 2	Year 3
Continuous buffer	1.06	0.89	0.38
Patch buffer	0.61	0.67	0.91
Clearcut harvest	1.53	1.10	0.84
Patch buffer with outlier removed	0.73	0.72	0.16

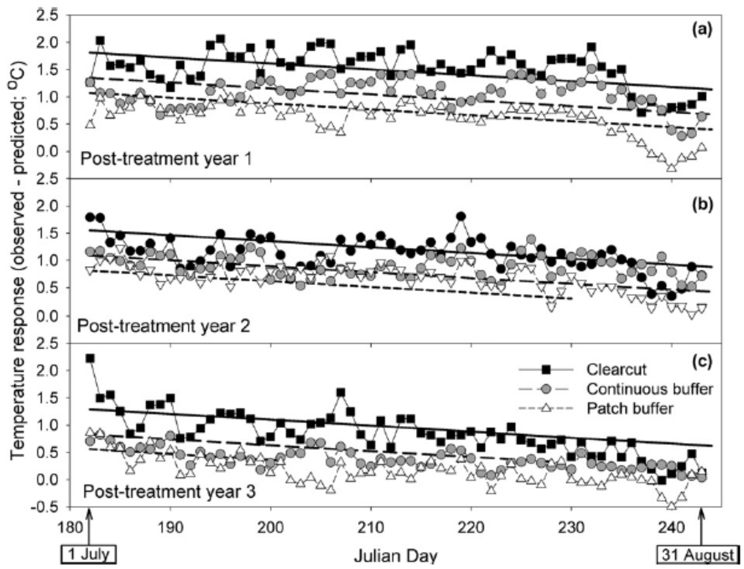

Fig. 4. Fit of the repeated-measures statistical model to the observed changes in stream temperature. Points represent the change in maximum stream temperature for each day of July and August, averaged over all catchments within a treatment group. The bold lines are the temperatures predicted from the statistical model where treatment, years post-treatment, and day of year were all fixed effects. These lines are only drawn for the dates over which the statistical model indicated a significant effect (i.e., stream temperatures were significantly different from 0.0 °C, $\alpha = 0.05$). Sample sizes per year for the clearcut, continuous, and patch treatments, respectively, were (A) Year 1: 5, 6, 5; (B) Year 2: 5, 6, 5; (C) Year 3: 3, 5, 5.

The observed variability of temperature response among catchments of the continuous buffer catchments, ranged from 0 to 2.8 °C in the first year after logging. Wetted stream length was shown to be a significant factor influencing the temperature response associated with riparian treatments, with greater responses associated with longer wetted stream lengths. In addition, the type of substrate was also shown to be a significant factor influencing temperature response, with a low response associated with coarse-substrate channels, and a large response associated streams with fine-texture streambed sediments. Shorter stream segment lengths were associated with coarse-substrate channels. The authors concluded that overall, the area of surface water exposed to the ambient environment best explained aggregated temperature response.

Temperature response successively decreased in the three years following the treatment; however there was still a significant response in temperature at post-harvest year 3.

1.11 - Vegetation Buffers and Water Quality – Oregon Department of Forestry Stream Shade Study

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Allen M., and L. Dent. 2001. Shade Conditions Over Forested Streams In the Blue Mountain and Coast Range Georegions of Oregon – ODF Technical Report #13.

Location: Coast Range of Oregon (45^o Latitude)

Synopsis: The Oregon Department of Forestry implemented a shade monitoring project in basins within the north coast and northeastern regions of Oregon (ODF Blue Mountain and Coast Range georegions). Discussions in this document will focus on sites associated with the Coast Range georegion. Data were collected on both harvested stream reaches and those with no recent history of harvest. One goal of this project was to determine the range of shade levels provided over streams under varying forest management scenarios. A second goal was to investigate possible links between site and stand characteristics and shade. The authors stated that the results from the Coast Range georegion are most appropriately applied to sites managed with a no-cut buffer.

Riparian Stand and Harvest Conditions:

Sites**:** 30 sites in the Coast Range of Oregon, of which 16 sites were managed with a “no-cut” buffer (however only 13 of these sites had both shade and buffer width data collect at them).

Stand Conditions: Riparian areas are typically dominated by an alder overstory and a salmonberry/sword fern understory. Riparian conifer species typically include western hemlock, western redcedar, and/or Sitka spruce. Douglas-fir is more prevalent farther away from the stream. Pre-harvest stand ages averaged 65 years.

Stream Conditions: The average stream width was 6.6 feet, and ranged from 3.2 to 12.8 feet.

Harvest conditions: The 13 sites in the Coast Range managed with a “no-cut” buffer had an average “no-cut” buffer width of 49.3 feet (15 m). Clearcut harvest occurred outside of this no-cut zone. Unharvested stand data were collected at sites adjacent, or in close proximity, to harvested stands in order to sample shade conditions that may have existed prior to entry. In order to collect data on a wide range of unharvested stands, this sample includes both young, intensively managed areas, as well as older stands.

Stream Length Logged: The plot had a minimum length of 500 feet and maximum length of 1000 feet.

Time line: Not described

Summary of Results:

Stream Shade Response - Thirteen of 16 no-cut sites in the Coast Range georegion had both shade measurements (collected by hemispherical photography at 3 feet over the stream surface) and the buffer width measurements. Buffer width was defined as the distance from the highwater mark to the first cut tree measured every 200 feet along the sample reach. The black circles on Figure 11 in the ODF report (shown below) depict these 13 no-cut sites for the Coast Range.

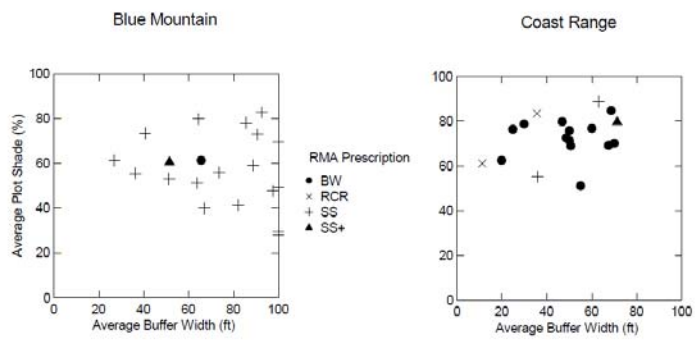
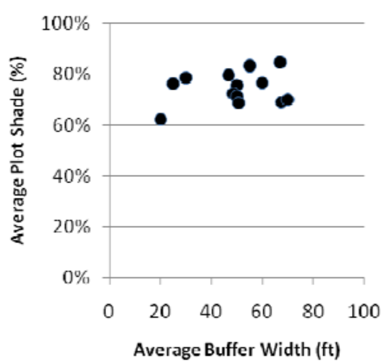


Figure 11. Average Plot Shade by average buffer width and RMA prescription for each georegion. SS = Site-Specific Prescription, SS+ = average buffer widths contain values that exceed 100 feet, BW = No-Cut Buffer, RCR = Riparian Conifer Restoration. Note: Only 38 sites had buffer width data.

Information for these 13 sites was obtained from Appendix A and B in this ODF technical report, along with the Microsoft Access database associated with this project (USEPA partially funded this project and the project database was a project deliverable). The image below illustrates this information for the 13 no-cut Coast Range sites. There is a difference in shade conditions at one of the sites presented below – The Microsoft Access database verified all of the information within Appendix A and B of this ODF technical report, except for this one shade measurement.



These 13 sites were located along small (11 sites) and medium (2 sites) stream size classes. The average stream width for these sites was 6.6 feet, and ranged from 3.2 to 12.8 feet. There were five small and medium sized unharvested streams in the Coast Range. The average shade measured at these unharvested sites was 89 % (i.e., 95, 85, 89, 93, and 83). The average difference in shade conditions associated with these 13 no-cut streams in the Oregon Coast Range was 14.5 units of shade, ranging from 4 to 27 units. The response would have been 16 units of shade reduction without the shade measurement correction described above.

<u>Stream Temperature Response -</u> Not measured

2.1 - Riparian Thinning with "Warm" Headwater Conditions – North Central B.C. Project

Mellina. E., R.D. Moore, S.G. Hinch, J. S. Macdonald. 2002. Stream temperature responses to clearcut logging in British Columbia: the moderating influences of groundwater and headwater lakes. *Can. J. Aquat. Sci.* 59:1886–1900.

Location: North-Central British Columbia (55^o – Latitude)

Abstract: Although the future timber supply in the northern hemisphere is expected to come from boreal and subboreal forest, little research has been conducted in these regions that examines the temperature responses of small, lake-headed streams to streamside timber harvesting. We examined the temperature patterns of two subboreal outlet streams in north-central British Columbia for 1 year before and 3 years after clearcut logging and found only modest changes (averaging 0.05-1.1 C) with respect to summer daily maximum and minimum temperatures, diurnal fluctuations, and stream cooling. A multi-stream comparative survey conducted in the same geographic region revealed that streams headed by small lakes or swamps tended to cool as they flowed downstream, and headwater streams warmed, regardless of whether or not timber harvesting took place. Stream cooling was attributed to a combination of warm outlet temperatures (promoted by the presence of the lakes) and cold groundwater inflows. A regression model revealed that summertime downstream warming or cooling in headwater and outlet streams could be predicted by upstream maximum summer temperatures and canopy cover. Lentic water bodies and groundwater inflows are important determinants of stream temperature patterns in subboreal forests and may subsequently moderate their responses to streamside harvesting.

Riparian Stand and Harvest Conditions:

Sites: Three small, lake headed, forested streams. Two streams were harvested and one was a no-cut control.

Stand Conditions: Located in subboreal spruce biogeoclimatic zone. Canopy cover > 70%.

Stream Conditions: Three small, lake headed, forested streams, <2 m BFW, headed by a small (<20 ha), relatively shallow lake.

Harvest conditions: Two sites (118/16 and 118/48) had thinning out all mature commercial timber (>15 cm dbh for lodgepole pine and >20 cm dbh for spruce and subalpine fir) within a 30 m buffer surrounding the stream and clearcut occurred outside of this zone. The third site was an unharvested control. Harvested 40 ha and 36 ha around the stream, representing 13 to 9% of the drainage area at the downstream sites.

Stream Length Logged: 607 m and 372 m for the treatment reaches and 430 m for the unharvested reach.

Time line: Four year – one year pre-harvest, and three years of post-harvest data.

Summary of Results:

Harvesting removed around 50% of streamside vegetation. Following harvest, canopy cover over the stream decreased from 88% to 48% and 51% for sites 118/16and 118/48, respectively.

Maximum stream temperatures and diurnal fluctuations increased as a result of harvesting, but the magnitude of change was lower than expected because the water entering the treatment reach was warm lake water discharge and therefore the treatment reach was a “cooling” reach.

Relative to pre-harvest patterns, maximum temperatures for the two treatment streams increased by a net average of 0.4 C, and diurnal fluctuations increase by a net average of 1.1 C. The authors concluded that these are modest changes (compared with literature values) may reflect the effect of headwater lakes on outlet stream temperature.

The dominate downstream cooling observed both before and after harvest was attributed to the combination of warm source temperature associated with the lakes and the strong cooling effect of ground water inflow through the clear-cut, as well as the residual shade provided by the partially logged riparian buffer.

No apparent temperature recovery was observed over three years.

2.2 - Riparian Thinning with "Warm" Headwater Conditions – White River Harvest Impact Project

Kreutzweiser, D. P., S. S. Capell, and S.B. Holmes (2009). Stream temperature responses to partial-harvest logging in riparian buffers of boreal mixedwood forest watersheds. *Can. J. For. Res.* 39:497–506.

Location: Ontario, Canada (48^{o} Latitude)

Abstract: As part of a larger study to examine the operational feasibility, ecological benefits, and environmental impacts of partial-harvest logging in riparian buffers along boreal mixedwood forest streams, we determined the effects on summer stream temperatures. Three logged study reaches were compared with three reference reaches over two prelogging and two postlogging summers. Partial-harvest logging resulted in an average removal of 10%, 20%, and 28% of the basal area from riparian buffers at the three logged sites. At the two more intensively logged sites, there were small (<10%) reductions in canopy cover (P = 0.024) and no significant changes in light at stream surfaces (P> 0.18). There were no measurable impacts on stream temperatures at two of the three logged sites. At the most intensively logged site, daily maximum temperatures were significantly higher (~4°C) for about 6 weeks in the first summer after logging than in prelogging years or at the reference sites (P< 0.001). Temperature increases were attributed to a logging-induced temporary disruption of cool water inputs from ground disturbance in a lateral-input seep area. Our results indicate that partial-harvest logging in riparian buffers of boreal mixedwood forest streams can sustain effective canopy cover and mitigate logging-induced water temperature increases.

Riparian Stand and Harvest Conditions:

Sites: Six sites - Three sites had not been previously been logged and serve as reference conditions. Three sites were logged.

Stand Conditions: Boreal mixwoods, defined as various proportions of least two of five species: white spruce, black spruce, balsam fir, trembling aspen, and white birch. Six study blocks located with a 120 km2 area. Reference sites had not been previously logged, although not discussed, it could be assumed that the "harvest" were in similar condition.

Stream Conditions: All streams originated from beaver ponds and flowed downstream through the harvest or reference blocks. Stream-reach length (distances between the beaver pond and bottom of the study reach) ranged from 240 to 600 m. Average BFW ranged from 2.6 to 6.4 meters. During the summer, wetted widths were 30-50% of the BFWs. None of the beaver ponds were "headwater" ponds.

Harvest conditions: Thirty to 100m wide riparian buffers were "thinned" to basal area reduction of 20.4% (Site WR1), 28.6% (WR2), and 10.8% (WR6) (It is important to note that the preharvest basal area volume was not presented.). There was a 5 m no entry zone. These levels were assessed by postlogging measurements of residual trees and stumps.

Stream Length Logged: 600 m, 840m and 550m.

Time line: Four years – Site WR6 was harvested during the second year so there was only one year of preharvest data for this site, and three years of post-harvest data. The other two harvest sites (WR1 and WR2) had two years of pre-harvest data and two years of post-harvest data.

Summary of Results:

All streams originated from beaver ponds and flowed downstream through the harvest or reference blocks. Accordingly, all sites exhibited as much as 6-8 C of cooling in the forested reaches over the 240-600m distances between upstream pond outflows and downstream locations during the monitoring period. This is an expected condition (Mellina et al., 2002: Story et al., 2003). The only site that had reduced cooling during the post harvest summer period was WR2 (28.6% of basal area removed). The authors inferred that is possible that shallow groundwater inflow temperatures were elevated by increase solar radiation and soil warming in the upland clearcut and parts of the riparian forest around this site.

Site WR1 (20.4% of basal area removed) had a 12% reduction of canopy cover but no increase in ambient light (PAR) reaching the stream surface. WR2 (28.6% of basal area removed) had no detectable change in canopy cover removed but average light reaching the stream surface increase (but not significantly). Canopy density and PAR were not measured for site WR6 because the "logging occurred in only small sections of one side of the stream, and mature streamside trees at WR6 tended to be further removed from the stream edges than at WR1 or WR2."

Instream temperature downstream of WR 2 (28.6% of basal area removed) increased by around 4.4 C in the first post-logging year. Temperatures returned to pre-harvest levels by the second post-harvest year. Stream temperatures at WR1 (20.4% of basal area removed) became more variable following harvest, but were within the range of "preharvest weekly temperatures". Stream temperatures at WR6 (10.8% of basal area removed) were elevated in one of the three post-harvest monitoring years.

The authors summarized that the temperature impacts were not observed on the second post harvest year (i.e., the last year of the study).

2.3 - Riparian Buffer with "Warm" Headwater Conditions – Copper Lake Watershed Study

Curry R.A., D. A. Scruton, and K. SD. Clarke. 2002. The thermal regimes of brook trout incubation habitats and evidence of changes during forestry operations. *Can. J. For. Res.* 32: 1200–1207.

Location: Western Newfoundland, Canada (48.5° Latitude)

Abstract: The thermal regimes in streambed substrate used by brook trout, *Salvelimus fontinalis* Mitchell, for incubation of embryos were examined in reference and treatment (0- and 20-m riparian buffer strips) streams in a clear-cut harvested, northern temperate forest of western Newfoundland. In these streams, incubation habitats (redds) were primarily composed of down welling surface waters with variable but minor mixing of upwelling groundwater. The result in incubation temperature were cold (<1 C) and surface water temperatures were accurate predictors of red temperatures. Both treatment streams displayed evidence of warming in the fall and spring of the 2 years beginning the year of initial harvesting. The increase was most pronounced in the stream without a riparian buffer strip. Clear-cut harvesting with and without a riparian buffer strip altered the thermal regime of surface water and the hyporheic zone in this northern temperate forest where, in addition to salmonid incubation, many biological processes take place. The potential for impacts on stream ecosystems is estimated to be high for the managed forest of the region. Future studies should strive to enhance our understanding of the hydrological connections between forests and streams on this landscape to determine the full effects of timber harvesting on the hydrology and biology of a watershed and its streams.

Riparian Stand and Harvest Conditions:

Sites: Four headwater streams originating from ponds/marshes.

Stand Conditions: Northern temperate forest dominated by balsam fir and black spruce.

Stream Conditions: Headwater streams that range from 2.5 to 5.0 m wide. Upstream areas are pond/march systems and therefore the boundary temperatures are elevated.

Harvest conditions: 19 ha were harvested in one stream without a buffer strip (Site T1-1). A harvest area of 33 ha with a 20 m buffer strip was applied to another stream. The 20m buffer strip was primarily on one side of the stream (Site T1-2). There was a control (no harvest) watershed.

Stream Length Logged: Not Provided

Time line: Five Years - 1993 through 1997. Harvest occurred November 1994 through January 1995, along with June and July 1996.

Summary of Results:

Harvest reaches were downstream of lakes and therefore stream temperatures entering the reach are elevated.

Because this study was focusing on affects to brook trout, the evaluation period was fall, winter, and spring. Summer period results were not presented.

Stream temperatures trends in the control (no harvest) basin paralleled air-temperature trends.

Compared to control reach, spring stream temperatures in 20m buffer increased by an average of 2.7 *C in the three years following treatment activities. Authors speculate the warming of stream water in the

20 m buffer stream suggests “the mechanism of temperature change was related to groundwater flow to the stream and not direct solar inputs, i.e., there was forest buffer zone to protect the stream from solar radiation.” That is, temperature increases are a result of elevated surface temperature associated with the clearcut zones warming up the groundwater which enters the stream.

The authors observed a temperature recover in the last year of the study, however it appeared that the spring period during this last year was an extremely cool period (i.e., the clearcut harvest treatment reach was cooler than pre-harvest temperature conditions.)

3.1 Stream Shade Modeling – Effects of Riparian Buffer Width, Density and Height

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DeWalle, David R., 2010. Modeling Stream Shade: Riparian Buffer Height and Density as Important as Buffer Width. ***Journal of the American Water Resources Association*** (JAWRA) 46(2):323-333.

Location: Modeled shade conditions (40^{o}N Latitude)

Abstract: A theoretical model was developed to explore impacts of varying buffer zone characteristics on shading of small streams using a path-length form of Beer's law to represent the transmission of direct beam solar radiation through vegetation. Impacts of varying buffer zone height, width, and radiation extinction coefficients (surrogate for buffer density) on shading were determined for E-W and N-S stream azimuths in infinitely long stream sections at 40°N on the summer solstice. Increases in buffer width produced little additional shading beyond buffer widths of 6-7 m for E-W streams due to shifts in solar beam pathway from the sides to the tops of the buffers. Buffers on the north bank of E-W streams produced 30% of daily shade, while the south-bank buffer produced 70% of total daily shade. For N-S streams an optimum buffer width was less-clearly defined, but a buffer width of about 18-20 m produced about 85-90% of total predicted shade. The model results supported past field studies showing buffer widths of 9-11 m were sufficient for stream temperature control. Regardless of stream azimuth, increases in buffer height and extinction coefficient (buffer density) were found to substantially increase shading up to the maximum tree height and stand density likely encountered in the field. Model results suggest that at least 80% shade on small streams up to 6-m wide can be achieved in mid-latitudes with relatively narrow 12-m wide buffers, regardless of stream azimuth, as long as buffers are tall (≈30 m) and dense (leaf area index ≈6). Although wide buffers may be preferred to provide other benefits, results suggest that increasing buffer widths beyond about 12 m will have a limited effect on stream shade at mid-latitudes and that greater emphasis should be placed on the creation of dense, tall buffers to maximize stream shading.

Riparian Stand and Harvest Conditions:

Sites: Sensitivity analysis of shade production for a theoretical stream at a 40^{o}N Latitude

Stand Conditions: 30 m tall trees (variable height for the tree height modeling)

Stream Conditions: 3 m wide BFW, which results a buffer height ⁄ stream width ratio = 10 (This was used in order to produce results where the majority of energy reaching the stream centerline was transmitted by vegetation.) Variable stream aspects were modeled.

Harvest conditions: The riparian buffer was modified to illustrate the effects of various buffer attributes and resulting shade conditions.

Stream Length Logged: None

Time line: One day – summer solstice

Summary of Results:

Although the magnitude and response and the shape of the relationship might be different from field measurements, the general principles still apply: 1) vegetation closer to the stream has a greater potential to provide shade (i.e., the tree behind tree principle), and that 2) there are different intrinsic potential for shade production for streams with different aspects, but these differences vary depending on the season.

Vegetation on the north bank buffer of an east-west aspect stream can produce up to 30% of the daily shade occurring on the stream surface.

Stream Shade and Buffer Density –

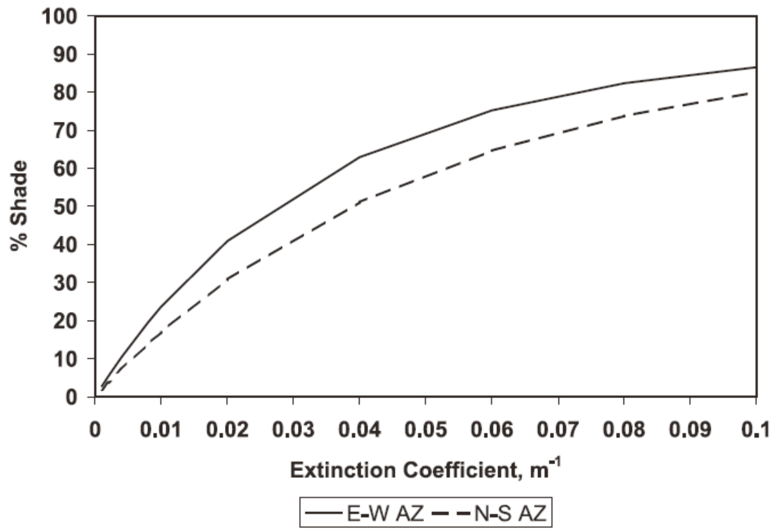


FIGURE 9. Effects of Increasing Radiation Extinction Coefficients (surrogate for buffer density) in Beer's Law (Equation 1) on Shading by Buffer Zones for Two Stream Azimuths at 40°N on the Summer Solstice. Conditions represent a small 3-m wide stream shaded by a 12-m wide and 30-m tall buffer.

The authors reported that model results suggest that buffer density is one of the most important controls on buffer shading. Relatively high shading was only achieved with the high buffer densities.

The author noted that Beer's law (used in the model in this study to estimate radiation transition through the vegetation) may underestimate total shading by buffers, as dense natural forests are known to produce >90% shading.

Stream Shade and Buffer Width –

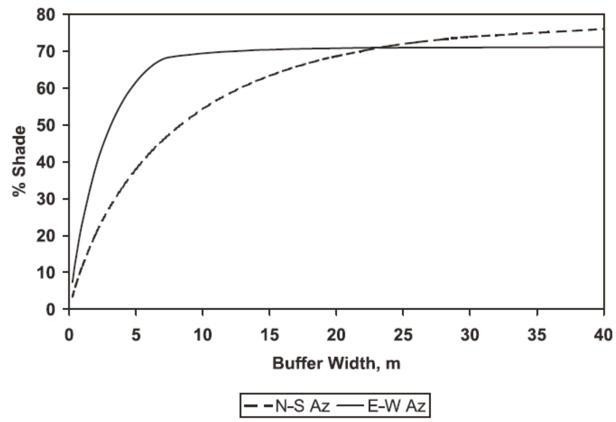
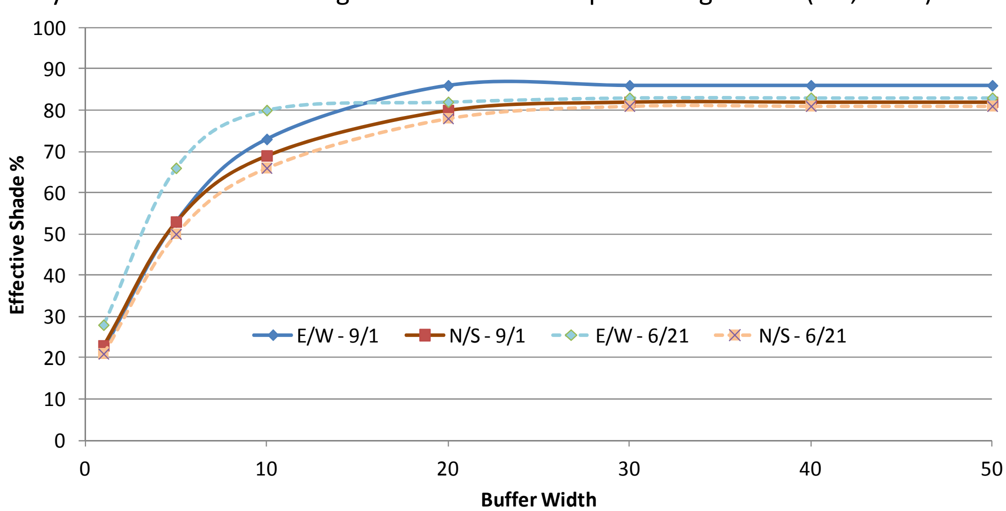
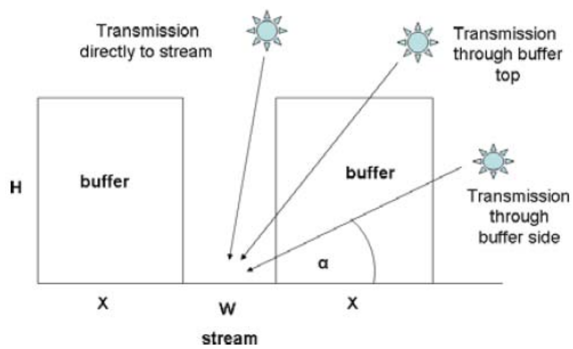


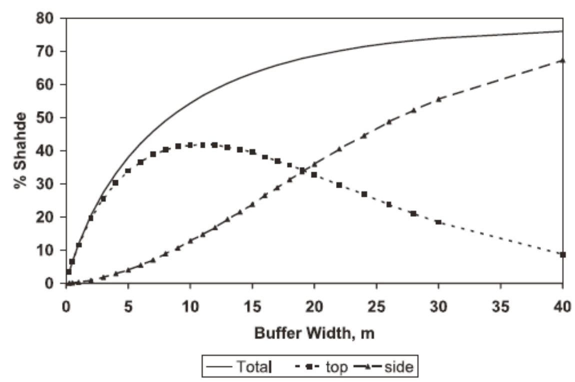
FIGURE 3. Effects of Increasing Buffer Width on Shading for Two Stream Azimuths at 40°N on the Summer Solstice. Shading with increasing buffer width indicated an optimum width of about 6-7 m for E-W azimuth stream, whereas an optimum width was less clearly defined for a N-S stream. Conditions represent a small 3-m wide stream shaded by 30-m tall vegetation with an average extinction coefficient of 0.05 m^{-1} in Equation (1).

Shading by vegetation along a N-S aspect stream gradually increased as buffer width was increased, with 88% of the total occurring in the first 18-20 meters of buffer. The "outer" buffer from 20 meters to 30 m was responsible for the remaining of the shade production (12%). Alternatively, shading by vegetation along an E-W aspect stream increased relatively rapidly for the model scenario used in his study. The author concluded that buffer widths of only about 6-7 m were needed to and further increases in buffer width up to about 30 m had little additional effect. It is important to point out that the modeling period was summer solstice. It is also important to point out that the distance associated shade production in an E-W stream becomes similar to a N-S stream as the sun is located lower in the sky during the later summer period (see image below). (Shade values in the image below were calculated using the Washington Ecology shade model - www.ecy.wa.gov/programs/eap/models.html, using 30m tall trees, canopy density of 85%, and BFW of 3.0m). In both scenarios, buffers wider than 30 meters resulted in very little change in stream shade conditions and are directly related with shade length of the modeled riparian vegetation (i.e., 30 m).



For N-S aspect streams, shading is primarily associated with the top of the vegetation (i.e., shadow length) at narrower buffer widths (< 10 meters). Beyond a 10m buffer width, sunlight traveling through the side of the buffer increases in importance towards shade production. When sunlight travels through the side of the buffer, the density of the buffer become important toward shade production. At around an 18 m buffer width, shade associate with side part of the buffer becomes the dominant shade producing feature.





Overall for E-W streams, the north-bank buffer accounted for 30% of the total shading, and south-bank buffer accounted for the remaining 70%. Shading patterns were similar to trends just described, however the transition between a top dominated vs. side dominated shading system was around an 8 m buffer width. Once again these scenarios are for the summer solstice and results would be expected to different in later summer periods.

Stream Shade and Buffer Height -

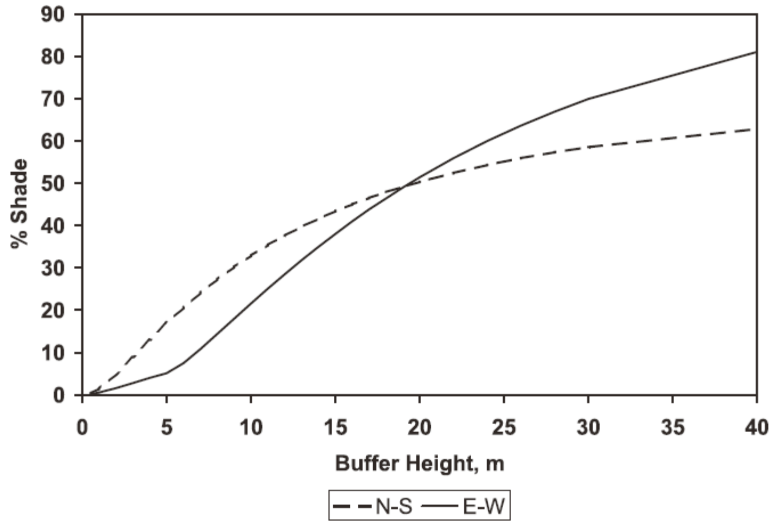


FIGURE 6. Effects of Increasing Buffer Height on Shading for Two Stream Azimuths at 40°N on the Summer Solstice. Shading increased rapidly up to heights of 30-40 m regardless of stream azimuth. Conditions represent a small 3-m wide stream shaded by a 12-m wide buffer with an average extinction coefficient of 0.05 m^{-1} in Equation (1).

Stream shading increased rapidly with increased buffer height regardless of stream azimuth. In contrast to shading due to buffer width changes, increased buffer height for N-S streams gradually increases shading along solar tracks through the tops of buffers and becomes dominant after a height of about 19 m. A similar trend was observed for an E-W stream except the transition from side dominated to top dominated occurred at around 6 meters.

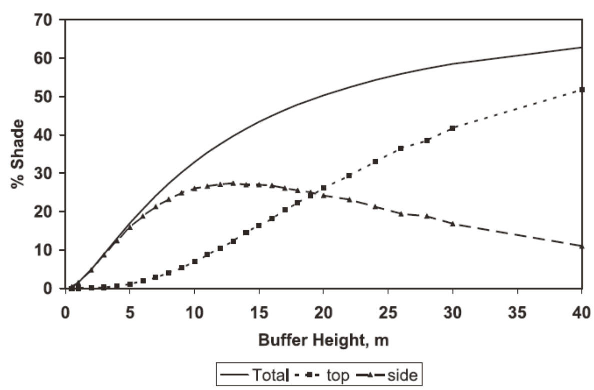


FIGURE 7. Shading Along Solar Tracks Through the Sides and Tops of Riparian Buffers on Both Banks of a N-S Azimuth Stream as Buffer Height Increased. In contrast to trends shown in Figure 3 for buffer width changes, importance of shading along solar tracks through the top of buffers gradually dominated and shading for tracks through buffer sides gradually diminished as buffer height increased. Conditions are otherwise similar to those represented in Figure 6.

3.2 Stream Shade Modeling – Potential Shadow Length Associated with Riparian Vegetation

Leinenbach, P, 2011. Technical analysis associated with this project to assess the potential shadow length associated with Riparian vegetation

Location: Modeled shadow length of riparian vegetation (45.7^{o}N Latitude)
Abstract (Synopsis): Results indicate that a tree located on a flat hillslope along the stream **within a distance of its height** can be influential on shade production (i.e., the shadow length associated with the tree is long enough to reach the stream), and ultimately on stream temperature during the summer period (July/August). However, there are commonly occurring situations which trees outside of this distance can contribute to shade production (For example, a 100 foot tall tree located on a hillslope of 20 degrees can cast a 169 foot long shadow at 4 PM during the late summer.).

Riparian Stand and Harvest Conditions:

Sites: Sensitivity analysis of shadow length associated with vegetation at a 45.7^{o}N Latitude

Stand Conditions: Variable tree height

Stream Conditions: Not Relevant (Only determining shadow length)

Harvest conditions: Not Relevant (Only determining shadow length)

Stream Length Logged: None
Time line: Estimates during the spring, summer, and fall period.

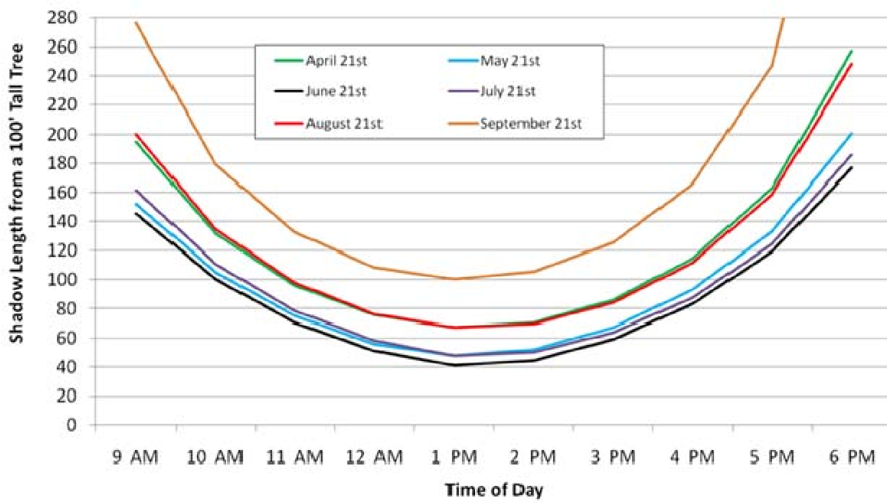
Summary of Results:

The distance of a shadow cast by a tree can be estimated by the following trigonometric equation[1]:

$$Shadow\ Length = \frac{Tree\ Height * \cos(Hillslope\ Angle)}{\tan(Sun\ Angle - Hillslope\ Angle)} - Tree\ Height * \sin(Hillslope\ Angle)$$

Solving this equation provides insight into the distance from a stream a tree could potentially provide stream shade. The tree will not have any effect of stream shade production when it is located further away from the stream than the calculated shadow length. The figure below shows that the shadow distance associated with a 100' tall tree varies throughout the course of the day, along with the season[2]. The shadow distance increases as the sun is lower in the sky during the mid morning (9 am to 11 am) and mid afternoon (2 pm to 4 pm) periods. The figure also indicates that shadow lengths are longer during late spring and late summer, than during the summer equinox.

[1] See Attachment A below for the derivation of this equation.
[2] The "Altitude of the Sun" reference location associated with analysis was within the Tillamook Forest and the model used to determine the "Altitude of the Sun" (i.e., SolRad) was obtained from Washington Ecology's TMDL model webpage - http://www.ecy.wa.gov/programs/eap/models.html



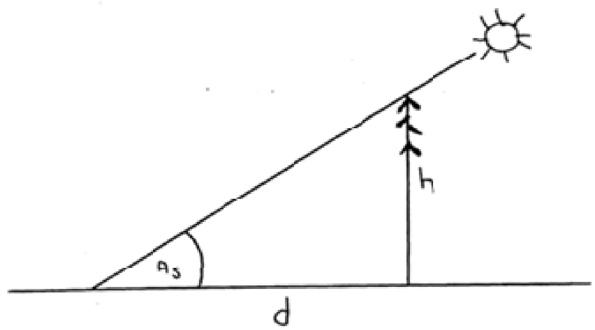
Stream temperatures are often at a maximum during the July to August period and therefore stream shade is particularly important at this time[3]. The table below presents the average shade length associated with riparian vegetation during these summer months. On a flat stream bank, the shadow length can equal the height of the tree in the afternoon, when stream temperatures are often at their daily maximum and potential solar heat loading is still high (i.e., 4 pm conditions). The table below also shows that the shadow length increases for vegetation located on sloped stream banks.

Average July 21st and August 21st shadow length (feet) associated various tree height conditions.										
Height of Tree	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm
Flat Hillslope										
20	36	25	18	13	11	12	15	20	28	43
40	72	49	35	27	23	24	30	40	57	87
60	108	74	53	40	34	36	44	60	85	130
80	145	98	71	54	46	48	59	80	113	174
100	181	123	88	67	57	60	74	100	142	217
120	217	147	106	81	69	72	89	120	170	260
140	253	172	124	94	80	84	104	140	198	304
20 Degree Hillslope										
20	120	48	28	19	16	16	22	34	64	334
40	240	96	56	38	31	33	44	68	129	668
60	360	143	84	57	47	49	65	101	193	1002
80	480	191	112	76	62	66	87	135	257	1336
100	599	239	140	95	78	82	109	169	321	1669
120	719	287	167	115	94	99	131	203	386	2003
140	839	335	195	134	109	115	152	237	450	2337

[3] July and August (and sometimes September) conditions are often associated with low stream flows, long days, and warm air temperatures, which can result in high stream temperatures. Therefore, rivers/streams often have lower assimilative capacity for the addition of heat loads.

Attachment A – Estimating Shadow Distances

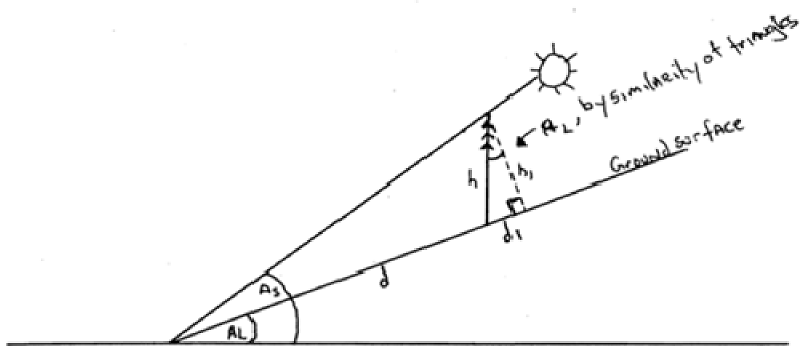
Case 1: Ground has Zero Slope



A_S = sun angle, h = tree height, and d = shadow distance

$$\tan(A_S) = \frac{h}{d} \Rightarrow d = \frac{h}{\tan{(A_S)}}$$

Case 2: Ground is sloped, with a slope angle = A_L and assume that the tree grows vertically



A_S = sun angle above the horizon, not the ground surface, h_1 = height of the line drawn from the tree tip, perpendicular to the ground, and d_1 = distance from interception of that line with the ground, to the base of the tree.

Using the same argument as in Case 1,

$$\tan(A_S - A_L) = \frac{h_1}{(d_1 + d)}$$

Solve this for d, the shadow distance:

$$d = \frac{h}{\tan\,(A_S - A_L)} - d_1$$

Since,

$$h_1 = h * \cos(A_L)\; and\; d_1 = h * \sin(A_L)$$

Thus,

$$d = \frac{h * \cos(A_L)}{\tan(A_S - A_L)} - h * \sin(A_L)$$

In other words,

$$Shadow\ Length = \frac{Tree\ Height * \cos(Hillslope\ Angle)}{\tan(Sun\ Angle - Hillslope\ Angle)} - Tree\ Height * \sin(Hillslope\ Angle)$$

Note: When A_L = 0 (flat ground), this equation reduces to Case 1, because sin(0) = 0, and cos(0) = 1

3.3 Stream Shade and Temperature Modeling - Variable Buffer Widths/Thinnings and Water Quality

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Science Team Review. 2008. Western Oregon Plan Revision Draft Environmental Impact Statement – Science Team Review. http://www.blm.gov/or/plans/wopr/files/Science_Team_Review_DEIS.pdf

Location: Water quality modeling of Canton Creek, North Umpqua Basin, Western Oregon

Abstract (Synopsis):

The ODEQ evaluated the Western Oregon Plan Revision (WOPR) Alternatives using the mathematical model Heat Source Version 7.0. Heat Source simulates open channel hydraulics, flow routing, heat transfer, effective shade, and stream temperatures. Modeling was performed for a stream segment roughly 18 km in length. Modeling simulated base conditions were verified with empirical data sets for surface and instream temperature. Alternatives varied vegetation only.

This simulation suggested that for this reference stream segment (i.e., Canton Creek): (1) Current (baseline) conditions are 1-2° C above "natural thermal potential" conditions; (2) A 46 m (150 ft) no-touch buffer width produced only very small changes in stream temperature; (3) A 31 m (100 ft) no-touch buffer width produced changes in stream temperature in excess of 0.5° C; (4) and a 31 m (100 ft) variable retention buffer (i.e., 18 m (60 ft) no-touch buffer, with a 12 m (40 ft) 50% canopy cover outside of the "no-touch" zone) produced changes in stream temperature in excess of 0.6° C. Stream temperatures are expressed as the maximum change in the seven day average of the maximum daily temperature during the modeling period (July 12^{th} through July 31^{st}).
Shade and temperature response to buffer width changes was site was highly variable along the stream reach.

Riparian Stand and Harvest Conditions:

Sites: Canton Creek, North Umpqua Basin, Western Oregon

Stand Conditions: "System Potential Vegetation" which represented riparian vegetation at a mature state. The authors acknowledged that natural disturbance would reduce system potential vegetation and that it is not possible for an entire stream to be at its maximum potential everywhere, all the time. In this analysis system potential vegetation was disturbed by modeling a 50 year interval historical disturbance regime. The severity of disturbance ranged from low to very high. Pre-thinning canopy associated with large conifers is 80%.

Stream Conditions: 3^{rd} order stream

Harvest conditions: A 46 m (150 ft) no-touch buffer width, a 31 m (100 ft) no-touch buffer width, and a 31 m (100 ft) variable retention buffer (i.e., 18 m (60 ft) no-touch buffer, with a 12 m (40 ft) 50% canopy cover outside of this zone).

Stream Length Logged: BLM administered land along the riparian zone of Canton Creek (Approximately 5 kilometers)

Time line: Simulation for July 12-31.

Summary of Results:

The 46 m (150 ft) no-touch buffer width produced only very small changes in stream shade and temperature.

Figure 8. Temperature increase due to harvest on all BLM administered land managed according to Alternative 1.

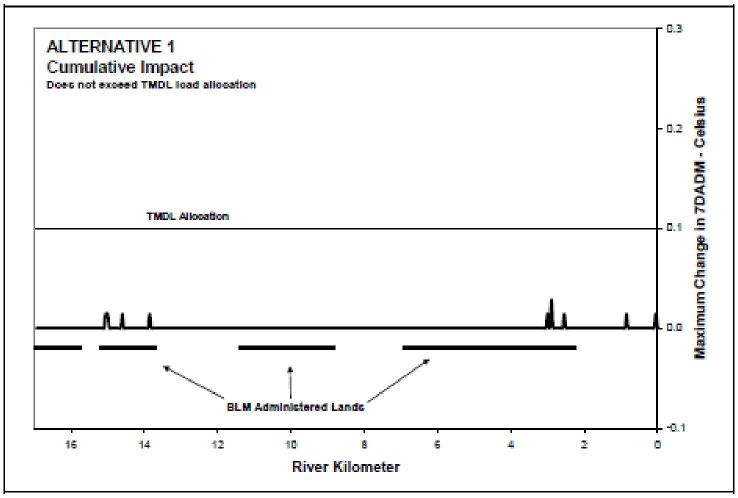
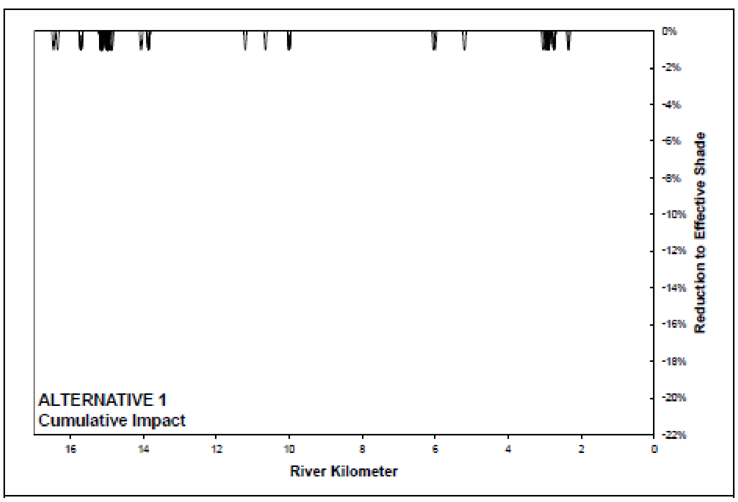


Figure 9 Reduction to effective shade due to harvest on all BLM administered land managed according to Alternative 1.



The 31 m (100 ft) no-touch buffer had shade reductions of over 10 units at several locations, while other areas had only minimum reductions (i.e. 1 unit of percent shade). There were many more areas with only 1 unit of shade reduction than as observed for the 46 m no-touch buffer.

The 31 m no-touch buffer produced changes in stream temperature in excess of 0.5° C, expressed as the maximum change in the seven day average of the maximum daily temperature during the modeling period (July 12th through July 31st). In addition, temperature increases of over 0.2 C were observed at several other locations.

Figure 14 Temperature increase due to harvest on all BLM administered land and managed with 100 ft buffers.

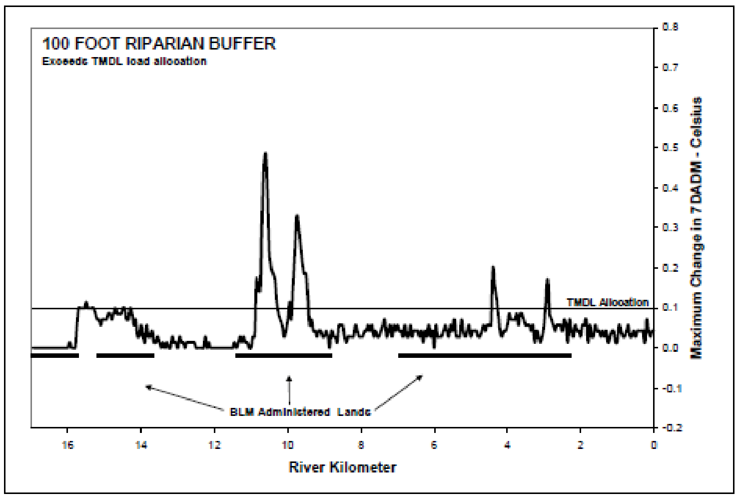
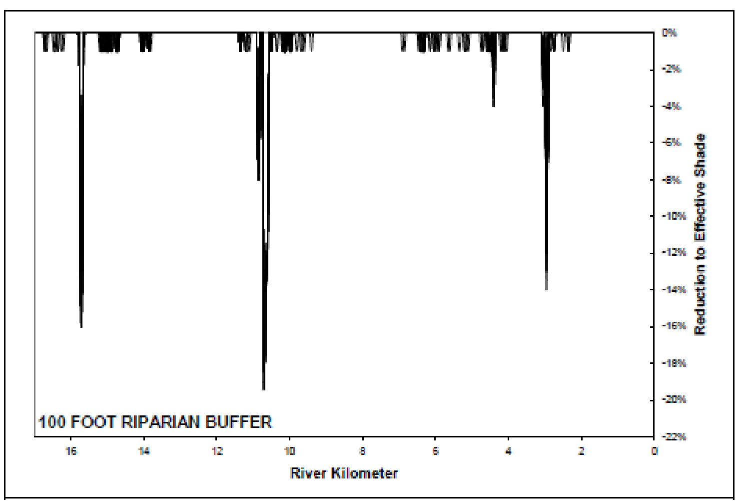


Figure 15 Change to effective shade due to harvest on all BLM administered land



The 31 m (100 ft) variable retention buffer (i.e., 18 m (60 ft) no-touch buffer, with a 13 m (40 ft) 50% canopy cover outside of the “no-touch” zone) had shade reduction of over 12 at several locations along the river, with two regions of the river approaching a reduction of 20 units of shade There were many more areas with only 1 unit of shade reduction than as observed for the 46 m and 31 m no-touch buffers.

A 31 m variable retention buffer produced changes in stream temperature in excess of 0.6° C, expressed as the maximum change in the seven day average of the maximum daily temperature during the modeling period (July 12th through July 31st). In addition, temperature increases of over 0.2 C were observed at several other locations.

Figure 12 Temperature increase due to harvest on all BLM administered land managed according to Alternative 2

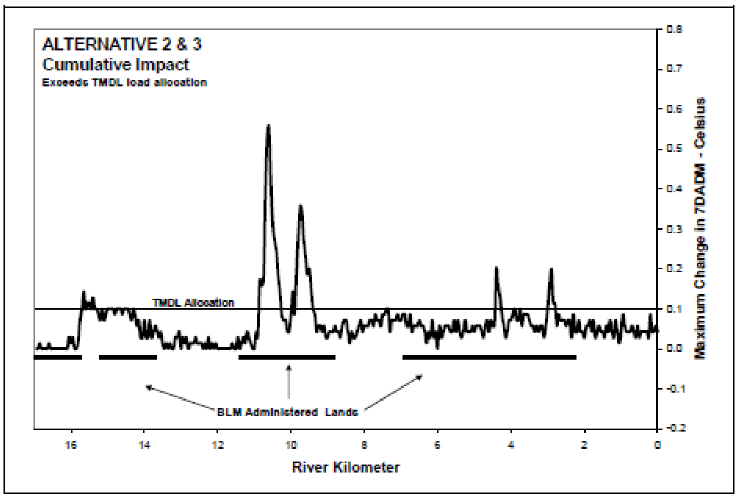
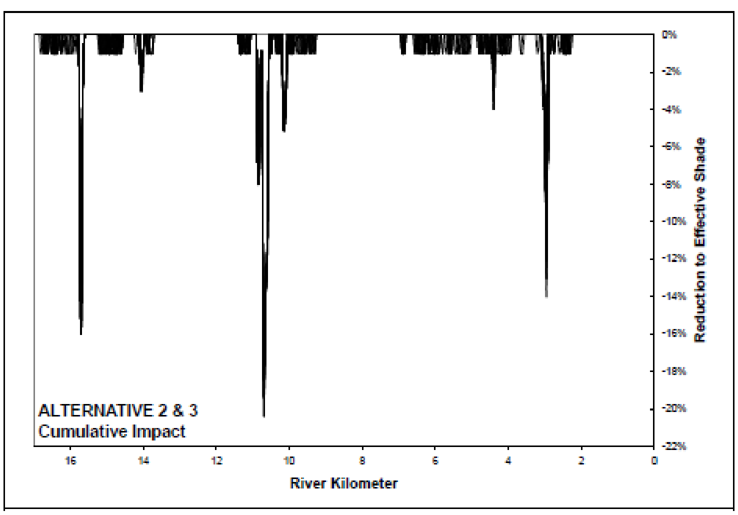


Figure 13. Reduction to effective shade due to harvest on all BLM administered land managed according to Alternative 2.



3.4 Stream Shade and Temperature Modeling - Variable Buffer Widths/Thinnings and Water Quality

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Oregon Department of Environmental Quality Memorandum. 2008. Modeling result reporting document – Evaluation WOPR FEIS Riparian Area Land Use Allocation. Obtained from Ryan Mitchie at ODEQ.

Location: Water quality modeling of Canton Creek, North Umpqua Basin, Western Oregon

Abstract (Synopsis):

The ODEQ evaluated the Western Oregon Plan Revision (WOPR) Alternatives using the mathematical model Heat Source Version 7.0. Heat Source simulates open channel hydraulics, flow routing, heat transfer, effective shade, and stream temperatures. Modeling was performed for a stream segment roughly 18 km in length. Modeling simulated base conditions were verified with empirical data sets for surface and instream temperature. Alternatives varied vegetation only.

This simulation suggested that for this reference stream segment (i.e., Canton Creek): (a) A 46 m (150 ft) variable retention buffer (i.e., 18 m (60 ft) no-touch buffer, with a 28 m (90 ft) 50% canopy cover outside of the "no-touch" zone) produced changes in stream temperature approaching 0.2° C. Stream temperatures are expressed as the maximum change in the seven day average of the maximum daily temperature during the modeling period (July 12th through July 31st).
Shade and temperature response to buffer width changes was site was highly variable along the stream reach.

Riparian Stand and Harvest Conditions:

Sites: Canton Creek, North Umpqua Basin, Western Oregon

Stand Conditions: "System Potential Vegetation" which represented riparian vegetation at a mature state. The authors acknowledged that natural disturbance would reduce system potential vegetation and that it is not possible for an entire stream to be at its maximum potential everywhere, all the time. In this analysis system potential vegetation was disturbed by modeling a 50 year interval historical disturbance regime. The severity of disturbance ranged from low to very high. Pre-thinning canopy associated with large conifers is 80%.

Stream Conditions: 3rd order stream

Harvest conditions: A 46 m (150 ft) variable retention buffer (i.e., 18 m (60 ft) no-touch buffer, with a 28 m (90 ft) 50% canopy cover outside of the "no-touch" zone).

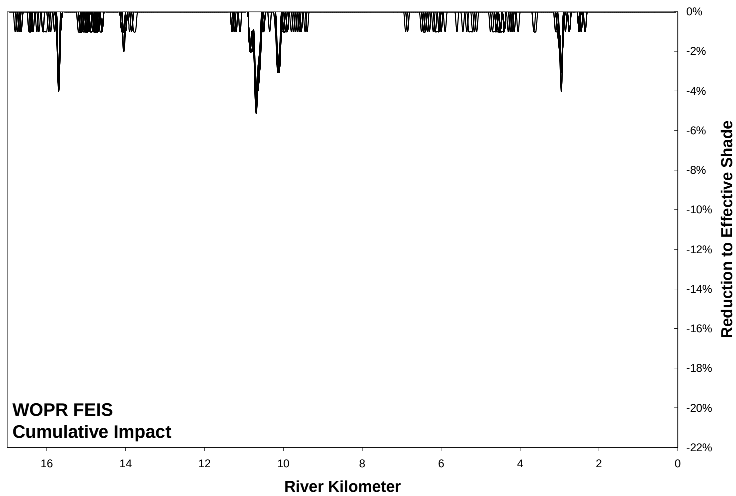
Stream Length Logged: BLM administered land along the riparian zone of Canton Creek (Approximately 5 kilometers)

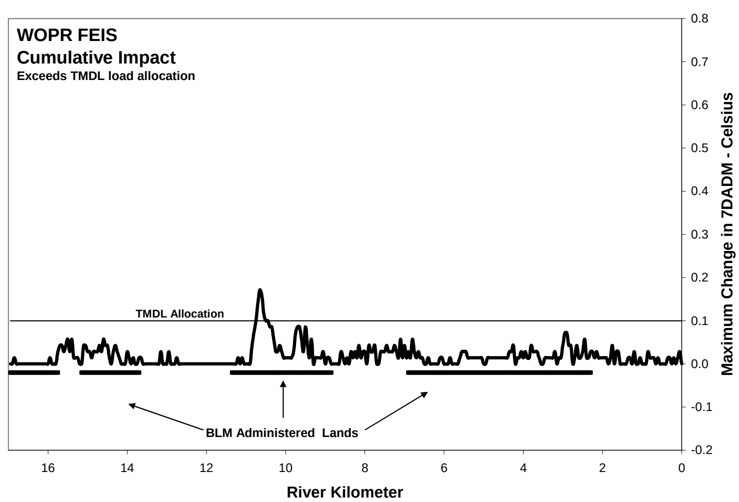
Time line: Simulation for July 12-31.

Summary of Results:

The 46 m (150 ft) variable retention buffer (i.e., 18 m (60 ft) no-touch buffer, with a 28 m (90 ft) 50% canopy cover outside of the “no-touch” zone) had shade reductions of around 4 units at several locations along the river. There were many more areas with only 1 unit of shade reduction than observed for the 46 m “no-touch” buffer.

The 46 m variable retention buffer produced changes in stream temperature approaching 0.2° C, expressed as the maximum change in the seven day average of the maximum daily temperature during the modeling period (July 12th through July 31st).





3.5 Stream Shade and Temperature Modeling - Variable Buffer Widths and Water Quality

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Cristea N., and J. Janisch. 2007. Modeling the Effects of Riparian Buffer Width on Effective Shade and Stream Temperature. *Washington Department of Ecology* Publication No. 07-03-028:1–64.

Location: Water quality modeling for streams in Western Washington

Abstract: To evaluate the effects of converting riparian hardwood-dominated stands to coniferous-dominated stands on western Washington stream temperatures, we combined a shade model and water quality model to explore the stream heating potentials of three buffer-width scenarios. Changing one variable at a time, we then ran a series of model simulations for various buffer-width (30-75 feet) and harvest-length (500-1500 feet) scenarios. Results of each simulation were expressed as the change in maximum daily temperature relative to the unharvested state (i.e., upstream boundary condition).

When a 500-foot harvest unit and 50-foot buffer were then applied to our model channel, the downstream temperature of the 10-foot-wide stream increased 0.13°C relative to the upstream state. Temperature continued to rise as harvest-unit length increased, with the 1500-feet-long unit showing the most change (+0.36°C, or approximately +0.12°C per 500 feet of harvest length). Wider buffers (75 feet), in contrast, continued to dampen temperature increases for the 10-foot stream, even at a harvest-unit length of 1500 feet. Results for the 20-foot-wide stream showed a similar pattern, but temperature increases in response to harvest-unit length were higher: 0.15°C (500 feet) – 0.60°C (1500 feet), or about 0.18°C per 500 feet of harvest length. Temperature of the 10-foot-wide stream was more sensitive to buffer width than the 20-foot-wide stream. In contrast, all buffer scenarios cooled the 20-foot-wide stream less effectively, with predicted downstream temperatures converging somewhat when harvest-unit length reached 1000 feet. Inferences vary depending on the shade curve used.
Overall, results indicated that, for the stream scenarios analyzed, riparian vegetation and harvest-unit length exerted greatest control on stream temperature at lower flow rates. Conditions favoring high daily maximum stream temperatures include: shallow and wide streams, north-south channel orientation, low groundwater influx or hyporheic exchange with the channel, and low gradient.

Riparian Stand and Harvest Conditions:

Sites: Modeled streams which were designed to represent streams in western Washington (46.65° Latitude).

Stand Conditions: Represent baseline stand condition for red alder (50 ft tall). Assumed uniformed canopy closure in buffer, and a uniformed buffer width.

Stream Conditions: Variable stream widths (10 ft and 20 ft), and stream aspects (zero, 45 and 90).

Harvest conditions: Variable "no-touch" buffer widths were tested (i.e., 30ft, 50 ft, and 75 ft) with a vegetation height of 50 feet tall (represents baseline stand condition for red alder). Harvest unit on only one side of the stream. Angular canopy density for each buffer width condition was estimated using two models (Brazier and Brown, 1973; Steinblums et al., 1984), which was used as an estimate of canopy cover condition in the "Shade.xls" model. Shade conditions associated with the various channel width and buffer combinations were modeled for temperature response using QUAL2Kw.

Buffer Width (feet)	Angular Canopy Density (%)	
	Brazier and Brown, 1973	Steinblums et al., 1984
30	55	30
50	70	45
75	75	60

Stream Length Logged: Fiver Lengths – 500 ft, 750 ft, 1000 ft, 1250 ft, and 1500 ft
Time line: Modeled August 1st

Summary of Results:

Effective Shade – The effect of riparian density has a very dramatic effect on stream shade conditions for both 10- and 20 foot wide streams. N-S aspect stream channels have the lowest shade conditions during mid day which is associated with maximum air temperatures and solar loading is near the daily peak values. E-W aspect streams may experience a "double sunrise and sunset": One daily maximum solar loading in the early morning; and the other maximum solar loading in the late afternoon.

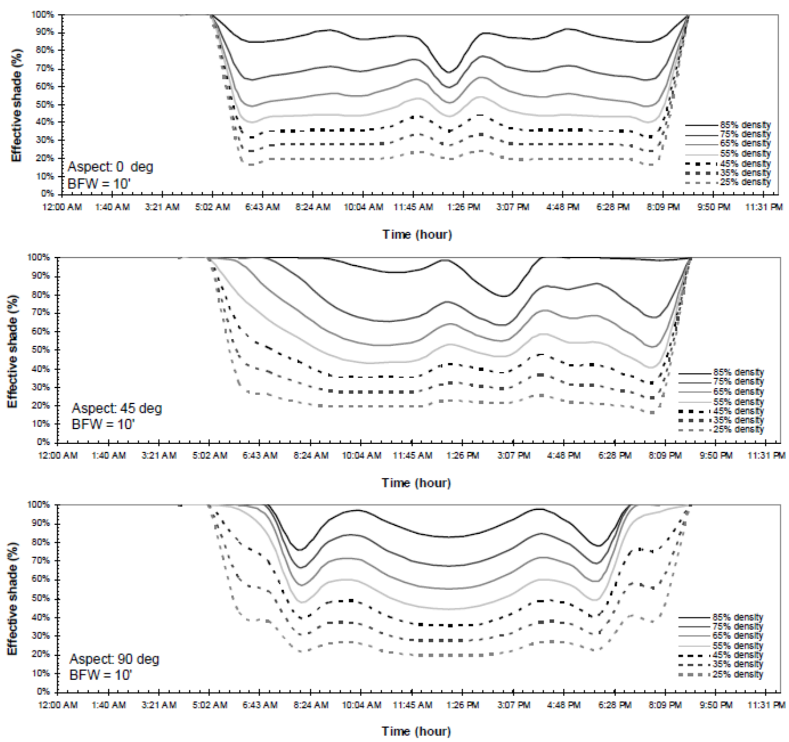


Figure 7. Daily effective shade for three channel orientations provided by a 120-foot buffer of canopy cover varying from 25% to 85%. Channel width is 10 feet.

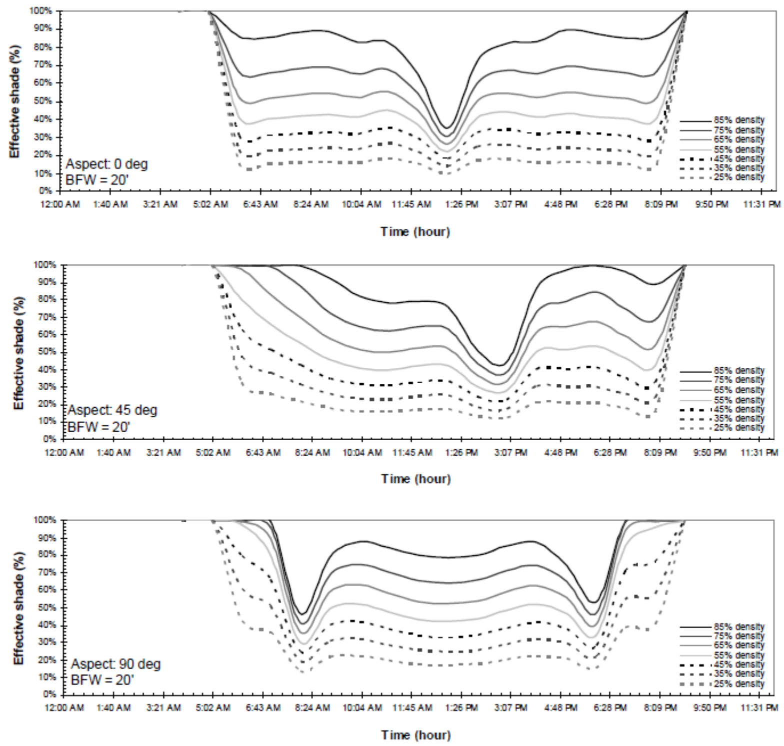


Figure 8. Daily effective shade for three channel orientations provided by a 120-foot buffer of canopy cover varying from 25% to 85%. Channel width is 20 feet.

<u>Stream Temperature</u> –

The baseline vegetation conditions used in the temperature modeling scenarios was a 50’ tall tree. The canopy cover associated with the modeling was calculated using two different canopy cover models (Brazier and Brown (1973) and Steinblums et al. (1984)). There were two channel widths in the analysis. Effective shade conditions were calculated for each of these scenarios, and was an input parameter into the temperature model (Qual2kw).

Channel Width (feet)	Riparian Buffer Differences	Brazier and Brown (1973) Canopy Cover (CC) Model		Steinblums et al. (1984) Canopy Cover (CC) Model	
		Shade Change	Temperature Change (A 1500’ long channel)	Shade Change	Temperature Change (A 1500’ long channel)
10	23m to 15 m	4	0.11 C	8	0.17 C
	23m to 9 m	12	0.27 C	16	0.33 C
20	23m to 15 m	5	0.01 C	10	0.04 C
	23m to 9 m	16	0.05 C	18	0.21 C

Canopy density was shown to be more influential on **stream temperature** response in the narrow 10 ft channel, than it was observed for the wider channels (20 ft).

For a 10 foot wide stream channel, stream temperatures in creased between 0.11 and 0.17 C as the riparian buffer width was reduced from 23 m to 15 m for a 472 m channel length. The corresponding change in shade conditions was 4 to 8 units of shade reduction, respectively. As riparian buffers width was reduced from 23 m to 9 m for a 472 m channel length, stream temperatures increase from 0.27 to 0.33 C. The corresponding change in shade conditions was 12 to 16 units of shade reduction, respectively.

Temperature results associated with the 20ft channel indicate that the "shadow length" from the 50' tall vegetation was not sufficient to cast a proper shadow across the stream leading to very low shade conditions (see image below). Accordingly, despite greater shade conditions associated with the wider riparian buffers, the temperature response was muted in the 20ft stream channel. In other words, shade levels for the 20ft stream are low for all buffer width conditions and therefore stream temperature increases are high for all scenarios.

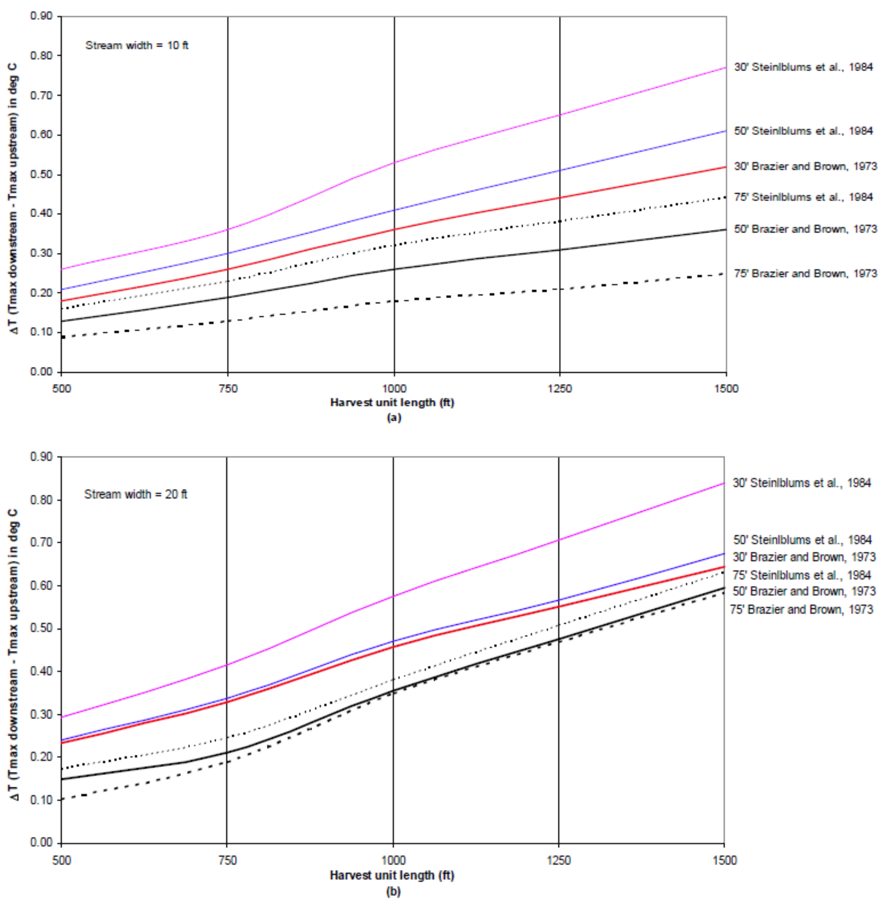


Figure 11. Stream temperature response in the (a) 10-foot-wide and (b) 20-foot-wide streams for different buffer widths and shading curves.

Chan S., P. Anderson, J. Cissel, L. Larson, and C. Thompson. 2004a. Variable density management in Riparian Reserves: lessons learned from an operational study in managed forests of western Oregon, USA. ***For. Snow Landsc. Res*** 78(1/2):151-172.

Location: Western Oregon

Abstract:

A large-scale operational study has been undertaken to investigate variable density management in conjunction with riparian buffers as a means to accelerate development of late-seral habitat, facilitate rare species management, and maintain riparian functions in 40–70 year-old headwater forests in western Oregon, USA. Upland variable retention treatments include matrices of four thinning intensities embedded with patch openings and leave islands. Additionally, four types of streamside buffer delineation are being examined. The study includes 13 sites, each averaging about 100 hectares. Metrics of stand structure and development, microclimate, aquatic ecology, invertebrate populations and biology, lichens, and bryophytes, are being evaluated with respect to overstory thinning, patch openings and riparian buffer treatments. Results of this study can contribute to a development of riparian buffer delineations based on ecological functions and linkages to upland forest conditions.

Early findings suggest that the near-stream riparian environment provides critical functions and habitat for diverse populations of organisms. Using large, operational experimental plots we are able to demonstrate statistically significant initial responses to a complex suite of treatments for selected vegetation and environment parameters. It remains to be determined if the experimental design will be robust for long-term temporal trends in vegetation and microclimate, or synthesis with companion studies focusing on invertebrates or aquatic-dependent fauna. Meaningful interdisciplinary inferences are more likely achieved if integration is explicitly incorporated into study design and implementation, rather than post-study component synthesis. Conducting a large-scale interdisciplinary study with adaptive management implications requires a strong commitment to collaboration between management and research partners.

Riparian Stand and Harvest Conditions:

Sites: The DMS includes 12 sites dispersed among BLM lands in both the Coast Range and the west-side of the Cascade Mountains in western Oregon. On seven sites, the prescribed thinning treatments were first entries to the regenerating stands. Thinning treatments were applied to an additional five sites that had been previously thinned.

Stand Conditions: Characteristics of 40-to70 year old forests on BLM lands throughout western Oregon.

Stream Conditions: Not specifically presented but assume similar to Anderson et al (2007) description - First and 2nd order streams and active channel ranged from 0.2 to 3.7 m (averaged 1.1 m). Nearly 70% of the streams were summer intermittent.

Harvest conditions: The Density Management Study (DMS) consists of four thinning treatments, each applied to 20 ha or larger treatment units within 80 ha or larger sites. The thinning treatments include: 1) Unthinned control – 500 to 750 trees per ha (tph) greater than 12.7 cm dbh. 2) High density retention – 70 to 75% of area thinned to 300 tph, 25 to 30% unthinned Riparian Reserves or leave islands. 3)

Moderate density retention – 60 to 65% thinned to 200 tph, 25 to 30% unthinned Riparian Reserves or leave islands, 10% circular patch openings. 4) Variable density retention – 10% thinned to 100 tph, 25 to 30% thinned to 200 tph, 25 to 30% thinned to 300 tph, 20 to 30% unthinned Riparian Reserves or leave islands, 10% circular patch openings.

Stream Length Logged: Not specifically presented but assume similar to Anderson et al (2007) description - Variable – results summarized from 40 transects and results for each transect was a discrete value (i.e., there was no cumulative effect).
Time line: None presented

Summary of Results:

This is an initial document associate with the Density Management Study describing the first year of data.

Thinning to 200 tph decreased stand density by up to 70%, but only increased available light from 13–19% in the unthinned buffer to about 29% in the thinned buffer. The increase in light (~10% absolute increase) associated with heavy thinning to 200 tph is small relative to the number of trees removed. Light values derived from the hemispherical canopy images indicate that upland thinning to 200 tph increases available light within the first 20 m of the adjacent riparian buffer. Thus, thinning may result in some significant (but potentially transitory) changes in stand light and microclimate conditions.

Chan S., D. Larson, and P. Anderson. 2004b. Microclimate Pattern Associated with Density Management and Riparian Buffers – An Interim Report on the Riparian Buffer Component of the Density Management Studies.

Location: Western Oregon

Abstract:

Riparian Stand and Harvest Conditions: (assumed similar to that of Chan et al 2004b)

Sites: The DMS includes 12 sites dispersed among BLM lands in both the Coast Range and the west-side of the Cascade Mountains in western Oregon. On seven sites, the prescribed thinning treatments were first entries to the regenerating stands. Thinning treatments were applied to an additional five sites that had been previously thinned.

Stand Conditions: Characteristics of 40-to70 year old forests on BLM lands throughout western Oregon.

Stream Conditions: Not specifically presented but assume similar to Anderson et al (2007) description - First and 2nd order streams and active channel ranged from 0.2 to 3.7 m (averaged 1.1 m). Nearly 70% of the streams were summer intermittent.

Harvest conditions: The Density Management Study (DMS) consists of four thinning treatments, each applied to 20 ha or larger treatment units within 80 ha or larger sites. The thinning treatments include (Fig. 3): 1) Unthinned control – 500 to 750 trees per ha (tph) greater than 12.7 cm dbh. 2) High density retention – 70 to 75% of area thinned to 300 tph, 25 to 30% unthinned Riparian Reserves or leave islands. 3) Moderate density retention – 60 to 65% thinned to 200 tph, 25 to 30% unthinned Riparian Reserves or leave islands, 10% circular patch openings. 4) Variable density retention – 10% thinned to 100 tph, 25 to 30% thinned to 200 tph, 25 to 30% thinned to 300 tph, 20 to 30% unthinned Riparian Reserves or leave islands, 10% circular patch openings.

Stream Length Logged: Not specifically presented but assume similar to Anderson et al (2007) description - Variable – results summarized from 40 transects and results for each transect was a discrete value (i.e., there was no cumulative effect).

Time line: None presented

Summary of Results:

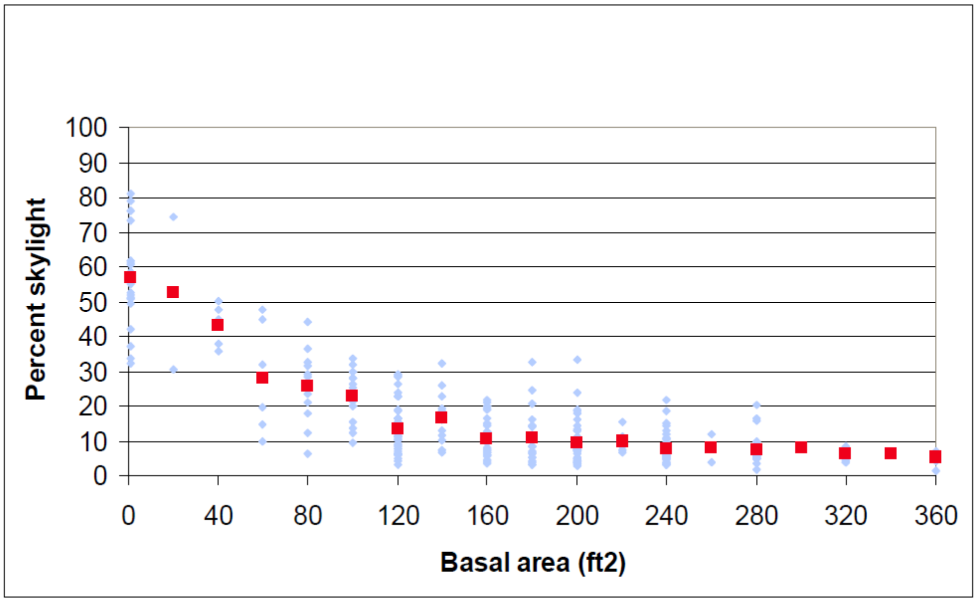


Figure 7a. Basal area and corresponding percent skylight derived from 6 Density Management Study sites during summer conditions. Scatter points represent individual plot values while squares represent means.

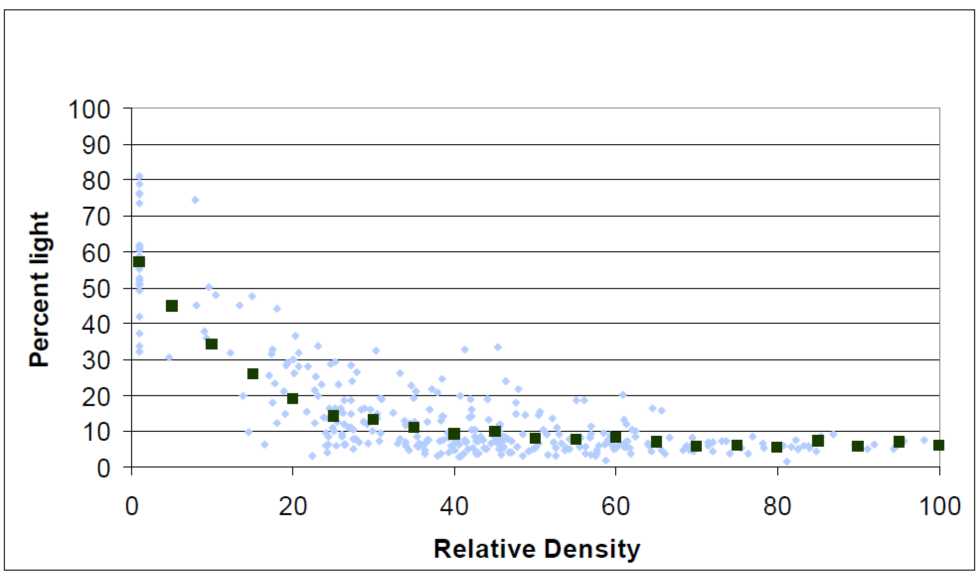


Figure 7b. Percent skylight in relation to Curtis' Relative Density. Derived from six Density Management Study sites during summer conditions. Scatter points represent individual plot values while squares represent means.

Commercial thinning substantially increased understory light when stand density was decreased to a basal area (BA) less than 120 ft^2/ac, or in other terms, below a relative density (RD) of 30. At BA ≥ 160 ft^2/ac, and RD ≥40, light levels average about 10% of open conditions, similar to those of unthinned stands. The corresponding BA of 120 and 160 ft^2/ac, in units of m^2/ha, is 28 and 37, respectively.

Anderson P. D., D. J. Larson, and S.S Chan. 2007. Riparian Buffer and Density Management Influences on Microclimate of Young Headwater Forests of Western Oregon ***Forest Science*** 53(2):254-269.

Location: Western Oregon

Abstract: Thinning of 30- to 70-year-old Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands is a common silvicultural activity on federal forest lands of the Pacific Northwest, United States. Empirical relationships among riparian functions, silvicultural treatments, and different riparian buffer widths are not well documented for small headwater streams. We investigated buffer width and density management effects on riparian microclimates of headwater streams in western Oregon. Spatial variations in stand density, canopy cover, and microclimate were measured along transects extending from stream center upslope into thinned stands, patch openings, or unthinned stands, with riparian buffers ranging from <5 m up to 150 m width. For treated stands, summer mean daily air and soil temperature maxima increased, and mean daily humidity minima decreased with distance from stream. Microclimate gradients were strongest within 10 m of stream center, a distinct area of stream influence within broader riparian areas. Thinning resulted in subtle changes in microclimate as mean air temperature maxima were 1 to 4°C higher than in unthinned stands. With buffers 15 m or greater width, daily maximum air temperature above stream center was less than 1°C greater, and daily minimum relative humidity was less than 5% lower than for unthinned stands. In contrast, air temperatures were significantly warmer within patch openings (+6 to +9°C), and within buffers adjacent to patch openings (+3°C) than within unthinned stands. Buffers of widths defined by the transition from riparian to upland vegetation or topographic slope breaks appear sufficient to mitigate the impacts of upslope thinning on the microclimate above headwater streams.

Riparian Stand and Harvest Conditions:

Sites: Five sites – Four along the Oregon Coast Range, and one site in the western edge of the Cascade Range in Oregon. In total, data from 40 transects distributed among 26 reaches across five sites were used in the analysis.

Stand Conditions: All sites were within the western hemlock vegetation zone and Douglas-fir dominated the 45- to 65 year old forests. Other vegetation in the stands included western hemlock and western red cedar. Basal area in unthinned stands ranged from about 44 to 58 m^2/ha.

Stream Conditions: First and 2nd order streams and active channel ranged from 0.2 to 3.7 m (averaged 1.1 m). Nearly 70% of the streams were summer intermittent.

Harvest conditions: There were two no-cut buffer treatments with clearcut harvest occurring outside of this inner zone: 1) “B1-P”– The no-cut buffer width average 69m; and 2) “VB-P” - The no-cut buffer width average 22m wide. There were several no-cut buffer treatments with thinning activities occurring outside of this inner zone: 1) “B1-T” (average 69m inner zone no-cut width); 2) “VB-T” (average 22m inner zone no-cut width); and “SR-T” (average 9m inner zone no-cut width). Thinning was to a density of 198 tree per hectare (tph). Unharvested controls reaches had around 500 to 750 tph (Chan et al., 2004). Unharvested control treatments were also included in the study (“UT”).

Stream Length Logged: Variable – results summarized from 40 transects and results for each transect was a discrete value (i.e., there was no cumulative effect).
Time line: None presented

Summary of Results:

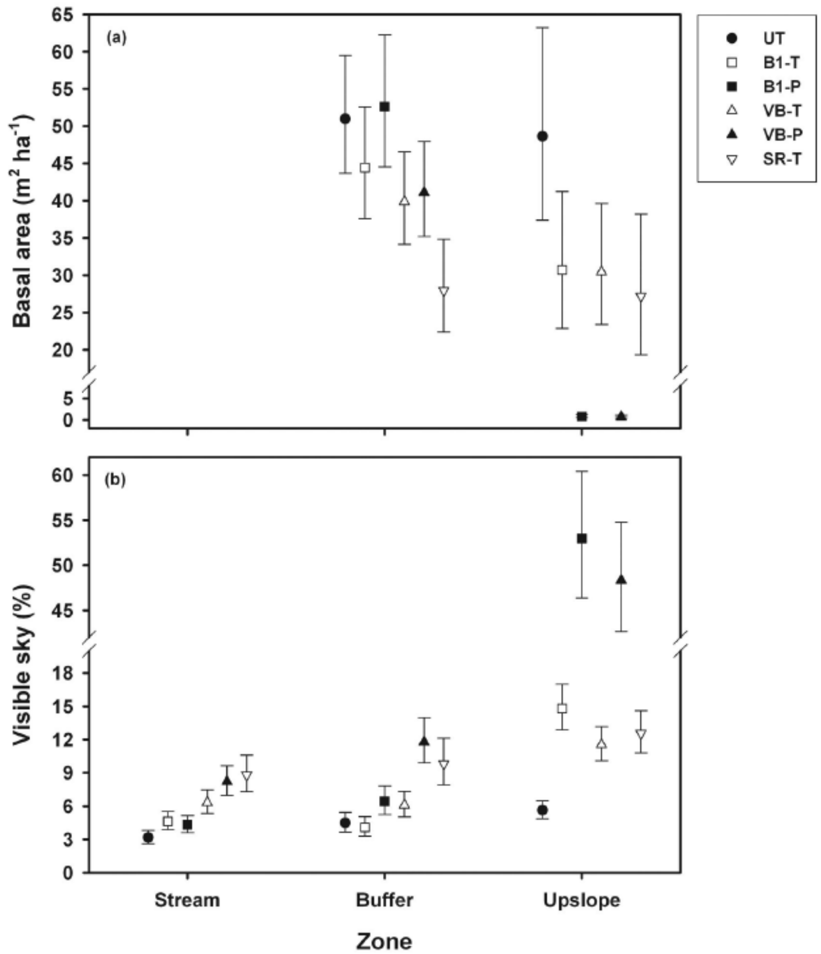


Figure 3. Treatment least-squares means (±1 standard error) for (a) basal area and (b) percentage visible sky as measured over stream center, within buffers, and within the upslope stands. Means and confidence intervals for *n* = four to five observations. Values are back-transformed from model estimates based on log-transformed data.

Stream Shade Response - Clearcut harvest outside of the 69m no-touch buffer ("B1-P") did not result in a significantly different light condition over the stream than the unharvested condition ("UT") and appears to be decreasing less than 1 unit of percent visible sky.

Clearcut harvest outside of the 22m no-touch buffer ("VB-P") resulted in significantly higher light conditions over the stream ($p = 0.002$), increasing 5.1 units of percent visible sky.

Stream Temperature Response - Not measured

4.4 - Effects of Riparian Thinning Over Time - Oregon Coast Range Project

Chan S.S., D.J. Larson, K. G. Maas-Herner, W.H. Emmingham, S. R. Johnston, and D. A. Mikowski. 2006. Overstory and understory development in thinned and underplanted Oregon Coast Range Douglas-fir stands. ***Can. J. For. Res.*** 36:2696-2711.

Location: Oregon Coast Range

Abstract: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests managed for timber in western Oregon frequently lack structure and diversity associated with old-growth forests. We examined thinning effects on overstory and understory development for 8 years after treatment. Three 30- to 33-year-old Oregon Coast Range plantations were partitioned into four overstory treatments: unthinned (~550 trees/ha) and lightly (~250 trees/ha), moderately (~150 trees/ha), and heavily (~75 trees/ha) thinned. Within each overstory treatment, two understory treatments were established: underplanted with Douglas-fir and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) or not underplanted. Thinning increased overstory stem growth, crown expansion, and retained crown length. Thinned overstory canopies began to close rapidly the third year after thinning, decreasing % skylight by approximately 2%/year, whereas % skylight in unthinned stands increased slightly. All seedlings planted in unthinned stands died, whereas eighth year survival in thinned stands averaged 88%. Natural regeneration densities and distributions were highly variable. Understory shrub cover was reduced by harvesting disturbance but recovered by the fifth year. Thinning increased understory plant species diversity, and no shrub species were lost. Thinning to low densities and underplanting has the potential to accelerate development of multilayered stands characteristic of old-growth Douglas-fir forests.

Riparian Stand and Harvest Conditions:

Sites: Three forest blocks in the Oregon Coast Range

Stand Conditions: Thirty to 35 year old Douglas-fir plantation on highly productive sites on the west slope of the Oregon Coast Range

Stream Conditions: Not Available

Harvest conditions: (1) Unthinned (≈550 trees/ha (i.e., tph)); (2) light thinning (≈250 tph); (3) moderate thinning (≈150 tph); and heavy thinning (≈75 tph).

Stream Length Logged: Not Available

Time line: Eight years since thinning activities

Summary of Results:

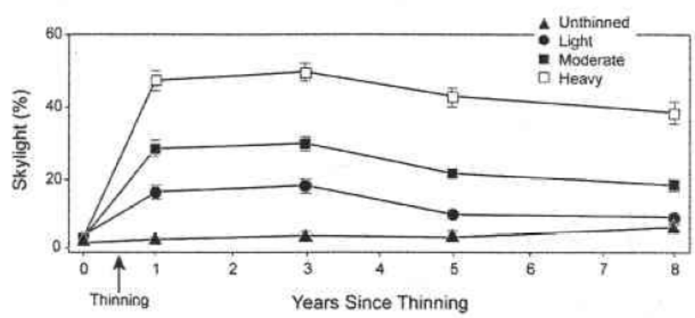
Thinning reduced basal area (BA) by 51%, 67%, and 84% in lightly, moderately, and heavily thinned stands, respectively. Tree densities in thinned stands were reduced in the moderate and heavily thinned stands by windthrow and stem breakage during severe winter storms in the first 4 years of the study. Immediately after thinning, % skylight through the canopy ranged from 2% in unthinned stands to 48% in heavily thinned stands. After 8 years, % skylight in lightly thinned stands was similar to levels in unthinned stands, and % skylight in moderately thinned stands had diminished to levels similar to those in lightly thinned stands just after thinning. Percent skylight for the moderate and heavy thinned stands were elevated above unthinned stand conditions for the eight year period associated with this study.

Table 2. Stand densities before thinning, immediately after thinning (year 1), and 4 and 8 years after thinning.

Density measure	Treatment	Mean density (95% CI) Prethinning	Year 1	Year 4	Year 8	% Change Years 1–4	Years 5–8
Trees/ha	Unthinned	547 (493–601)	547 (493–601)	510 (454–568)	496 (435–558)	–6.8	–0.3
	Light	686 (556–816)	252 (225–279)	244 (215–274)	242 (212–273)	–3.2	–0.8
	Moderate	598 (512–683)	138 (120–156)	128 (119–138)	126 (117–136)	–7.2	–1.6
	Heavy	671 (526–816)	72 (68–77)	70 (64–75)	68 (63–73)	–2.8	–2.9
Basal area (m^2/ha)	Unthinned	44 (40–47)	44 (40–47)	45 (40–51)	49 (44–54)	2.3	8.9
	Light	47 (43–50)	23 (21–26)	27 (23–31)	31 (27–35)	17.4	14.8
	Moderate	43 (39–46)	14 (11–16)	15 (13–18)	18 (16–21)	7.1	20.0
	Heavy	45 (40–50)	7 (6–8)	8 (7–9)	10 (8–13)	14.3	25.0
Relative density[a]	Unthinned	7.7 (7.2–8.2)	7.7 (7.2–8.2)	7.8 (6.9–8.7)	8.2 (7.4–9.0)	1.3	5.1
	Light	8.6 (7.7–9.4)	4.0 (3.6–4.3)	4.4 (3.8–5.0)	4.9 (4.3–5.5)	10.0	11.4
	Moderate	7.7 (7.0– 8.4)	2.3 (1.9–2.7)	2.4 (2.0–2.8)	2.8 (2.4–3.1)	4.3	16.7
	Heavy	8.3 (7.2–9.4)	1.2 (1.1–1.3)	1.3 (1.1–1.5)	1.6 (1.3–1.9)	8.3	23.1

Note: The percentage of change in density was calculated for the first 4 years (years 1–4) and the second 4 years (years 5–8) post-thinning.
[a]Relative density = $(BA/QMD)^{0.5}$, where BA is the basal area (m^2/ha) and QMD is the quadratic mean stand diameter (cm; Curtis 1982); RD (Imperial) = 6.945 28 × RD (metric).

Fig. 4. Changes over 8 years in % skylight through the canopy by thinning treatment. Error bars are 95% confidence intervals. Data points are slightly offset for presentation.



Example of % Skylight for 1 and 8 years after thinning within each stand.		
	Post-thin	Year 8
Unthinned (≈ 550 tph)	2%	6%
Light thin (≈ 250 tph)	14%	8%
Moderate thin (≈ 150 tph)	29%	16%
Heavy (≈ 75 tph)	44%	26%

4.5 – Effects of Riparian Harvest on Microclimate Gradients –Western Washington

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Brosofske, K.D., J. Chen, R.J. Niaman, J.F. Franklin. 1997. Harvesting Effects on Microclimatic gradients from Small Streams to Uplands in Western Washington. *Ecological Applications* 7(4):1188-1200.

Location: Western Washington

Abstract: Riparian zones are vital components of the landscape. Much attention has been focused on the question of how wide a buffer is needed to protect the original riparian environment. We sampled five streams 2-4 m wide and associated riparian ecosystems before and after clearcutting in western Washington. Buffers ranging from 17 to 72 m wide were left intact at all sites when harvesting. Our objectives were: (1) to characterize pre-harvest microclimatic gradients across riparian ecosystems, from the stream to the upland; (2) to identify effects of harvesting on these gradients; and (3) to describe effects of buffer width and near-stream microclimate on stream microclimate. Six weather stations measuring air temperature, soil temperature, surface air temperature, relative humidity, short-wave solar radiation, and wind speed were installed along transects running across the stream and into the upland, and two reference stations were established, one in an upland clearcut and one in an upland interior forest. Pairwise comparison tests were used to evaluate statistical differences between stations along transects for determination of gradient extent. Pre-harvest riparian gradients existed for all variables except solar radiation and wind speed, and values generally approached forest interior values within 31-62 m from the stream. After harvesting, microclimate values at the buffer edge and each subsequent location toward the upland began to approximate clearcut values instead of forest interior values, indicating an interruption or elimination of the stream-upland gradient. In addition, regression analyses showed that stream microclimate was affected to some degree by buffer width and microclimate in the surrounding area. We conclude that a buffer at least 45 m on each side of the stream is necessary to maintain a natural riparian microclimatic environment along the streams in our study, which were characterized by moderate to steep slopes, 70-80% overstory coverage (predominantly Douglas-fir and western hemlock), and a regional climate typified by hot, dry summers and mild, wet winters. This buffer width estimate is probably low, however, since it assumes that gradients stabilize within 30 m from the stream and that upslope edge effects extend no more than 15 m into the buffer (a low estimate based on other studies). Depending on the variable, required widths may extend up to 300 m, which is significantly greater than standard widths currently in use in the region (i.e., ∼10-90 m). Our results indicate that even some of the more conservative standard buffer widths may not be adequate for preserving an unaltered microclimate near some streams. Additional site-specific data are needed for different site conditions in order to determine whether generalizations can be made regarding near-stream microclimate.

Riparian Stand and Harvest Conditions:

Sites: Five streams in three locations in Western Washington

Stand Conditions: Canopy cover was 70-80%, Douglas Fir, western hemlock

Stream Condition: width ranged - 2-4 meters

Harvest conditions: Variable no cut riparian buffer width: 23m (and 17m on other bank), 17m(23m), 25m (60m), 60m (25m), and 60m (25m).

Stream Length Logged: Not relevant
Time line: One year of pre-harvest and one year of post-harvest data collection

Summary of Results:

They found that solar radiation and relative humidity did appear to have some association with buffer width. Edge influences appeared to allow solar load to penetrate the forest buffer and affect stream microclimate. Accordingly, they surmise that as the buffer widens the amount of solar radiation able to penetrate the vegetation and reach the stream station would decrease.

They did not find any relationship between water temperature and buffer width. The water temperature response associated with each treatment was not presented so it is not possible to determine the impact of various riparian buffer widths on stream temperature.

They observe a strong influence of soil temperature in the surrounding land area on water temperature, even for sites well away from the stream. They concluded that this suggests that activity in the watershed up to or more than 180 m away may affect stream microclimate even when a buffer strip is left intact.

Authors conclude that a buffer at least 45 m on each side of the stream is necessary to maintain a natural riparian microclimatic environment along the stream.

4.6 - Effects of Riparian Harvest on Blowdown – Coast Range of Washington Study

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Jackson, C.R., D.P. Batzer, S.S. Cross, S.M. Haggerty and C.A. Sturm. 2007. Headwater Streams and Timber Harvest: Channel, Macroinvertibrate, and Amphibian Response and Recovery. *Forest Science* 53(2):356–370.

Location: Coast Range, Washington

Abstract: Abiotic and biotic responses of 15 first-order streams to timber harvest were monitored at four sites in Washington's Coast Ranges (six watersheds clearcut to streambanks; four clearcut with stream buffers; and four references). Surveys of geomorphology, macroinvertebrates, and amphibians were conducted in 1998 (baseline), 1999 (immediately postharvest), 2000 (macroinvertebrates only) and 2001. Logging slash immediately covered or buried clearcut channels with 0.5 to 2 meters of slash, increasing roughness and trapping fine sediments, and slash still dominated channel conditions in 2001 when fine sediment fractions remained elevated relative to reference streams. In buffered and reference streams, particle size distributions were almost unchanged. Buffer blowdown was extensive (33% to 64%); increased light stimulated streamside vegetation. In 1999, clearcut streams supported higher macroinvertebrate densities of collectors and shredders, likely due to increased detrital resources. Collector response persisted into 2001, and new responses included higher overall macroinvertebrate biomass in buffered streams. No macroinvertebrate groups declined significantly in the three summers after harvest. Clearcutting to stream channels appeared to have short-term negative effects on local giant salamander and tailed frog populations but not torrent salamanders.

Riparian Stand and Harvest Conditions:

Sites: fifteen first and second order streams in the coast range of Western Washington. Four of the 15 streams basins were not harvested, and these streams served as references. Four for each harvest type ("Reference", clearcut, full buffer, and non-merchantable buffer)

Stand Conditions: Not described

Stream Conditions: 1st and 2nd order streams

Harvest conditions: No adjacent harvest (reference stream), standard clearcut, full riparian buffer and a non-merchantable harvest (There was very little non-merchantable vegetation so these effectively became clearcut harvest.). Widths of buffers applied to the buffered streams were dictated by operational considerations, and the buffer widths were around 8 to 10 meters on each side of the stream.

Stream Length Logged: Not described

Time line: Two years of water temperature data – one pre and one post-harvest

Summary of Results:

This study was a follow-up to the Jackson et al., 2001 which described the immediate effects of harvest activities on stream channel and riparian conditions on small headwater streams. The salient information provided in this new study concerns the effects of blowdown on the buffer stand condition in years following harvest activities. Buffer blowdown was extensive in 2001 (two years following harvest activities associated with buffered streams). Blowdown ranged from 33 to 64% of buffered trees with attendant effects on canopy cover. After blowdown, the newly fallen trees either spanned the channels or lay beside the channels, so blow down trees were not adding woody debris to the channels or altering channel structure at the time of the study.

Table 4. Summary of buffer blowdown and canopy cover as measured by a spherical densitometer

Stream	Buffer type	Blowdown (2001) (%)	Canopy cover[1] (%)		
			1998 (pre)	1999	2001
21W	Non-merchantable	44	90	65	10
21M	Full	52	93	15[2]	15[2]
17E	Full	33	92	51	35
13E	Full	64	87	23	72[3]
12E	Partial (within buffer of fish-bearing stream)	42 32 along fish-bearing stream	95	NM	90

[1] These canopy cover estimates should be used with caution. The densitometer readings were taken within the survey section. However, both the buffers and the blowdown of the buffers were patchy, so these numbers are not an average for the whole stream.
[2] The buffer on 21M was much wider and denser downstream of the survey reach where these densitometer measurements were taken.
[3] Canopy coverage on 13E in 2001 was provided by dense scrub-shrub vegetation growing adjacent to the channel. On this stream the channel-adjacent herbaceous vegetation had grown to a height of 2 meters in many places.