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The Density Management and Riparian Buffer Study: A large-scale silviculture experiment informing riparian management in the Pacific Northwest, USA

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ABSTRACT

The advent of the Northwest Forest Plan (NWFP) in the early 1990s signaled a new paradigm for management of 9.9 million ha of federal forest lands in western Washington and Oregon, USA. The emphasis shifted from commodity timber production to ensuring sustained ecological functioning to meet a broad array of ecosystem services including economic benefits. Under interim guidelines of the NWFP, approximately 1.1 million ha are allocated to riparian reserves intended to conserve the ecological functions and processes required to create and maintain habitat for aquatic and riparian-dependent organisms. The Density Management and Riparian Buffer Study (DMS), an operational-scale management experiment, has evaluated the effectiveness of alternative buffer widths in meeting ecological objectives for riparian areas in headwater forests subjected to spatially heterogeneous thinning. Observations in unthinned stream-reaches revealed spatial structuring of amphibian and invertebrate species assemblages in relation to headwater habitats. Riparian buffers defined by the transition between distinct riparian habitat features and upslope forest were sufficient to moderate the effect of thinning on near-stream microclimates and wetted streambed temperatures. These same variable-width buffers were less effective when adjacent to 0.4-ha patch openings. Thinning had little impact on the abundance of aquatic amphibians and there was no evidence of species loss. Results of the study are being used to devise headwater forest management and species conservation strategies, and to improve monitoring methods and watershed assessment tools.

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1. Introduction

The advent of the Northwest Forest Plan (NWFP) in the early 1990s signaled a new ecosystem management paradigm for management of 9.9 million ha of federal forest lands (U.S. Department of Agriculture, Forest Service (USFS) and U.S. Department of the Interior, Bureau of Land Management (BLM)) in western Washington and Oregon, USA. The primary objective shifted from commodity timber production to ensuring sustained ecological functioning to meet a broad array of ecosystem services including economic benefits. Ecosystem management under the Northwest Forest Plan encompasses a contemporary view of forests and landscapes as comprising integrated aquatic, riparian and terrestrial ecosystems. Two primary objectives of the NWFP are: (1) management to develop late-successional habitat for associated species such as the Northern Spotted Owl (*Strix occidentalis caurina*) and Marbled Murrelet (*Brachyramphus marmoratus*) and (2) the restoration and conservation of aquatic and riparian systems important to biodiversity and iconic anadromous salmonid fisheries (USDA and USDI, 1994). Reflecting the regional importance of aquatic and riparian issues, the NWFP designated approximately 1.1 million ha as riparian reserves to conserve the ecological functions and processes required to create and maintain habitat for aquatic and riparian-dependent organisms (Reeves, 2006).

The forests of western Oregon and Washington fall within the very productive temperate coniferous forest zone (Franklin and Dyrness, 1988). Old-growth, climax forests are dominated western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and western redcedar (*Thuja plicata* Donn ex D. Don). Since the early 1900s, wildfire, harvesting and reforestation practices have converted large proportions of the forest landscape from old-growth to young, even-aged Douglas-fir forests. On forest industry lands, generally located at lower foothill elevations, these young forests have been managed predominantly for timber production on 40–60 year rotations. On federal lands, which tend to occupy larger contiguous blocks at mid-to-higher elevations, the forests were managed for multiple uses, with timber

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production becoming increasingly prevalent from the 1950s to the 1980s. However, by the 1990s, public opinion had turned against further harvests of old-growth, even-aged management and clearfelling in particular, on federal lands (Peterson and Anderson, 2009). The NWFP emerged as an attempt to reconcile divergent environmental, economic and other interests behind a science-based regional strategy for ecosystem management of federal lands.

To investigate alternative approaches to forest management several large-scale management experiments (LSME) were undertaken on federal lands within the NWFP area. These studies are focused predominantly on silvicultural alternatives to clearfelling regeneration harvests and accelerating the development of late-successional characteristics in young, even-aged Douglas-fir forests previously managed for wood production.

The Density Management and Riparian Buffer Study (DMS) is distinct among regional LSMEs because it integrates aquatic and riparian ecosystem restoration considerations with alternative silvicultural approaches to enhancing biodiversity and structural development of young, managed headwater forests (Cissel et al., 2006; Poage and Anderson, 2007). Designed as an experiment at an operational scale, the DMS is a platform for assessing the effectiveness of alternative riparian buffer designs with respect to forest harvest activities as currently practiced on federal lands in much of western Oregon and Washington.

The objectives for the Riparian Buffer Component of the DMS include: (a) characterization of headwater habitats and associated species and species assemblages; (b) assessment of alternative riparian buffer widths in sustaining aquatic and riparian habitats, species and species assemblages following upland density management harvests; and (c) developing methods for effective monitoring of aquatic and riparian ecosystem components and processes. Our purpose in this paper is threefold: (1) summarize some key findings associated with the riparian component studies from the first decade of reporting, (2) discuss how the study and its findings have influenced riparian management practices and policy, and (3) illustrate some of the distinct benefits and limitations of operational-scale management experiments in addressing resource management issues.

2. Study design

2.1. Density Management and Riparian Buffer Treatments

The BLM undertook the DMS to provide operational-scale demonstrations of silvicultural options based on variable-density thinning concepts. The DMS comprises an initial thinning study applied to young, previously unthinned 50–80 year-old Douglas-fir stands of at least 13 ha (13.8–68.9 ha). The study was implemented between 1996 and 2000 at eleven headwater forest sites (10 BLM sites and 3 USFS sites) distributed among the western Cascade Range and the Coast Range of Oregon (Fig. 1).

The initial thinning treatments included an unthinned reference (~500–865 trees ha^{-1}) and harvesting to high (~297 trees ha^{-1}), moderate (198 trees ha^{-1}) or variable residual density (roughly equal thirds of the treatment area thinned to ~99, 198 and 298 trees ha^{-1}). Within each of these thinning treatments, fine-scale structural variability was created by incorporating "leave islands" – areas of aggregated green-tree retention (all harvest treatments) and clear-felled patch openings (moderate and variable density treatments). Leave islands and patch openings were circular areas of three sizes – 0.1 ha, 0.2 ha and 0.4 ha; approximately 5–10% of stand area was leave islands and 5–10% in patch openings. The patch openings were subsequently planted with a species mixture including Douglas-fir, western hemlock, and western redcedar (*Thuja plicata* Donn ex D. Don) at a nominal 4.6 m × 4.6 m spacing (~475 trees ha^{-1}) and then allowed to develop without further manipulation of non-conifer vegetation.

The riparian buffer component of the DMS evaluates the use of unharvested streamside buffers within riparian reserves to meet aquatic conservation objectives in the presence of spatially heterogeneous thinning treatments. The riparian buffer study is nested within the overarching density management study. Four riparian buffer alternatives are included (Fig. 2). Two alternatives based on interim guidelines defined in the NWFP are a two site-potential-tree-height buffer (2-tree-height) and a one site-potential-tree-height buffer (1-tree-height). Under the NWFP, 2-tree-height buffers were to be applied to fish-bearing streams and 1-tree-height buffers were to be applied to non-fish-bearing streams, which are generally smaller. For the DMS, 1-tree-height buffers ranged in width among sites from 55 m to 73 m. Because of the dense headwater stream network in the complex, steep topography of the western Cascade and Coast Ranges, the prescribed 2-tree-height buffer widths (110–146 m)commonly exceeded the distance from stream to the subtending ridge tops, thus limiting the opportunities for implementing the 2-tree-height buffer treatment in the DMS. Two less conservative buffer types were also included: streamside retention buffers considered the minimum needed to stabilized stream banks and to provide direct canopy cover to the stream channel; and variable-width buffers that extend from the stream through the zone of distinctly riparian features. Streamside-retention buffers have a minimum width of 8.1 m and average about 11.3 m. Variable-width buffers have a minimum width of 20.2 m and average about 29.5 m. The streamside-retention alternative reflects the narrower buffers typical of small streams on private and/or state lands. The variable-width buffer was conceived as an alternative defined by the discernible extent of riparian zones; this is in contrast to the wider NWFP alternatives, which extend beyond the riparian zone into the terrestrial forest. Conceptually variable-width buffers provide direct streamside shade, bank stabilization, and stream wood recruitment functions, as well as additional habitats and processes important to riparian-dependent organisms and ecosystem functions. Further description and rationale for these buffer width alternatives is provided in Anderson et al. (2007), Cissel et al. (2006) and Olson et al. (2007).

The riparian buffer options were implemented along small headwaters stream reaches (<2 m width) encompassed by the moderate-density thinning treatment (198 trees ha^{-1}) at the 11 sites (Fig. 3). Wherever possible each buffer alternative was implemented at least once per site. However, the density of stream reaches within the DMS moderate-density treatment units typically constrained the implementation to a subset of the four buffer alternatives at a given site. Stream reaches, or the associated small catchments (typically less than 15 ha), are the experimental units being monitored. Buffer treatment replication occurs across sites.

2.2. Response variables and monitoring

The riparian buffer sub-studies have had two predominant monitoring foci: (1) stream and riparian habitats for amphibians and other aquatic–riparian vertebrate fauna and (2) riparian microclimates and microsites. Stream habitats are characterized by reach length, stream gradient, average and maximum width and detailed characterization of streambed substrates; the numbers, sizes, decay condition and source distances of channel and near-channel, downed wood; general descriptions of near-channel vegetation; and a classification of the seasonal hydrologic flow regime of study reaches (Cissel et al., 2006). Stream–riparian habitat use has been characterized through monitoring of riparian and aquatic vertebrates, mostly amphibians and fishes and to a lesser extent terrestrial amphibians, mollusks and macroinvertebrates

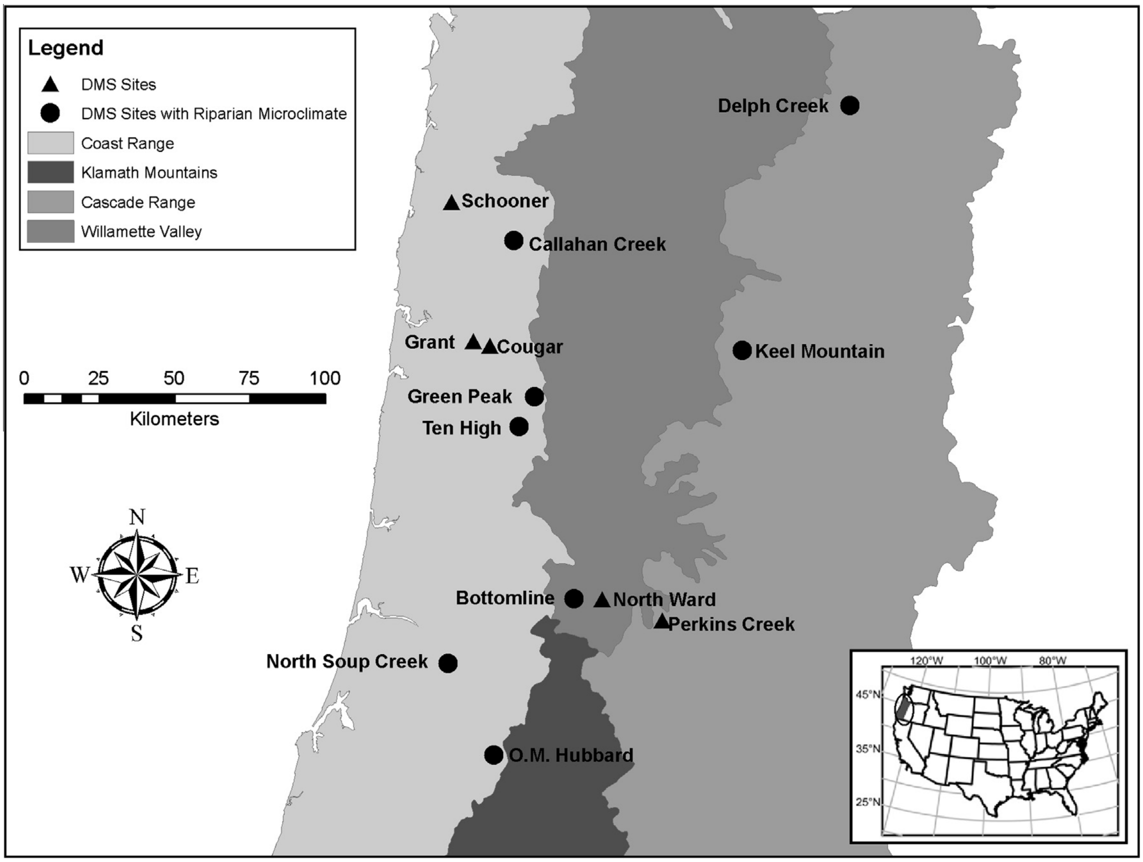

Fig. 1. Conceptual representation of alternative buffer width and upslope treatment conditions evaluated in the riparian buffer component studies of the Density Management Study.

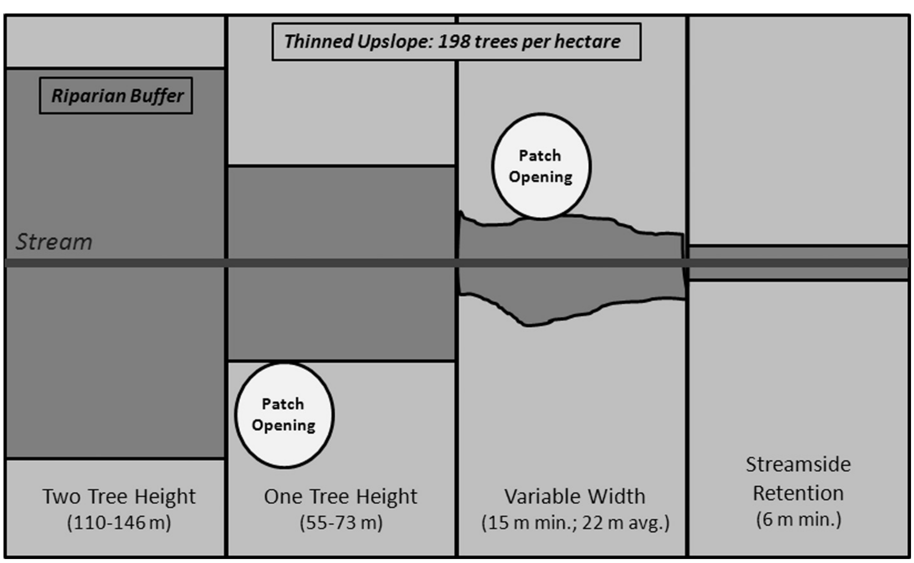

Fig. 2. Locations of DMS riparian buffer study sites in western Oregon. Microclimate monitoring sites are indicated by solid circles; all sites include stream habitat and amphibian monitoring.

(Cissel et al., 2006; Olson and Rugger, 2007; Kluber et al., 2009). These surveys have focused on identifying temporal and spatial trends in faunal species occurrence and abundance and the delineation of species assemblages in relation to habitat attributes (Sheridan and Olson, 2003).

Microclimate and microsite monitoring has focused on discerning air temperature, relative humidity and soil temperature gradients from stream center through the riparian zone and upslope into the terrestrial forest based on transects spanning reach catchments, as well as water temperature variations over the length of stream reaches (Chan et al., 2004; Cissel et al., 2006; Anderson et al., 2007). The emphasis on microclimates reflects the importance of distinct, localized environmental conditions that define streams and riparian areas as hotspots of biodiversity and also the strong linkage to spatial patterns of vegetation composition and structure influenced by buffer width and overstory thinning

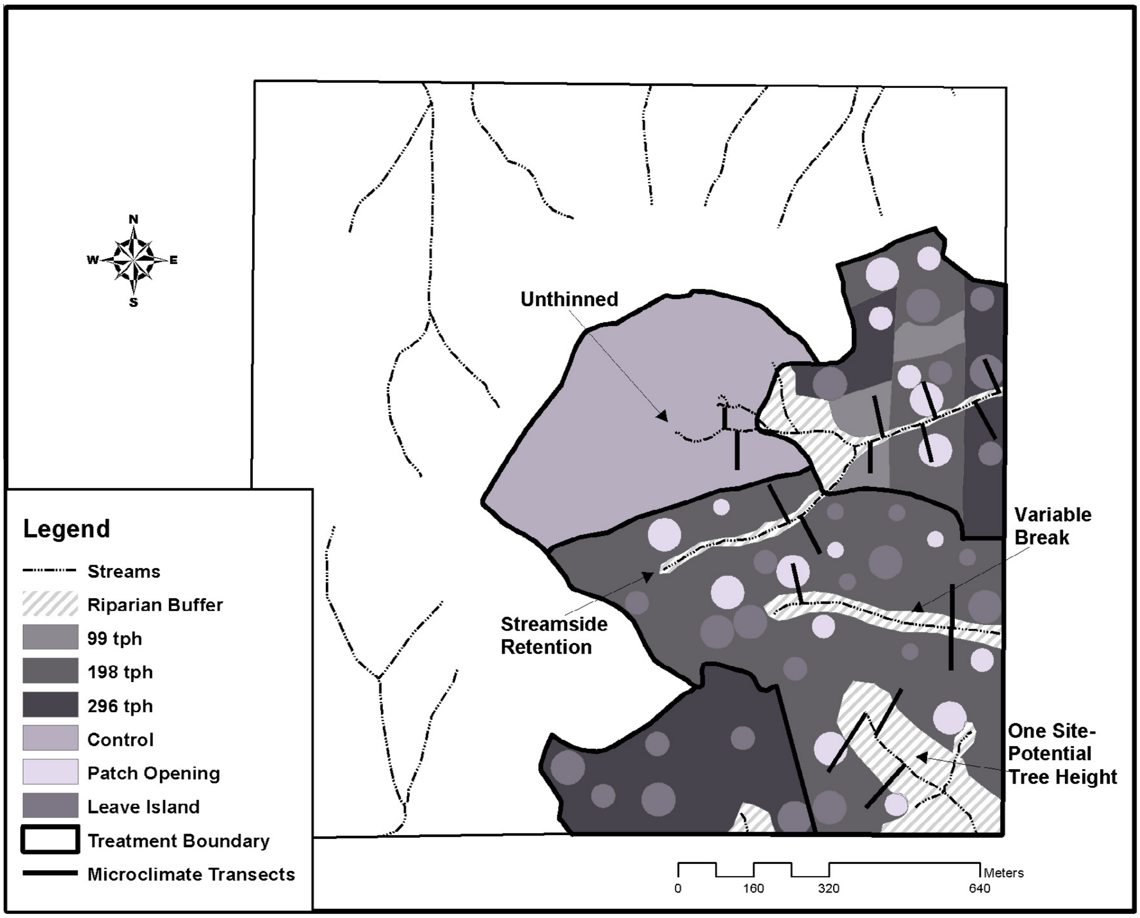

Fig. 3. Treatment map of the DMS Green Peak installation of the initial thinning study. Treatments consist of unthinned reference (control), high density retention (296 trees ha^{-1}), moderate density retention (198 trees ha^{-1}) and a variable density retention with the unit split into thirds with high density, moderate density or low density (99 trees ha^{-1}) retention. Sub-stand features include circular uncut "leave Islands" and clear-felled patch openings 0.1, 0.2 and 0.4 ha in size. Riparian buffer treatments are implemented on three stream reaches within the moderate density retention treatment: streamside retention, variable-width and 1-site-potential-tree-height buffer widths. The stream reach within the unthinned unit serves as a reference to the buffer treatments.

(Olson et al., 2007). In many respects, the catchment sampling of microclimates and microhabitats serves as a linkage between the stream-centric sampling of aquatic–riparian habitats and fauna and a larger-scale, grid-based sampling of the upland thinning treatment units (Cissel et al., 2006).

Reach-based sampling for aquatic–riparian habitats and vertebrate diversity has been conducted for more than 80 reaches across 12 sites (Cissel et al., 2006). For inclusion, minimum study reach length is equal to 2.5-times the potential height of dominant trees for a given location (minimum reach lengths of 135–185 m). Study reaches are predominantly zero-, first- and second-order headwater streams. Physical stream habitat attributes are inventoried longitudinally, with habitat units being stratified among pools, riffles, or dry channels and detailed measurements of channel morphology, substrate and downed wood collected to provide estimates per total reach length and per unit reach length. Sampling for aquatic and riparian fauna is performed by subsampling discrete habitat units in proportion to their occurrence in the reach. Typical methods for amphibians include time-constrained hand searches (temporary manual displacement of cover objects) focused on suitable habitats in-stream or along stream banks or channel slopes; fishes are sampled by electroshocking in pool or riffle habitats (Cissel et al., 2006).

Riparian–terrestrial gradients in microclimate and microhabitat have been surveyed using repeated sampling along transects originating at stream center and extending through the riparian zone into the upland thinned or unthinned forest (Anderson et al., 2007; Anderson and Meleason, 2009; Eskelson et al., 2013). The original sampling protocols used transects that extended a minimum of 60 m beyond the riparian buffer into the upslope forest, or to the ridge top defining the catchment boundary if less than 60 m from a buffer edge. A higher density of transect sample points near the stream has been used to capture the stronger microclimate gradients hypothesized to occur near the streams (Cissel et al., 2006; Anderson et al., 2007).

The various component studies have followed slightly different sampling timelines but generally data collections have occurred four times: 1–2 years pre-treatment, and 1–2 years, 3–7 years and 10–11 years post-treatment. Most publications to date address findings trough 3–7 years; several papers addressing 10–11 year findings are in preparation for publication in the near future.

2.3. Analyses

The riparian buffer study is a multidisciplinary effort involving several investigators and sub-studies within the framework of the overarching DMS study design. Individual sub-studies have applied a variety of analytical approaches to developing findings. For the purpose of this summary we direct the reader to the primary publications for those details. However, to build a framework for a discussion of the findings across studies we have tabulated selected results to compare the responsiveness of various environmental and habitat attributes to alternative buffer widths. We calculated relative treatment effect size based on treatment level means and using the unthinned reaches as a control (Steidel and Thomas, 2001). The relative effect size for a given buffer width is expressed as a percentage deviation from the control

$$\text{Relative Effect Size}(\%) = ((Xt - Xu)/Xu) \cdot 100 \qquad (1)$$

where *Xt* is the mean for treated reaches with 1-tree-height, variable-width, or streamside-retention buffers adjacent to either moderately thinned matrix or 0.4-ha patch openings and *Xu* is the mean for similar stream, buffer or upslope locations of untreated units.

This simple metric is intended to illustrate the magnitude of treatment response differences across studies and does not account for differences in the precision of means estimates. Therefore, we also present the probability of treatment effects significance as reported in the source publications to illustrate the respective strengths of inference.

3. Key findings

3.1. Riparian ecosystem characteristics

Headwater streams and riparian areas are characterized by habitats that are distinct from the adjacent uplands. As evidenced by unthinned stands typified by relatively closed canopies, there are strong stream to upslope gradients in air and soil microclimates (Chan et al., 2004). Temperature increases and humidity decreases with distance from stream. Stream influences on riparian microclimates in these headwater reaches are evidenced by distinctly steeper gradients in the first 10 m from stream than from beyond 10-m (Chan et al., 2004; Anderson et al., 2007; Olson et al., 2007). Pre-treatment surveys identified 12 amphibian species and fishes of three species groups over 12 DMS sites (Olson et al., 2006; Olson and Weaver, 2007). The distribution of species and species assemblages within headwater catchments varied longitudinally and laterally along the reach network in relation to important habitat attributes of reach hydrotype, stream size, gradient and substrate composition (Sheridan and Olson, 2003; Olson and Weaver, 2007). Patchy occurrence of tailed frogs and sculpins, in addition to the occurrence of torrent salamanders in spatially intermittent streams, suggests that these species warrant consideration in forest management activities that potentially impact small headwater streams. Furthermore, life-history functions that require specific structural features or substrates (e.g. large-downed wood for nesting) may have an added influence on local abundances of near-stream and upslope terrestrial salamanders (Olson et al., 2006).

3.2. Buffer width effectiveness

To assess the effectiveness of buffers it is important to characterize the disturbance they are intended to mediate. In the DMS, buffer alternatives were assessed with respect to a moderate-density thinning treatment which included finer-scale clear-felled patch openings and uncut leave islands embedded in a thinned matrix.

Disturbance severity differed markedly between the thinned matrix and clear-felled patch openings (Anderson et al., 2007; Table 1). Three-to-five years following implementation, moderate thinning from below had decreased stand basal area by about 40% relative to the unthinned stands. Clear-felling decreased basal area about 99% in 0.4-ha patch openings. The magnitude of this difference was greater in terms of canopy closure. Relative to unthinned stands there was a decrease of 100–160% for the thinned matrix and a decrease of 760–840% for 0.4-ha patch openings. The greater relative effect sizes for canopy closure compared to basal area are important for canopy shading and thermal loads in the understory.

Upslope harvests had varying impacts on canopy closure in adjacent uncut buffers and their stream channels (Anderson et al., 2007; Table 1). Canopy closure in buffers adjacent to thinning was essentially unaffected in 1-tree-height buffers but decreased with decreasing buffer width (−119% in narrow streamside-retention buffers). Indicative of the more severe disturbance, adjacent patch openings decreased buffer canopy closure 36% and 159% for 1-tree-height and variable-width buffers respectively. At stream center, relative treatment effect sizes were somewhat greater than in the uncut buffers as canopy closure for treated reaches decreased 35–60% relative to the decreases observed in the adjacent uncut buffers. The observed canopy closure decreases in the uncut buffers was indicative of increased side-lighting at the buffer edge, with the effect varying among buffer widths in association with different edge-to-interior area ratios and the different topographic positions of buffer edges. The greater treatment effects at stream center relative to the adjacent buffers may reflect the cumulative influences from upslope thinning on both stream sides.

Harvest-induced changes in forest canopy structure can influence understory microclimate through alterations of thermal loading, insulation and air movement. In general, the relative effect sizes 3–5 years following treatment were less for microclimate responses than observed for canopy closure (Table 1). One-tree-height and variable-width buffers adjacent to thinning moderated alterations of daily maximum air temperature (avg. <1.6 °C increase) and daily minimum relative humidity (avg. <5% decrease) relative to unthinned reaches (Anderson et al., 2007). Significant microclimate differences relative to unthinned stands were observed in streamside-retention buffers adjacent to thinning and in one-tree-height and variable-width buffers adjacent to 0.4-ha patch openings (Anderson et al., 2007). In spite of greater decreases in canopy closure for the stream channels than for adjacent buffers, the relative effect sizes of treatments for stream center microclimate were generally less than 10% and statistically insignificant (Table 1). An exception to this was the average 26% increase in daily maximum air temperature observed for reaches with narrow streamside-retention buffers. Streambed daily maximum temperatures (temperature of the water saturated hyporheic substrate) were very insensitive to treatments, with effect sizes ranging from −8% to 1% for all buffer widths and harvest intensities (Table 1).

Understory vegetation and downed wood are important habitat elements for riparian-dependent organisms, providing cover and nutrition and contributing to shade and favorable microclimate.

Vegetation and downed wood cover responses to a range of treatments were similar in magnitude to that of the microclimate attributes, but tended to have a greater degree of variation and therefore less frequent statistical significance (Table 1; Anderson and Meleason, 2009). For example, shrub cover within buffers generally declined for all treatments by −8% to −61% relative to the untreated condition yet the differences lacked statistical significance (Table 1). In contrast, cover by herbaceous vegetation within buffers tended to increase relative to untreated conditions with the increases being greatest for variable-width (151%) and streamside-retention (60%) buffers. Changes in herbaceous vegetation cover were negligible for the wider one-tree-height (−1%) buffers. Upslope, herbaceous cover responses were consistently large across treatments (39–207%), but greater variability precluded statistical significance.

Three-to-five years after treatment downed wood cover in the upslope treated stands decreased from −2% to −14% relative to untreated stands. Conversely, cover of large downed wood in the buffers was 22–80% greater than for similar locations in untreated stands (Table 1). Repeated sampling at 1–2 years and 3–5 years

Table 1
Summary of relative treatment effect size and treatment main effect significance for a variety of DMS response variables as reported in selected publications for riparian buffer component studies. The experimental unit is a stream reach.

Response variable	Strata	Relative effect size by buffer type and upslope treatment					
		Adjacent to 80 tPa thinning			Adjacent to 1-ac patch opening		
		One-tree-height % Deviation from unthinned reference	Variable width	Streamside retention	One-tree-height	Variable width	Main effect significance p-Value
[a]Basal area ($m^2\ ha^{-1}$)	Upslope	−37	−37	−44	−98	−99	<0.001
	Buffer	−13	−22	−45	03	−19	0.145
	Stream	na	na	na	na	na	na
[a]Visible sky (%)	Upslope	163	105	124	842	760	<0.001
	Buffer	−9	36	119	43	163	0.001
	Stream	46	100	178	36	159	0.009
[a]Air temp. maximum (°C)	Upslope	14	19	25	48	32	0.002
	Buffer	7	12	22	21	18	0.019
	Stream	−3	1	26	−4	9	0.096
[a]Rel. Humidity Minimum (%)	Upslope	−15	−16	−23	−38	−19	0.019
	Buffer	−11	−8	−32	−23	−12	0.075
	Stream	2	9	−24	4	−4	0.167
[a]Soil or streambed temp. maximum (°C)	Upslope	5	5	3	24	12	0.021
	Buffer	2	2	−4	6	4	0.057
	Stream	−4	−3	1	−8	0	0.602
[b]Shrub cover (%)	Upslope	−23	−23	−30	−49	10	0.019
	Buffer	−61	−48	−11	−8	−25	n.s.
[b]Herb cover (%)	Upslope	207	91	157	39	97	n.s.
	Buffer	−1	151	60	−2	40	<0.0065
[b]Moss cover (%)	Upslope	−54	21	−43	−27	−13	0.0436
	Buffer	−24	−25	−26	−21	23	n.s.
[b]Large down wood cover (%)	Upslope	−2	−11	−14	−14	−6	n.s.
	Buffer	27	80	40	22	33	n.s.
[b]Small down wood cover (%)	Upslope	−58	−46	5	11	0	n.s.
	Buffer	50	83	131	49	11	n.s.
[c]Large log temp. maximum (°C)	Upslope	na	12	36	na	Na	Not est.
	Buffer	na	5	8	na	Na	Not est.
[c]Small log temp. maximum (°C)	Upslope	na	17	22	na	Na	Not est.
	Buffer	na	3	15	na	Na	Not est.
[c]Soil temp. maximum (°C)	Upslope	na	16	22	na	Na	Not est.
	Buffer	na	16	17	na	Na	Not est.
[c]Air temp. maximum (°C)	Upslope	na	30	44	na	na	Not est.
	Buffer	na	6	20	na	na	Not est.

Relative treatment effect size is calculated as the difference of the mean for a given thinning treatment and the mean of the unthinned control, divided by the mean for the unthinned control. Not est. indicates that statistical analyses were not run to test buffer width main effects. Source studies are: (a) Anderson et al. (2007); (b) Anderson and Meleason (2009); and (c) Kluber et al. (2009). Analyses of Kluber et al. (2009) were run separately for each buffer treatment; n.s. indicates statistical insignificance. Values unmeasured or unavailable from the publication are indicated by ‘na’.

post-treatment indicated a trend towards more homogenous abundances of downed wood as initially large post-treatment abundances in the streamside-retention buffer and variable-width buffer adjacent to 0.4-ha patch openings were diminished with time (Anderson and Meleason, 2009).

Thinning had little impact on aquatic vertebrates for all buffer alternatives. Pre-treatment and initial (1-2 years) post-treatment surveys of bank and stream amphibians (>3000 observations including 13 species) revealed a general trend for interannual decline in abundances that was significant only for the bank-dwelling Western red-backed salamander (*Plethodontid vehiculum* Cooper). The interannual differences in abundance were associated with changes in stream habitat conditions including: decreased pool to riffle ratios and reach widths, increased flow fragmentation and intermittency and increased downed wood densities post-harvest (Olson and Rugger, 2007). However, there was no evidence for treatment-related declines for any of the buffer alternatives. Instead, there were tendencies for first-year increased abundances of the rough-skinned newt (*Tarica glanulosa* Skilton) and Coastal giant salamanders (*Dicamptodon tenebrosus* Baird and Girard) in the narrowly buffered reaches.

Although a pattern emerged showing a decrease of upland salamanders in years 1-2 post-treatment (Rundio and Olson, 2007) sampling 5–6 years post-treatment did not detect differences in the abundance of upland amphibian captures among riparian buffer treatments. However, the availability of a variety of covers and substrates may have ameliorated negative impacts associated with the harvest (Kluber et al., 2008). Both *P. vehiculum*, the most common species, and *Ensatina eschscholtzii* demonstrated affinities for a variety of cover materials and substrate. Yet *P. vehiculum* was more commonly found in the cooler, more humid near-stream environments, suggesting that retention of stream-side buffers may be needed. *E. eschscholtzii* salamanders tended to occurwith greater upslope abundance and, by using a variety of cover and substrates they may have been more able to adjust to the altered habitat conditions associated with thinning disturbance (Kluber et al., 2008).

Large downed wood and soil environments can provide thermally suitable amphibian habitat in thinned stands and buffers. Daily maximum temperatures at the core of small-diameter (30–45 cm) and large-diameter (70–100 cm) logs and at a 15 cm soil depth was maintained within the thermal tolerances of western plethodontid salamanders in mid-summer, even when maximum air temperatures exceeded 30 °C (Kluber et al., 2009). Daily maximum air temperatures responses were greater for streamside-retention buffers than for variable-width buffers, yet the relative effect sizes for downed wood core temperature responses were substantially less than the air temperatures and differed less between buffer treatments (Table 1).

3.3. Monitoring methods development

Riparian forests are often more compositionally and structurally diverse than associated upland forests, making inventory and monitoring more challenging. Efficient forest structure and microclimate sampling designs were explored using simulation modeling based on very detailed datasets derived from 0.52-ha stem mapped plots on eight DMS reaches. Among 16 alternative designs for estimating stand attributes (conifer trees per hectare, basal area per hectare, and tree height to diameter ratio) in the conifer dominated stands, rectangular strip plots 3.6 m wide running upslope, perpendicular to the stream had the greatest accuracy (Marquardt et al., 2010). For characterizing the abundance of the infrequent hardwoods and snags, the sampling alternatives generally were less accurate, but the 3.6-m perpendicular strip plot design performed best (Marquardt et al., 2012). Eskelson et al. (2011a) developed procedures for modeling the understory shrub cover based on distance from stream and overstory leaf area index, a measure canopy foliage density. Using similar site variables and understory vegetation as covariates, Eskelson et al. (2011b) modeled spatial variations in microclimate. They demonstrated that following an initial determination of site-specific patterns of microclimate variation, sampling patterns could be optimized, leading to the concentration of sampling effort in key areas such as near-stream microclimate gradients (Eskelson et al., 2011b). By exploiting strong correlations with air temperature, further microclimate sampling efficiency was possible by sampling relative humidity at a subset of air temperature monitoring locations (Eskelson et al., 2013).

4. Discussion

4.1. Characterization of riparian ecosystems

The characterization of amphibian and invertebrate species assemblages and their distributions in small headwater basins (Sheridan and Olson, 2003; Olson and Rugger, 2007; Progar and Moldenke, 2002) has increased awareness of the need to consider buffering some of the smallest headwater reaches including seasonally intermittent stream channels (Olson et al., 2007). Historically, the presence of small intermittent or first-order headwater streams were often unmapped and frequently ignored or given little protection in the application of harvest and reforestation practices (Richardson and Danehy, 2007). For those riparian amphibians and invertebrate species having either limited mobility or strong affinity to these upper headwater reaches, retention of downed wood or moist, cool soils as refugia (sensu Kluber et al., 2009) may be critical to the species persistence following disturbances such as harvesting.

The distinct habitat requirements for various amphibian species and assemblages has important implications for the effectiveness of riparian corridors and buffers as dispersal habitat at stand, drainage basin and landscape scales. While all amphibians in the region have some association with streams or riparian areas for specific functions, many disperse overland through intact upslope forests (Olson and Burnett, 2009). Observations from the DMS have led to a conceptualization of headwater linkages to providing connectivity between adjacent drainages. Linkages across headwater ridges might consist of uncut stands as well as manipulations of downed wood to provide the microclimate and cover required by dispersing amphibians and other taxa (Olson et al., 2007). The prioritization of potential headwater linkage locations based on land-use patterns, species of concern, physiographic context, disturbance regime and other criteria could result in an optimization of connectivity to meet watershed and landscape objectives (Olson and Burnett, 2009). A limited proof of concept implementation to connect two small headwater drainages is being undertaken by the BLM.

4.2. Buffer effectiveness

The DMS riparian buffer study is distinct from most other buffer studies because it tests buffer widths against the partial overstory harvest practices likely to occur on federal lands. Under the NWFP, the most intensive regeneration harvests allowed on federal lands are mandated to retain a minimum of 15% of the area, with 70% of that in aggregates. However, the greatest proportion of harvests in the NWFP area occur as less intensive thinnings designed to meet ecological objectives consistent with late-successional or riparian reserve land designations. Two recent studies of stream temperature responses to harvest have demonstrated either increased buffer effectiveness with increased buffer width (Groom et al., 2011) or inconsistent effectiveness with varying longitudinal continuity of buffers (Janisch et al., 2012). While both of these studies provide useful information, the applicability to federal lands is compromised by context. The study of Groom et al. (2011) includes small and medium fish-bearing streams on private and state lands with 79% of the harvested study reaches being clearfelled. The study of Janisch et al. (2012) was conducted in western Washington in small headwater streams similar to those of the DMS, but again, the harvest activity adjacent to continuous buffer, patchy buffer or no buffer treatments was clearfelling.

Our finding that the variable-width buffers can be effective for moderating the impacts of thinning on small headwater streams has been used to partially justify buffers narrower than the 1-tree- and 2-tree-height guidelines in recent project-level and regional planning efforts for federal lands. The BLM cited the findings of Chan et al. (2004) and Anderson et al. (2007) in their assessment of environmental impacts on water quality of proposed management strategies as part of the regional-scale Western Oregon Plan Revision (commonly referred to as WOPR; USDI, 2008) which addressed management of 1.1 million ha of BLM administered lands in western Oregon. At smaller project and landscape scales, those same findings have recently been cited in environmental assessments by the Siuslaw National Forest for three restoration projects (North Nestuca, Niagra/Boulder, and North Fork Siuslaw) that include thinning from 360 to 2600 ha of 30- to 70-year-old Douglas-fir stands in the Oregon Coast Range. The federal agencies responsible for administering the NWFP continue to deliberate the merits of buffer width alternatives and an interagency science review team recently cited the DMS riparian buffer findings in a new synthesis of harvest impacts on stream temperature (Leinenbach et al., 2013) which was intended to inform a consensus state-of-knowledge among land management and regulatory agencies having divergent perspectives.

There are several reasons why more intensive initial thinning or subsequent re-thinning, to lower densities may be of interest to forest managers. When originally conceived by managers and scientists, the 198 trees ha^{-1} moderate-density retention harvest was considered aggressive. However, this level of retention was substantially greater than the densities experienced by many residual old-growth stands when they were 50–80 years of age (Tappeiner et al., 1997; Poage and Tappeiner, 2002). Thus, thinning to lower residual densities may better emulate the conditions needed to produce desired late-successional tree and stand structures. There has also been increased interest in various forms of more intensive green-tree-retention harvests to create early-seral habitats that are underrepresented in current mesic forest landscapes west of the Cascade crest (Franklin and Johnson, 2012). Observations from the early applications of DMS and other large-scale management experiments has indicated canopy closure can occur rapidly in moderately thinned stands (Chan et al., 2006) and that the thinned stands can be relatively wind-firm when gaps and edges are located away from topographically vulnerable positions (Roberts et al., 2007). All of these suggest scenarios where forests on federal lands might be managed at lower densities indicative of more severe disturbance.

Our early findings indicate that 0.4-ha patch openings represent a more severe disturbance and a substantially greater challenge to 1-tree-height and variable-width buffers than moderate-intensity thinning. This suggests that further assessment of these buffers is warranted if more intensive harvests are proposed. For example, green-tree-retention harvests that retain residual trees as aggregated clusters may create areas of open canopy conditions having microclimate effects similar to those of the 0.4-ha patch openings considered in the DMS. The influences of more intensive harvest are being addressed in a second phase of the DMS. The initial thinning sites were re-thinned between 2009 and 2011, decreasing the moderate-density treatments from 198 to 86 trees ha^{-1}. Although the original 1-tree-height, variable-width and streamside-retention buffers were left intact, a limited number of the 2-tree-height buffers were thinned to 150 trees ha^{-1}. Initial post-second thinning monitoring of downed wood, microclimate and stream temperature occurred in 2012 and results are forthcoming.

4.3. Developments in monitoring and applications

DMS studies have led to improvements in sampling techniques for characterizing streams (Olson and Weaver, 2007), forest structure (Marquardt et al., 2010, 2012), microclimate (Eskelson et al., 2011b, 2013) and amphibians (Kluber et al., 2008). Most of these improvements have directly benefited the conduct of the studies by adding new monitoring components as case studies addressing specific hypotheses or as an evolution of core riparian monitoring approaches. For example, the monitoring of large downed wood internal temperatures (Kluber et al., 2009) was an innovation that addressed a specific hypothesis about habitat suitability for amphibians within and upslope of buffers. At another level, the DMS study of alternative sampling designs for characterizing stand structure (Marquardt et al., 2010, 2012) and spatial patterns of microclimate (Eskelson et al., 2011b) was motivated by a desire to improve the DMS microclimate and microsite monitoring protocols. However, it was conducted as an explicit study of sampling methodology that has broad applicability to riparian forest inventory and monitoring efforts beyond the DMS.

In application, the DMS study outcomes will contribute to larger watershed and landscape assessments and management plans. The regional aquatic conservation strategies defined in the NWFP rely on a consistent framework of management actions to improve watershed conditions; yet site specific context continues to influence local, project-level activities. As described above, the DMS has already demonstrated utility in development of basic ecosystem knowledge and riparian buffer effectiveness that can feed into the conceptualization of large-scale strategic frameworks. Moving forward, much of the applied project- and watershed-scale planning and assessment work will be performed using models and GIS decision support tools (Reeves, 2006). The DMS studies can be useful to informing the structure and local calibration of models and to empirically validate the outcomes of assessment tools application. As an example, the high cost of directly monitoring stream temperature has led regulatory and management agencies to monitor changes in stream shading as a substitute, proxy indicator of potential harvest impacts on thermal loading of streams. The DMS stream shade and water temperature data are being explored to evaluate the validity of reach-level monitoring of changes in shade as an indicator of harvest impacts on stream temperature. At the larger watershed assessment scale, a GIS-based tool (NetMAP; Benda et al., 2007) can provide estimates of potential radiant heat loads at any point within a watershed. The canopy closure, microclimate and stream temperature data from the DMS can be used to provide local field validation of the model-derived estimates of heat load.

4.4. Limitations

A limitation of the DMS riparian buffer study is its restricted focus on relatively small, mostly non-fish-bearing headwater streams. Fish-centric concerns about forest management impacts on water quality, including temperature and turbidity, and stream recruitment of downed wood and allocthonous inputs have been a strong impetus for stream buffering. Shading of the small, narrow stream channels can be provided by relatively short stature shrubs, trees and fairly narrow streamside buffers. Similarly, relatively small pieces of downed wood can serve to create desired in-stream structure due to the narrow confined channels and low hydrologic discharge rates. Similar functions in larger fish-bearing streams may require downed wood inputs of large piece size and shade from taller or denser forest canopies. Although small headwater streams represent a vast proportion of the drainage network area in western Oregon watersheds, they may inadequately represent the range of stream conditions important to the conservation of anadromous fisheries and other species of concern occupying the downstream portions of the watersheds.

The smallest practical experimental unit for assessing riparian responses to forest harvest manipulations may be the reach. Thus, experimental units need be larger than most conventional small-plot silviculture studies to encompass the greater inherent bio-physical variability associated with riparian ecosystems. Because differences in both inherent variability and treatment responsiveness were observed among the riparian vegetation and fauna attributes monitored in the DMS, there are varying degrees of statistical power for addressing different hypotheses. Thus, some of the results are represented as case study findings and others as experimental inferences; both of which can be effective in informing management and policy. The DMS is a good example of a large-scale management experiment that has balanced the trade-offs between the capacity to replicate large-scale experimental units and the ability to monitor meaningful ecological units. As Monserud (2002) concluded in his assessment of large-scale management experiments of the Pacific Northwest, only the DMS has a sample size large enough to have strong statistical power to detect treatment effects across treatment blocks.

5. Conclusions

The riparian component studies of the DMS have been important in filling information gaps identified by science review teams during formulation of the Northwest Plan in the early 1990s. In particular, the DMS studies have generated substantial knowledge about the identities of species and species assemblages that utilize headwater forest habitats and the topographic distribution of habitats within headwater landscapes. For the small headwater streams in constrained channels typical of federal lands in western Oregon, variable-width buffers that encompass the distinct riparian zone are effective in maintaining suitable microclimates and habitats for riparian-dependent fauna in the presence of moderate-intensity upslope thinning. Summer, low-flow streambed temperatures (effectively the temperatures of hyporheic water) remained either similar to- or cooler-than those of untreated reaches regardless of buffer width or thinning intensity. However, the effectiveness of these buffers may be questioned when adjacent to small clearings. Therefore, the influence of higher intensity thinning is currently being assessed in a second phase of DMS treatments and monitoring. It is becoming evident that explicit silvicultural activities such as downed wood manipulations and retention of uncut forest patches near upper headwater boundaries may provide terrestrial linkages among basins; a potentially important landscape conservation strategy for headwaters fauna that may not migrate through less suitable habitats resulting from upslope harvests or provided by riparian corridors in the lower portions of stream networks. Site-specific, reach-level research and monitoring efforts will continue to be needed to inform and validate emerging modeling, landscape assessment, and decision support tools applicable to larger-scale watershed and landscape planning and monitoring efforts.

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