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Edge-related gradients in microclimate in forest aggregates following structural retention harvests in western Washington

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Abstract

Aggregated retention is now a common method of regeneration harvest in forest ecosystems managed for both timber and ecological objectives. If residual forest aggregates are to serve as temporary refugia for species sensitive to disturbance or environmental stress, microclimatic conditions must be sufficiently buffered to allow for their persistence. In 1-ha aggregates at three experimental sites in western Washington, we quantified spatial gradients in microclimate (light, air and soil temperature, and soil moisture), effects of aspect on these gradients, and how microclimate compared to conditions in adjacent harvest areas and larger tracts of undisturbed forest (controls). Light availability and temperature were greatest at the edge, but declined sharply inside the aggregate, with most change occurring within 20 m of the edge. Beyond this distance, light generally declined to levels observed in the controls. Soil temperatures exhibited greater spatial variation and stabilized further from the edge (10–30 m), but air temperatures were generally higher than those in controls. Soil moisture exhibited no spatial trends and was comparable among aggregates, harvest areas, and controls. Aspect exerted strong effects on light and temperature, particularly within 15 m of the edge, as did forest structure. Where tree density was low, microclimatic gradients were less steep and aspect-related differences were small. Comparisons with previous studies of ground vegetation indicate that microclimatic effects were consistent, in part, with declines among some groups of vascular and non-vascular plants; however, these declines were restricted to edge environments (5–10 m) and were unaffected by aspect. Our results suggest that 1-ha aggregates are sufficiently large to contain areas with light, temperature, and soil moisture that are comparable to those in undisturbed forest and suitable, in the short-term, for persistence of forest-dependent species.

Keywords: Aggregated retention; Edge effects; Forest microclimate; Light; Temperature; Variable-retention

1. Introduction

Increasingly, forest managers are designing silvicultural systems to meet multiple objectives (e.g., maintaining biodiversity, producing timber, and enhancing wildlife habitat). Structural retention harvests that retain elements of the original forest (live trees, snags, and logs) have been adopted as one method to achieve these objectives (Franklin et al., 1997; Deal, 2001; Drever and Lertzman, 2003). On federal lands in the Pacific Northwest, the current policy for regeneration harvests within the range of the northern spotted owl requires that live trees are retained over at least 15% of the harvest unit, with 70% of this retention as 0.2- to 1.0-ha aggregates of undisturbed forest (USDA and USDI, 1994). Among other functions, aggregates are intended to provide refugia for disturbance-sensitive species and dispersal sources for recolonization of adjacent harvest areas (Franklin et al., 1997). However, this requires that microclimatic conditions within forest aggregates are sufficiently buffered to maintain species sensitive to environmental changes. Patches that are too small or permeable may be vulnerable to microclimatic changes that diminish their ecological integrity. Thus, understanding the potential for edge effects is critical to designing variable-retention systems that employ aggregates to maintain and facilitate recovery of biological diversity after harvest.

Studies of clearcut-forest boundaries provide the empirical basis for much of our understanding of edge effects. Radiation, temperature, and other physical processes can differ substantially between forest-edge and interior environments. Steep gradients in microclimate are typical along the boundary

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between recently cut and intact forest. Most change appears to occur within 40–50 m of the edge (e.g., Chen et al., 1993, 1995), however, stabilization may occur at considerably shorter distances for variables that are less sensitive to ambient conditions (e.g., soil temperature; Williams-Linera, 1990; Young and Mitchell, 1994; Camargo and Kapos, 1995; Davies-Colley et al., 2000). In contrast, some microclimatic variables (e.g., humidity, wind speed) are highly sensitive to forest edges and effects can be detected at distances >200 m (e.g., Chen et al., 1995). Topography and latitude can diminish or amplify the depth and magnitude of these effects through changes in solar angle or heat load (e.g., Camargo and Kapos, 1995; Chen et al., 1995; Turton and Freiburger, 1997). Forest structure can also affect these gradients. Edge contrast, the difference in canopy height between cleared and intact forest, and edge closure, the density and vertical distribution of foliage along the edge, can affect light penetration and air movement and thus gradients in temperature and humidity (Canham et al., 1990; Matlack, 1993; Chen et al., 1995). Moreover, both can change over time with growth of the regenerating forest and in-filling along the edge (e.g., Denyer et al., 2006).

In this study, we explore edge-related gradients in microclimate (light, temperature, and soil moisture) within residual forest patches resulting from aggregated-retention harvest of mature, coniferous forests in the southern Cascade Range of western Washington. To our knowledge, this is the first such study of forest aggregates and one of the few studies that have explored the microclimatic effects of structural retention (e.g., Barg and Edmonds, 1999; Chen et al., 1999; Zheng et al., 2000; Heithecker and Halpern, 2006). We utilize a subset of the aggregated retention and control treatments, from the Demonstration of Ecosystem Management Options (DEMO) Study, a large-scale experiment that examines ecological responses to variable-retention harvest (Aubry et al., 1999). We address the following questions: (1) do forest aggregates show consistently greater light availability, greater summer temperature, and lower soil moisture than larger blocks of undisturbed forest? Conversely, do they support microclimatic conditions that differ significantly from those in adjacent harvest areas? (2) How do light, temperature, and soil moisture vary with distance from forest edge? (3) How do these gradients vary with aspect? These characteristics represent important mechanistic links between the manipulation of forest structure and the responses of forest organisms to resulting changes in microclimate. We conclude by discussing the relevance of microclimatic patterns for biological responses at these sites using data on the edge-related responses of vascular and non-vascular plants (Nelson and Halpern, 2005a,b).

2. Methods

2.1. Study sites

Studies were conducted at three sites in the southern Cascade Range, Washington, within the framework of the DEMO study (Aubry et al., 1999; Halpern et al., 1999, 2005). The sites – Butte (BU), Paradise Hills (PH), and Little White Salmon (LWS) – occur at elevations between ~800 and 1158 m and vary in slope and aspect (Table 1). Soils are moderately deep and well-drained loams to loamy sands derived from andesite, basalt, or breccia parent materials, or from aerial deposits of pumice (Wade et al., 1992). The climate is characterized by warm, dry summers and cool, wet winters. Most precipitation falls between October and April resulting in a long period of summer drought (Franklin and Dyrness, 1988). Additional details on the physical environments of these sites are contained in Halpern et al. (2005).

All forests were dominated by Douglas-fir (*Pseudotsuga menziesii*), but stand age, structure, and species composition varied markedly (Table 2; see also Halpern et al., 1999, 2005; Maguire et al., 2007). Forests at BU were relatively young (70–80 years) and dense (830–1000 stems ha^{-1}) with a significant component of western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) in the subcanopy; canopy height averaged 28–33 m. Forests at PH were mature (110–140 years), moderately dense (590–1000 stems ha^{-1}), and structurally and compositionally more diverse than at BU or LWS. *T. heterophylla* comprised a significant proportion of canopy stems and Pacific silver fir (*Abies amabilis*) was common in the understory; canopy height averaged 27–32 m. Forests at LWS were the oldest (140–170 years) and very open (230–300 stems ha^{-1}), comprised of large *P. menziesii* with a well-developed shrub layer of vine maple (*Acer circinatum*) (~70% cover); canopy height averaged 49 m. Additional information on understory composition is contained in Halpern et al. (1999, 2005).

Table 1
Environmental attributes of forest aggregates and reference environments at each site

Site	Latitude, longitude (°)	Environment	Elevation (m)	Slope (°)	Aspect (°)
Butte (BU)	46.37N, 122.20W	Harvest area	988–1134	30	138
		Forest aggregates	988–1134	31	145
		Control	963–1158	28	146
Paradise Hills (PH)	46.01N, 121.99W	Harvest area	985–1027	6	157
		Forest aggregates	985–1027	6	155
		Control	853–902	6	133
Little White Salmon (LWS)	45.86N, 121.59W	Harvest area	792–939	29	74
		Forest aggregates	792–939	28	74
		Control	841–1000	23	316

Table 2
Variation in predicted heat load and overstory structure among forest aggregates and reference environments at each site

Site	Variable	Harvest area		Forest aggregates		Control		P
		Mean	(S.E.)	Mean	(S.E.)	Mean	(S.E.)	
Butte (BU)	Heat load[a]	0.77	(0.02)	0.78	(0.02)	0.81	(0.02)	0.261
	Basal area (m^2 ha^{-1})[b]	–	–	67	(3.6)	58	(2.2)	0.026
	Tree density (no. ha^{-1})[b]	–	–	830	(69.0)	1014	(111.9)	0.280
	Canopy height (m)[c]	–	–	33	(0.5)	28	(0.7)	<0.001
Paradise Hills (PH)	Heat load	0.90	(0.01)	0.91	(0.01)	0.89	(0.01)	0.101
	Basal area (m^2 ha^{-1})	–	–	61	(3.5)	77	(1.8)	<0.001
	Tree density (no. ha^{-1})	–	–	585	(40.0)	1001	(47.2)	<0.001
	Canopy height (m)	–	–	32	(0.8)	27	(0.3)	<0.001
Little White Salmon (LWS)	Heat load	0.55 a	(0.02)	0.58 a	(0.02)	0.79 b	(0.02)	<0.001
	Basal area (m^2 ha^{-1})	–	–	72	(11.8)	69	(7.9)	0.804
	Tree density (no. ha^{-1})	–	–	305	(55.3)	233	(29.6)	0.216
	Canopy height (m)	–	–	49	(1.1)	49	(0.6)	0.632

P-values for heat load are from one-way ANOVA (n = 19–26 microclimatic stations per environment); means followed by different letters differ significantly based on a Tukey HSD test. P-values for basal area, tree density, and tree height are from two-sample t-tests (n = 10 plots for forest aggregates and 19 or 20 plots for harvest area and undisturbed forest).

[a] Heat load (unitless) based on McCune and Keon (2002).

[b] Trees ≥5 cm dbh.

[c] Mean height of dominant and codominant trees.

2.2. Sampling design

At each site we used two of the six, 13-ha experimental treatments that comprise the DEMO study: 15% aggregated retention (15%A; 15% of the original basal area) and an undisturbed control (100%, no harvest). In 15%A, two 1-ha circular patches (56.4 m radius) were retained, separated by a distance of ~115 m (Fig. 1). All merchantable trees (>18 cm dbh) were cut and yarded from the surrounding harvest area. Smaller non-merchantable trees were left standing at BU, but were felled at PH (similar-sized stems were uncommon at LWS). Logging was completed in 1997 (BU and PH) or 1998 (LWS) (for details see Halpern and McKenzie, 2001; Halpern et al., 2005). Microclimatic measurements were made during summer 2004, 6 or 7 years after harvest.

To characterize microclimatic gradients within and adjacent to forest aggregates, we established two perpendicular transects extending from the center of each aggregate, across the edge, to a distance of 63 m into the harvest area (Fig. 1). Microclimatic conditions were sampled at 15 points (stations) along each transect: eight within the aggregate (0, 5, 10, 15, 20, 30, 40 and 56.4 m from the edge) and seven in the harvest area (5, 10, 15,

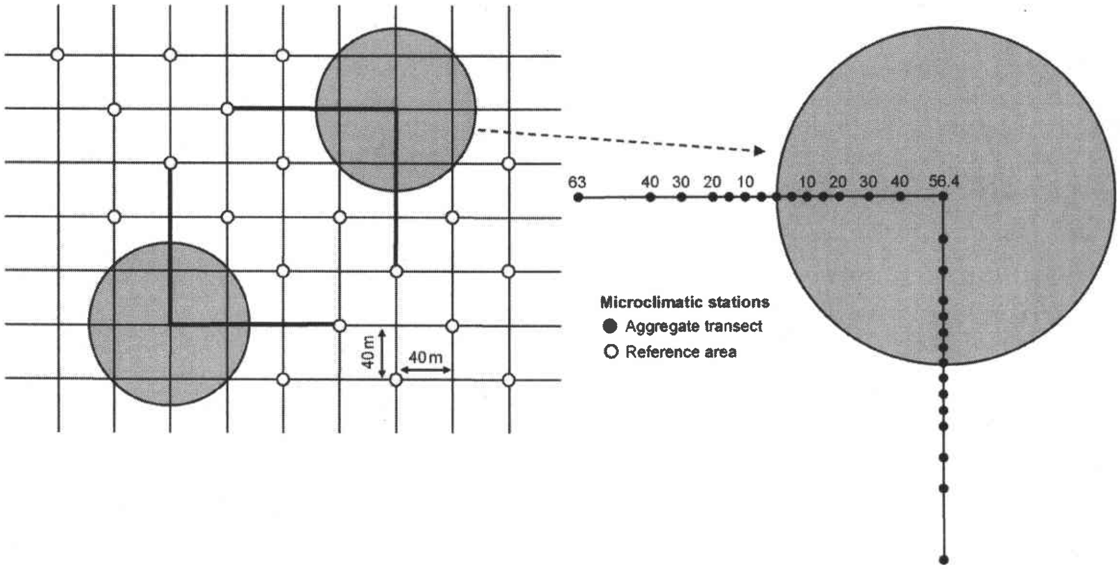

Fig. 1. Sampling design illustrating the distribution of microclimatic stations. For aggregates, stations were placed at 15 points spaced 5–23 m apart extending from the aggregate center 63 m into the harvest area. Reference stations in the harvest area (or undisturbed forest [control]; not shown) were established at 20 (in one case 19) points randomly selected from permanent plots on a systematic grid (40 m × 40 m spacing).

20, 30, 40, and 63 m from the edge). Edge was defined as a fixed distance from the aggregate center—56.4 m, the radius of a 1-ha circle.

In addition to these transects, microclimatic conditions were sampled in two reference environments at each site: 11 ha of harvested area surrounding the aggregates and 13 ha of undisturbed forest comprising the control treatment (henceforth, control). In each environment, microclimatic stations were established at 20 (in one case 19) locations randomly selected from permanent grid points evenly spaced on a 40 m × 40 m sampling grid (Fig. 1) (Aubry et al., 1999). Each station was located in a random direction, 1.5 m from the selected grid point.

2.3. Measurements of topography and overstory structure

To evaluate potential differences in microclimate due to variation in topography or overstory structure, we collected additional data at each station. At each point we measured slope and aspect; from these and latitude we derived an index of heat load (McCune and Keon, 2002). Data on overstory structure were obtained from measurements of permanent tree plots associated with the systematic grid in each experimental unit. For reference environments (harvest area and control), these corresponded to the randomly selected grid points (n = 19–20). For forest aggregates, they corresponded to the five grid points within each aggregate (n = 10 per site). Within each tree plot, all stems $\geq$5 cm diameter at breast height (dbh) were identified by species, assigned to one of four canopy classes (suppressed, intermediate, codominant or dominant), and measured for diameter. Heights of all dominant and codominant trees were estimated from species- and site-specific height:diameter equations (D. Maguire, unpublished data).

2.4. Microclimatic measurements

At each microclimatic station we sampled four variables—light, air temperature, soil temperature, and soil moisture. An index of light availability was obtained from hemispherical photography of the forest canopy (Lieffers et al., 1999). A Nikon Coolpix 990 digital camera with a Nikon FC-E8 fisheye converter was placed on a monopod 2 m above the ground surface (above most understory vegetation) and leveled, with the top of the camera oriented north. Photographs were taken under overcast sky conditions between June and November 2004. Images were analyzed with the software, Gap Light Analyzer 2.0 (GLA; Frazer et al., 1999), employing the standard overcast sky model (UOC). Total transmitted light or photosynthetic photon flux density (PPFD; mol m^{-2} day^{-1}) was calculated for the growing season (June–September) (Frazer et al., 1999; Drever and Lertzman, 2003).

Air and soil temperature were measured using temperature data loggers (Model DS1921G, iButton Thermochron, Maxim/Dallas Semiconductor Corp., Dallas, TX). Two loggers were installed at each station: the first, on a wooden stake 1 m above the ground surface (air), the second at 15 cm beneath the mineral soil surface (soil). For measurements of air temperature, loggers were placed on the inside of a small (10 cm long) plastic shield covered with aluminum foil to prevent direct radiation and perforated to allow airflow to minimize heat accumulation. Plastic containers were attached to a wooden arm extending perpendicular from the top of each stake. Temperature was recorded hourly at each point over a period of 2–3 weeks between late July and late September to sample the most stressful portion of the growing season. Measurements were taken synchronously within each site, but were staggered in time among sites (LWS = 19 July–5 August, BU = 10–31 August, and PH = 1–23 September).

Volumetric soil moisture was measured using time domain reflectometry (TDR; see Gray and Spies, 1995 for details). Stainless steel probes (30 cm) were inserted at an angle of 30° from the soil surface to sample the upper 15 cm of mineral soil. Measurements were taken multiple times during the growing season. At each measurement, all points within a site were sampled over a period of 1–2 days dry weather (no precipitation in the previous 48 h); all sites were visited within the same 1-week period. At the time of sampling, probes were attached to the TDR monitor with alligator clips soldered to coaxial wire; data were collected on a palmtop computer. Volumetric soil moisture was calculated using the calibration curves of Gray and Spies (1995).

2.5. Data reduction

From the continuous measurements of air and soil temperature at each site, 5 days were selected to represent physiologically stressful summer conditions (hot, sunny days). We focus on these rather than average conditions over the growing season because they are more likely to limit persistence of species associated with forest-interior environments. From hourly readings for each of these days, we calculated a daytime mean and maximum temperature at each microclimatic station for air (06:00–20:00 h) and soil (09:00–23:00 h, displaced 3 h to capture the heating lag between air and soil; e.g., Heithecker and Halpern, 2006). We then computed an average mean and maximum for the 5-day sample. For analysis of soil moisture, the driest measurement during the growing season (4–12 August) was selected from the set of periodic samples at each station. Although soil moisture often declines into September (Gray and Spies, 1997; Gray et al., 2002), several extended periods of precipitation precluded use of the September measurements.

For the aggregates, data representing distance from edge were averaged for pairs of transects within each site: south- and west-facing transects representing warmer exposures (S/W; >135° and <315°) and north- and east-facing transects representing cooler exposures (N/E; >315° and <135°).

2.6. Comparability of physical environments and overstory structure

Comparisons between forest aggregates and reference environments (harvest area and control) were conducted separately for each site because of marked differences in climate among locations. However, even within sites, there was variation in topography and overstory structure, which can affect light availability and temperature. To test for systematic differences in topography among the control, harvest area, and forest aggregates at each site, we used one-way analysis of variance (ANOVA) to compare predicted values of heat load ($n = 19$–26 stations per environment). If environments differed significantly ($P \leq 0.05$), individual means were compared with a Tukey HSD test (Zar, 1999). To test for significant differences ($P \leq 0.05$) in overstory structure between controls and aggregates, two sample *t*-tests ($n = 20$ and 10 plots, respectively) were used to compare tree density, basal area, and canopy height (average height of dominant and codominant trees).

2.7. *Microclimatic gradients within aggregates and comparisons to reference environments*

For aggregates at each site, microclimatic means (and S.E.s) were plotted relative to distance from the edge for each aspect groups (S/W and N/E). To compare these values to those in the harvest area and control, we used a simple and conservative approach that accounted for microclimate variation within these reference areas (see Laurance et al., 1998). From the 20 (or 19) microclimatic stations representing each reference environment, we generated a 95% confidence interval around the mean for each microclimatic variable. Means of aspect groups at each distance that fell outside the confidence interval were considered to differ from the reference environment. Formal statistical tests were not conducted due to the small sample size at each distance ($n = 2$). Instead, our primary objective was to document spatial trends and the range of distances over which means differed from the two reference areas.

3. Results

3.1. *Comparability of topography and overstory structure between aggregates and reference environments*

Heat load (predicted from slope and aspect) was comparable between forest aggregates and reference environments at BU and PH (Table 2). At LWS, however, heat load was significantly greater in the control than in the aggregates, reflecting its more westerly aspect (Table 1). As a result, reference temperatures were higher than expected in the control.

Overstory structure showed significant variation in two of the three sites (Table 2). At BU, where differences were fairly small, basal area was ~25% greater and canopy height 18% greater in the aggregates than in the control. However, at PH, density and basal area were 25 and 70% greater in the control; thus, reference values for light and daytime temperature were likely to be lower than expected.

3.2. *Transmitted light*

Transmitted light (PPFD) declined steeply inside the edges of aggregates at each site (Fig. 2). Patterns of decline were similar at BU and PH: PPFD dropped more rapidly along N/E than S/W transects, with the greatest reduction within 10–15 m of the edge (Fig. 2). At these distances, PPFD was 1.5 to nearly three times higher along S/W exposures. Beyond 15 m, PPFD generally declined to levels observed in the controls (except for S/W transects at PH).

Declines in PPFD were not as steep at LWS (Fig. 2) where tree density was markedly lower and the edges of aggregates were less continuous. As a result, differences between aspects were small and PPFD remained elevated above that in the control at nearly all distances from the edge.

At all sites, light levels within aggregates were consistently lower than those in the harvest area (Fig. 2). In addition, aggregates significantly reduced PPFD in the adjacent harvest area to distances of 10–30 m. For four of six aspect groups,

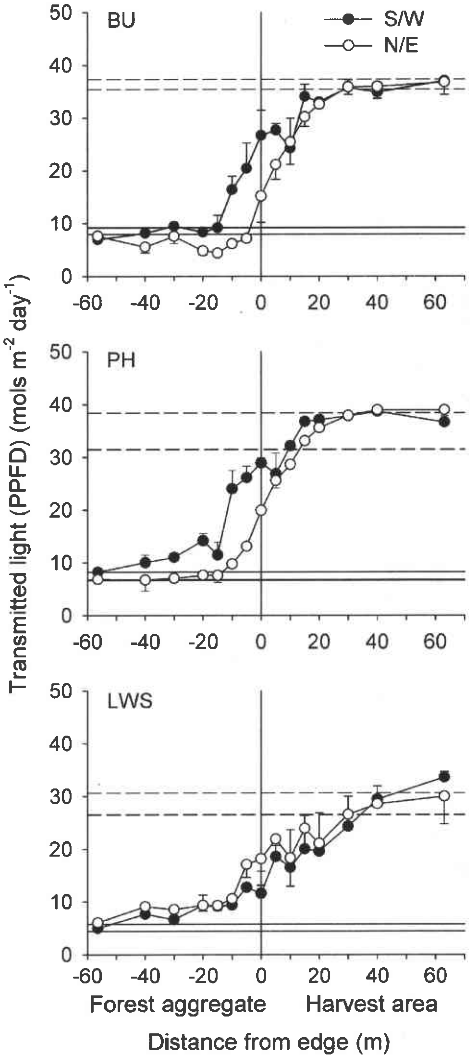

Fig. 2. Gradients in transmitted light (PPFD) with distance from the aggregate edge at each of the three study locations (BU = Butte, PH = Paradise Hills, LWS = Little White Salmon). Values are the means ('+' or '−' 1S.E.) at each distance of two transects representing south- and west-facing aspects (S/W) or north-and east-facing aspects (N/E). Solid and dashed lines are 95% confidence intervals of the mean ($n = 20$ [or 19]) for reference stations in the control (undisturbed forest) and harvest area, respectively.