Variation in microclimate associated with dispersed-retention harvests
in coniferous forests of the Pacific Northwest

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This is to certify that I have examined this copy of a master's thesis by:

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Abstract

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Green-tree or structural retention is becoming increasingly common as a method of regeneration harvest in the Pacific Northwest. It is assumed that amelioration of forest-floor microclimate is one mechanism by which retention of live trees enhances the survival of forest organisms and the potential for ecosystem recovery following timber harvest. However, limited information exists on the relationship between residual forest structure and changes in microclimate. In this study I examine variation in transmitted light (PPFD), air and soil temperature, and soil moisture across a broad gradient of dispersed retention in mature, coniferous forests at three locations in western Washington. Treatment means and within-treatment variation (coefficients of variation among sample points within treatments) were compared for warm, sunny days in 7- to 8-yr-old experimental harvest units representing 0, 15, 40, and 100% retention of original basal area. Multiple linear regression was used to model the effects of topography, overstory structure, understory vegetation, and logging slash on local microclimate. PPFD and mean and maximum daytime air and soil temperatures decreased with level of retention. PPFD showed the strongest response, but did not differ between 40% retention and the control. Mean and maximum air temperatures (at 1 m) were significantly greater in 0 and 15% retention than in the control. Among harvested treatments, mean temperature was greater in 0 than in 40% retention, but otherwise mean and maximum temperatures were comparable. Mean and maximum soil temperatures (15 cm depth) differed only between 0% and the control (100%). Minimum air and soil temperatures and late summer soil moisture did not differ among treatments. Within-treatment variability (CV) did not differ significantly with level of retention for any of the variables sampled, although CV for soil temperature showed a consistent increase with decreasing retention. Topography, residual forest structure, and ground-surface variables were good predictors of PPFD and mean and maximum temperatures (R^2 of 0.55-0.85 in multiple regression models), but were poorer predictors of minimum temperatures and soil moisture (R^2 of 0.10-0.51). Canopy cover was the most frequent predictor in all models and understory vegetation cover was a significant predictor in models of soil temperature. Variation in microclimate among experimental treatments appeared consistent with the responses of bryophyte, herbaceous, and fungal communities on these sites. In combination, these results suggest that 15% retention — the minimum standard on federal forestlands in the

Pacific Northwest — does little to ameliorate microclimatic conditions relative to those in clearcut sites.

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I would like to express deep gratitude and respect for my thesis advisor Charlie Halpern whose patience, knowledge, and guidance made this study possible. His intricate knowledge of forest ecosystems provided invaluable insight into a field, the complexity of which, I now barely have begun to understand. I would additionally like to acknowledge my advisory committee, Donald McKenzie and Andrew Gray, for their insight and analytical prowess. I would also like to thank Michael McClellan and Charles Peterson for supporting me both in my education and career, and for helping me find a home in the overwhelming field of ecological research.

Two field assistants deserve recognition - Michael Olsen and Timothy Erickson. Their hard work, patience, and ingenuity developing data collection techniques were fundamental for successfully completing this study's physically demanding and often excruciatingly tedious field work.

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INTRODUCTION

In the Pacific Northwest, variable-retention harvests that retain elements of older forest structure (large live trees, snags, and logs) have replaced clearcut logging on federal forest lands within the range of the northern spotted owl (Franklin et al. 1997, Aubry et al. 1999, Beese et al. 2003). Partial canopy retention is intended to moderate loss of biological diversity and to facilitate recovery of the regenerating forest. Although there are various mechanisms by which overstory retention can minimize species' loss and facilitate ecosystem recovery, it is generally assumed that amelioration of environmental stress (excess solar radiation, extremes in temperature, or soil moisture deficit) plays a critical role (Chen et al. 1992, Chen et al. 1995, Franklin et al. 1997, Barg and Edmonds 1999). However, few studies have examined the relationships between residual forest structure and microclimate in the context of variable-retention systems (but see Barg and Edmonds 1999, Chen et al. 1999, Zheng et al. 2000).

Some aspects of microclimate show strong and predictable relationships with forest structure. For example, solar radiation at the forest floor is directly related to the amount and spatial distribution of overstory cover (Drever and Lertzman 2003). Other elements of microclimate are less predictable from forest structure. For example, soil and ground-surface temperatures are affected by incoming (short-wave) and outgoing (long-wave) radiation, which are determined, in part, by the full vertical profile of vegetation cover (Yoshino 1975, Aussenac 2000, Prevost and Pothier 2003). Removal of canopy cover increases solar radiation which should elevate daytime temperatures; however, this should also result in greater loss of long-wave radiation, thus lowering nighttime temperatures and increasing potential for frost (Groot and Carlson 1996). Canopy removal can also facilitate growth of understory vegetation, thereby reducing heat exchange with the soil, and mitigating, to some degree, loss of overstory cover. Effects of forest structure on soil moisture may also be difficult to predict: reductions in canopy cover may lead to more evaporation from the soil surface (Morecroft et al. 1998, Chen et al. 1999), but less transpirational loss (e.g., Adams et al. 1991, Breda et al. 1995, Gray et al. 2002).

Dispersed retention of trees should serve to moderate forest-floor microclimate and thus benefit organisms sensitive to excess solar radiation or extremes in temperature. Logically, these benefits should increase with the amount of retention. However, little research has been devoted to understanding the nature of this relationship (e.g., the existence of thresholds), or to identifying the features of residual forest structure that most influence microclimatic variation (Barg and Edmonds 1999, Drever and Lertzman 2003). Relative to clearcut logging, dispersed retention should also affect the spatial variability of microclimate in the forest understory. Patchy shading by residual trees, local accumulations of logging slash, and differential survival and growth of ground vegetation should increase the spatial heterogeneity of light, temperature, and soil moisture, and thus spatial variability in the survival of forest organisms that are sensitive to variation in these environmental factors (Hungerford and Babbitt 1987, McInnis and Roberts 1995, Gray and Spies 1997, Grimmond et al. 2000, Martens et al. 2000). However, to date, studies of forest microclimate have emphasized the average conditions of treatments, not the magnitude or sources of variation within them (but see Chen et al. 1999, Zheng et al. 2000, Drever and Lertzman 2003).

In this study, I examine patterns of light availability, air and soil temperature, and soil moisture during mid- to late summer, among experimental harvest treatments that represent a broad gradient of overstory retention (0-100% of original basal area) in mature coniferous forests of western Washington, USA. The treatments are part of the Demonstration of Ecosystem Management Options (DEMO) study, a regional experiment in variable-retention harvest that evaluates the role of level and pattern of retention in persistence and recovery of organisms associated with late-seral forests (Aubry et al. 1999, Halpern et al. 2005). In this study, I compare mean conditions and variation within treatments, and identify elements of forest structure (including overstory attributes, understory vegetation, and logging slash) that show the strongest relationships to microclimate. I address the following specific hypotheses:

Hypothesis 1: Mean responses. (a) Light availability and mean and maximum air and soil temperatures decline with increasing overstory retention.

(b) In contrast, minimum air and soil temperatures and volumetric soil moisture increase with overstory retention.

Hypothesis 2: Within-treatment variability. Within-treatment variation in microclimate is greater at intermediate levels of retention (15 and 40%) than in clearcut (0%) or undisturbed forest (100%) reflecting the patchy distributions of sunny and shaded microsites created by dispersed trees.

Hypothesis 3: Predictors of microclimate. (a) Ability to predict local microclimate from residual forest structure (including overstory and understory) is greater for light and air temperature than for soil temperature or soil moisture. (b) Simple measures of topography and overstory structure are sufficient to model local light or air temperature, but are not sufficient to model soil temperature or soil moisture.

In combination, tests of these hypotheses yield insights into the ways in which variable-retention harvests and residual forest structure in particular, mediate patterns of light availability, temperature, and soil moisture. I conclude by considering whether patterns of microclimatic variation are consistent with biological responses observed in companion studies on these sites.

STUDY AREAS

This study was conducted at three of the six experimental blocks that comprise the DEMO study — Butte (BU), Little White Salmon (LWS), and Paradise Hills (PH). All are located in the southern Cascade Range of Washington (Aubry et al. 1999). The climate of this region is characterized by relatively warm, dry summers and cool, wet winters with most precipitation falling between October and April (Franklin and Dyrness 1988). However, local climatic conditions vary both among and within the experimental blocks, reflecting variation in latitude, elevation, and aspect (Table 1) (see also Halpern et al. 1999, Halpern et al. 2005). 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). Three forest zones are represented, defined by the climax tree species: *Tsuga heterophylla* (BU), *Abies grandis* (LWS), and *Abies amabilis* (PH). At the time of harvest, forests were dominated by *Pseudotsuga menziesii* with no previous history of management. Forest age and structure varied among blocks, and to a lesser degree, among treatment units within blocks (Table 1). BU (70-80 yr) and PH (110-140 yr) were relatively dense forests (~1000 trees/ha); LWS (140-170 yr) was characterized by large, widely spaced trees (~220 trees/ha) (Table 1). Understory development also varied markedly among blocks. Cover of herbs and tall shrubs (primarily vine maple) was much higher at LWS (means of 43 and 69%, respectively) than at BU (27 and 20%) or PH (19 and 13%) (Halpern et al. 2005).

TABLE 1. Environmental attributes, post-harvest forest structure, and ground conditions in the four treatment units in each block.

Block	Level of retention (%)	Lat., long. (deg)	Stand age[a] (yr)	Elevation (m)	Slope (deg)	Aspect[b] (deg)	Basal area[c] (m^2/ha)	Tree density[c] (no./ha)	Canopy cover[d] (%)	SDI[e]	Veg cover[f] (%)	Slash cover (%)
Butte	0	46.37N,	70-80	988-1134	30	138	0.8	61	42	14	38	22
	15	122.20W		1000-1195	31	151	13.3	151	64	72	34	20
	40			1195-1268	24	87	30.5	513	83	110	41	14
	100			963-1158	28	146	58.0	1014	89	152	19	0
Little	0	45.86N,	140-170	792-939	29	74	0.5	51	47	11	83	8
White	15	121.59W		902-1012	23	324	7.6	45	58	38	83	8
Salmon	40			829-981	25	325	35.8	121	78	119	81	14
	100			841-1000	23	316	65.5	223	91	152	48	0
Paradise	0	46.01N,	110-140	985-1027	6	157	0.2	48	39	4	25	32
Hills	15	121.99W		890-963	13	281	9.9	61	51	56	26	25
	40			927-972	5	346	23.0	128	71	93	26	16
	100			853-902	6	133	77.4	1003	90	176	18	0

Note: All values (except for Lat., long. and elevation) are based on means of 18-20 sample points per treatment.

[a] Age at time of harvest

[b] Derived from mean southwestness: $\cos(aspect - 225°)$

[c] Trees ≥ 5 cm dbh

[d] Overstory canopy cover estimated from hemispherical photographs using GLA software (Frazer et al. 1999).

[e] Stand density index: $(\text{basal area} * \text{tree density})^{1/2}$

[f] Cover of understory vegetation <1.5 m tall (maximum 100%)

METHODS

Experimental treatments

The DEMO experimental design consists of six, 13-ha treatments that differ in level of retention (percentage of original basal area) and/or the spatial pattern in which trees are retained (dispersed vs. aggregated) (Aubry et al. 1999). For this study, four of these treatments were selected to represent a gradient of dispersed overstory retention (Fig. 1):

(1) 100%: control (no harvest).

(2) 40% dispersed (40%D): residual trees are dominants or co-dominants evenly dispersed through the harvest unit.

(3) 15% dispersed (15%D): residual trees are dominants or co-dominants evenly dispersed through the harvest unit; 15% is the minimum standard for regeneration harvests on federal lands within the range of the northern spotted owl (USDA and USDI 1994).

(4) 0%: represented by the harvested portions of the 15% aggregated retention treatment (15%A) within which all merchantable trees (>18 cm dbh) were removed. Smaller non-merchantable trees were left intact at BU, were felled at PH, and were largely absent at LWS.

Because the initial density and basal area of trees varied widely among blocks, treatments at a common level of retention often exhibited wide variation in residual density and basal area (Table 1).

Yarding was conducted with helicopters at BU and LWS, and with ground-based machinery at PH. Harvest operations were completed in fall 1997 at BU and PH, and in fall 1998 at LWS (for details see Halpern and McKenzie 2001, Halpern et al. 2005). Microclimatic measurements (see next section) were taken during summer 2004, 6-7 yr after harvest.

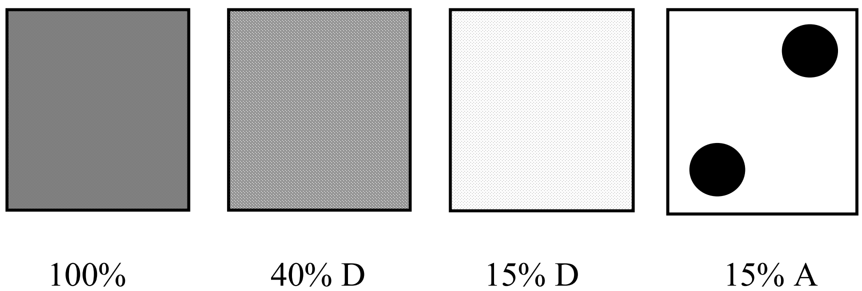

Figure 1. Schematic representation of experimental treatments sampled for microclimate. Harvest units are 13 ha in area. Treatment codes are: 100% = control; 40%D = 40% dispersed retention; 15%D = 15% dispersed retention; and 15%A = 15% aggregated retention. Sample points representing 0% retention were restricted to harvested areas of 15%A.

Sampling design

Within each experimental unit, I randomly selected 20 (in one case 21) from a pool of 22-32 permanent tree plots (0.04 ha; 11.3 m radius) spaced 40 m apart on a systematic grid of 7 x 9 or 8 x 8 points (Halpern et al. 2005). To represent the 0% retention treatment, only plots within the harvested portion of 15%A were considered. Within each plot a microclimatic station was established in a random direction 1.5 m from the plot center. At each point I measured slope, aspect (transformed to "southwestness" [*cos* (*aspect* – *225°*)]), and four microclimatic variables: light, air temperature, soil temperature, and soil moisture.

Light

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 leveled on a monopod 2 m from the ground (above understory vegetation except at LWS where vine maple was occasionally taller), 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 through September) (Frazer et al. 1999, Drever and Lertzman 2003).

Air and soil temperature

Air and soil temperature were measured using temperature data loggers (Model DS1921G, iButton Thermochron, Maxim/Dallas Semiconductor Corp., Dallas, Texas). Two loggers were placed at each point: the first on a wooden stake 1 m above the ground surface (air), the second at 15 cm beneath the soil surface (soil). For measurements of air temperature, loggers were placed on the inside of one-half of a small (10 cm long) plastic container shielded with aluminum foil to prevent direct radiation, and perforated to allow airflow and 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 2-3 wk period between mid July and late September 2004 to sample the most stressful portion of the growing season. Measurements were taken synchronously within each block, but sampling was staggered in time among blocks (LWS = 19 July to 5 August, BU = 10 to 31 August, and PH = 1 to 23 September 2004).

Soil moisture

Volumetric soil moisture was measured using time domain reflectometry (TDR; see Gray and Spies 1995 for details). Stainless steel probes, 30 cm long, were inserted at an angle of 30° from the soil surface to sample the upper 15 cm of soil; probes remained in place for the entire sampling period. Multiple measurements were taken over the growing season. At each measurement, all points within a block were sampled over a 1-2 day period of dry weather (no precipitation in the previous 48 hr) and all blocks were visited within the same 1-wk period. Probes were attached to a TDR monitor with alligator clips soldered to coaxial wire; data were recorded on a palmtop computer. Volumetric soil moisture was calculated using calibration curves of Gray and Spies (1995).

Overstory structure and understory cover

Within each tree plot, all stems ≥5 cm in diameter at breast height (dbh) were measured for diameter. Heights of all trees were estimated from species- and treatment-specific height:diameter equations (D. Maguire, unpublished data). Four predictors of overstory structure were then generated for each plot: total tree density, total basal area, a simple stand-density index ($[\text{density} * \text{basal area}]^{1/2}$), and total tree height (summed height of all trees; Drever and Lertzman 2003). In addition, overstory canopy cover was obtained from the hemispherical photo taken at the center of each plot using GLA software (Frazer et al. 1999).

To quantify the potential shading effects of understory vegetation and logging slash, two additional estimates were made at each microclimatic station. Using a 1-m^2 frame centered on each wooden post, visual estimates of percent cover (nearest 1%) were made for all vegetation <1.5 m tall and for logging slash (fine branches and other woody debris resulting from harvest operations).

Data reduction

From the continuous measurements of air and soil temperature, days were grouped as either warm/sunny or cool/cloudy (Fig. 2). Given the emphasis of this study on amelioration of microclimatic stress, 5 days were randomly selected from the pool of warm/sunny days at each block. Based on hourly readings at each sample point, I calculated a mean daytime temperature for air (06:00 to 20:00 hr) and soil (09:00 to 23:00 hr, displaced 3 hr to capture the heating lag between air and soil). I also identified the minimum and maximum temperature. I then computed means of the five sample days at each point. From these 5-day, point-scale means I generated a mean and coefficient of variation (CV) for each treatment unit. These yielded a total of 12 "response variables" for air and soil temperature.

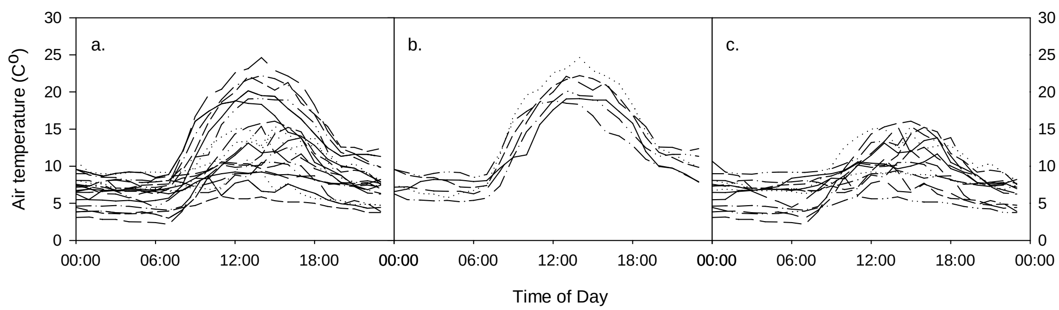

Figure 2. Daily fluctuations in air temperature (1 m from the ground surface) in the 0% retention treatment at PH for (a) all sample days (n = 22), (b) sunny days (n = 6), and (c) cloudy days (n = 16). Each line is the mean of 20 sample points.

For analysis of soil moisture, one measurement was selected for each block — the driest during the growing season. Although minimum soil moisture can occur during early fall in Pacific Northwest forests (Gray and Spies 1997), several extended periods of precipitation precluded use of September samples; instead, for each block a measurement during the period 4-12 August 2004 was used. As with air and soil temperature, a mean and coefficient of variation were computed for each treatment unit.

In six of the 12 treatment units, measurements of temperature or soil moisture from one or two sample points were deleted from the analysis because iButtons or soil moisture probes were damaged or disturbed; final sample sizes per treatment unit ranged from 18 to 20.

Statistical analyses

Analysis of variance (ANOVA) was used to confirm that residual forest structure differed significantly among treatments. A randomized block ANOVA model was run for each measure of forest structure: tree density, basal area, stand density index, total tree height, and overstory canopy cover (with degrees of freedom of 2 [block], 3 [treatment], and 6 [error]). Treatment effects were judged to be significant at $\alpha \leq 0.05$. Individual treatment means were then compared with a Tukey HSD test (Zar 1999). Tree density and total tree height were log transformed prior to analysis to correct for heterogeneity of variance.

Randomized block ANOVA was also used to compare microclimatic variables among treatments, both for mean responses (Hypothesis 1) and within-treatment variability (CVs) (Hypothesis 2). Variation attributable to geographic location and time of sampling (temperature measurements were staggered among blocks; see *Air and soil temperature*) was subsumed in the "block" term. Diagnostic tests revealed minimal departures from normality and homogeneity of variance among treatments, thus microclimatic data were not transformed. For ANOVA models in which there was a significant main effect, treatment means were compared with a Tukey HSD test. I tested for additional variation in microclimate attributable to topography and residual forest structure with analysis of covariance (ANCOVA). Covariates included treatment-level means for slope, southwestness (aspect), and the five predictors of overstory structure (see above). None of the covariates were significant in these models; consequently, only the results of ANOVA are presented.

Multiple linear regression was used to examine the strength of relationships between measures of plot-scale forest structure (including overstory and understory characteristics) and microclimate (Hypothesis 3). Because climate varied with locality, separate models were developed for each block (n = 77-80 sample points per block derived from all treatments). From the full set of predictors, stepwise selection (Zar 1999) was used to add those variables to the model with the lowest probability of F at each step; variables already present were dropped if their probability of F exceeded 0.05. Standard diagnostics were used to test the assumptions of normality and constant variance of residuals. As a result, tree density and total tree height were log transformed. Several models were based on a reduced set of predictors. For PPFD, the predictors slope, aspect, and overstory canopy cover were not considered because they are used implicitly in the calculation of light availability. For PPFD and mean, maximum and minimum air temperatures, cover of understory vegetation and slash were not considered.

RESULTS

Residual stand structure

ANOVA models confirmed that most measures of residual forest structure varied significantly with level of retention (Fig. 3). However, for several variables — basal area, density, and total height — one or more pairs of "neighboring" treatments did not differ significantly in *post-hoc* comparisons. Nevertheless, for all measures of residual forest structure, treatment means showed a monotonic increase with level of retention.

Microclimatic patterns

As expected, air and soil temperatures varied among blocks (Fig. 4), reflecting differences in geographic location, elevation, and time of sampling. Blocks differed both in the mean and range of daily temperatures. Trends over the course of the day were generally similar among treatments within each block except at LWS where minimum and maximum temperatures occurred ca. 2 hr earlier in the 0% retention treatment, reflecting its distinct easterly aspect (Fig. 4; Table 1).

Mean responses.— Transmitted light (PPFD) and mean daytime and maximum air and soil temperatures decreased significantly with level of retention, consistent with expectation (Hypothesis 1a) (Fig. 5). PPFD (Fig. 5a) showed the

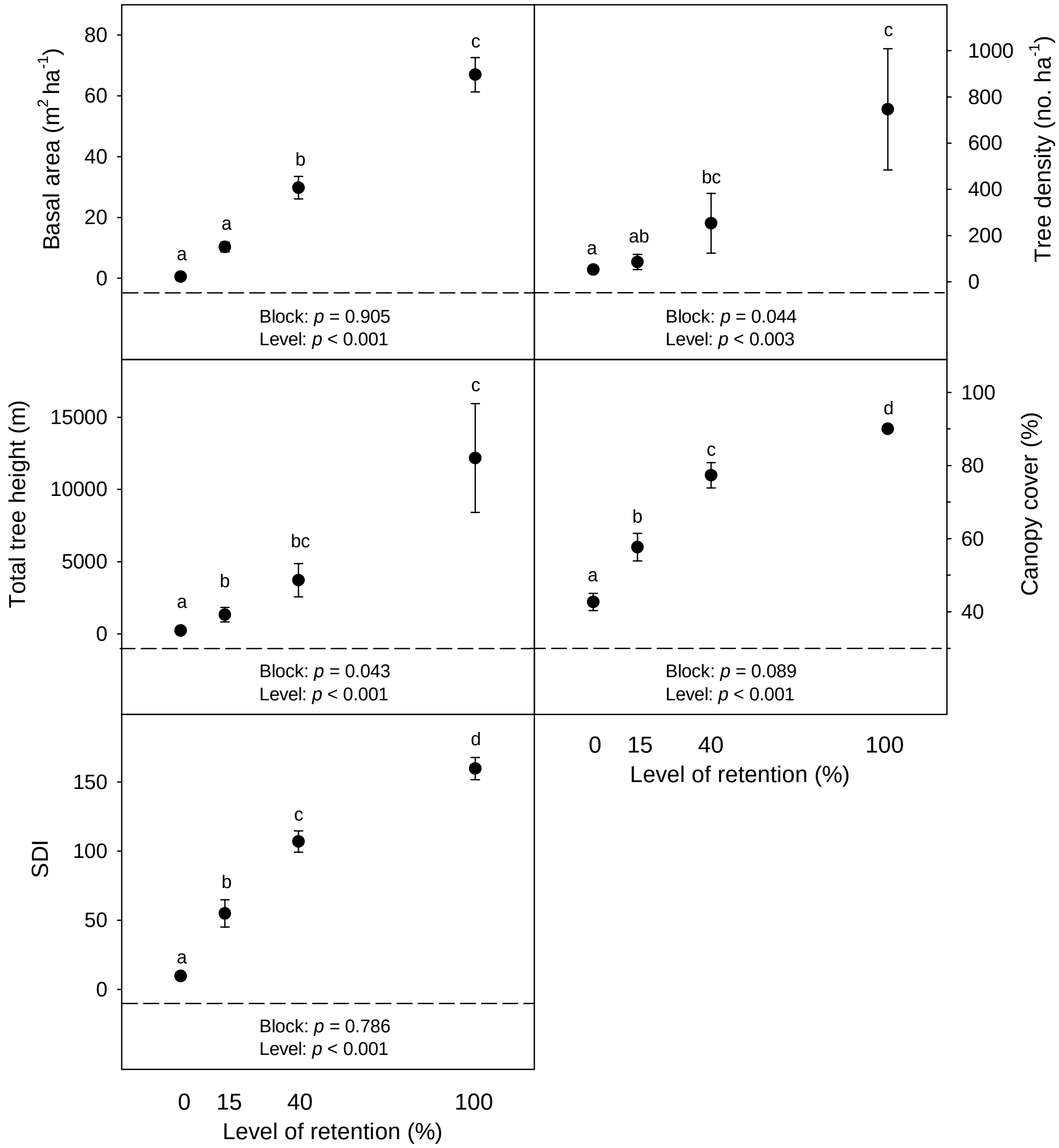

Figure 3. Mean values (±1 SE) of forest structural variables at four levels of retention. Block and treatment *p* values are from one-way randomized block ANOVAs. Treatments with different letters differ statistically ($p \leq 0.05$) based on a Tukey HSD test. Tree density and total tree height were log-transformed before analysis, but untransformed values are presented here.

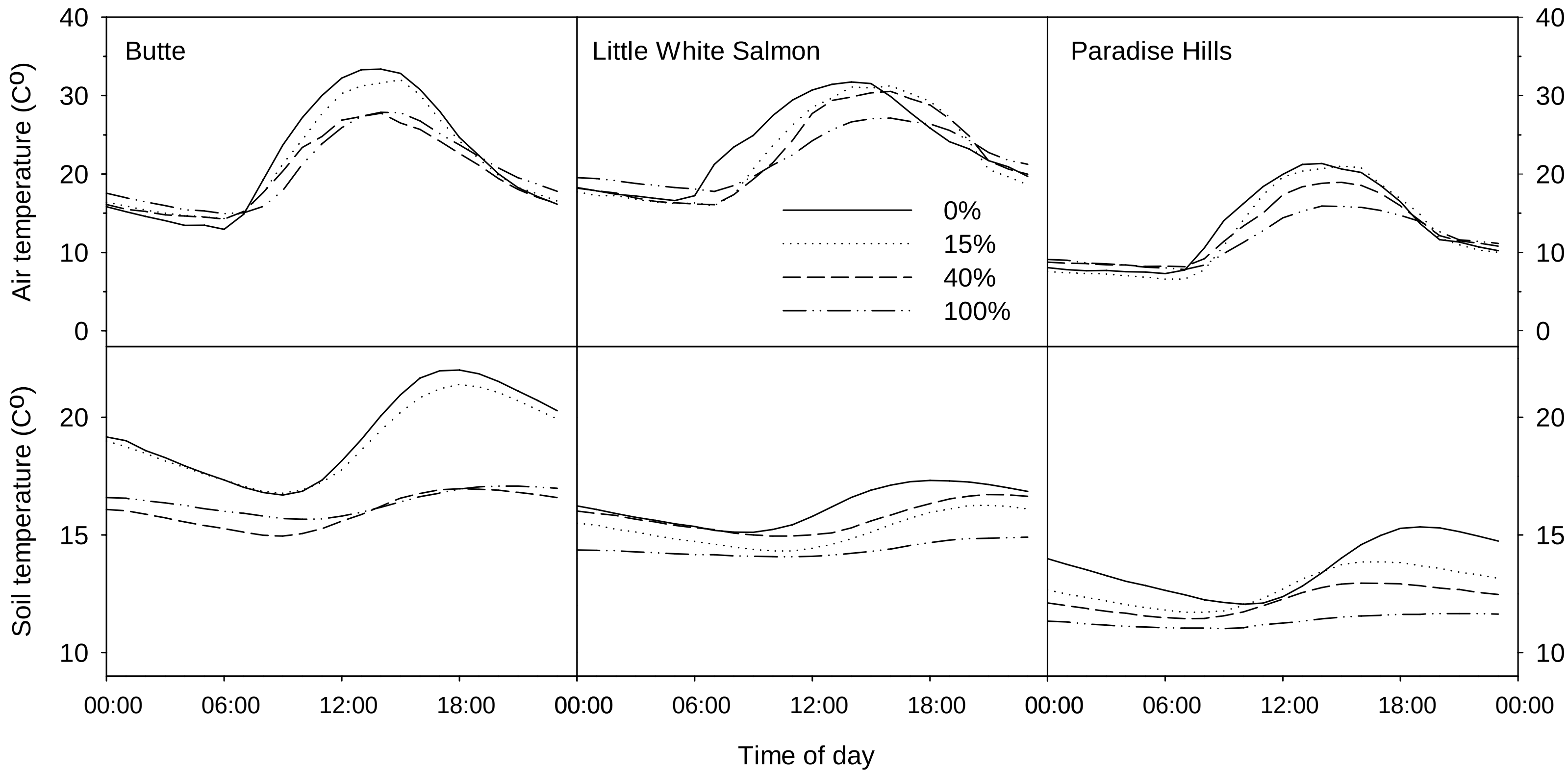

Figure 4. Average daily fluctuations in air and soil temperature among experimental treatments at each block. Lines represent the means of all sample points (n = 18-20) for the five days chosen (see *Data reduction*).

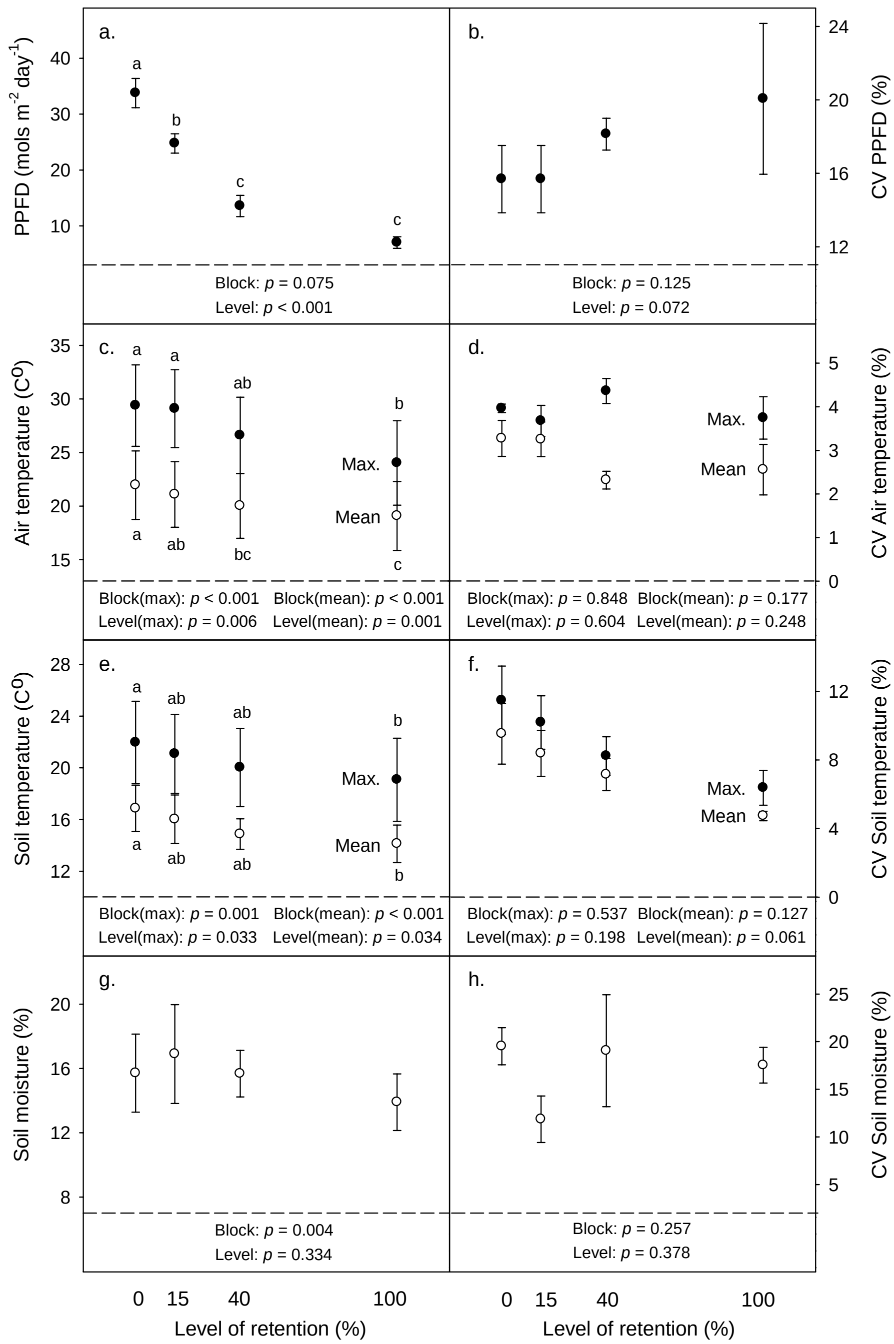

Figure 5. Mean values (±1 SE) (left column) and within-treatment variation (CVs ±1 SE) (right column) of microclimatic variables at four levels of retention. Block and treatment *p* values are from one-way randomized block ANOVAs. Treatments with different letters differ statistically ($p \leq 0.05$) based on a Tukey HSD test.

strongest response to treatment, but values did not differ between 40 and 100% retention. Mean air temperature was significantly lower at 40 and 100% retention than at 0%; however, the mean did not differ between "neighboring" levels of retention (Fig. 5c). Maximum air temperature was significantly lower in the control than at 0 or 15% retention, but it did not differ among 0, 15, and 40% retention or between 40 and 100% retention (Fig. 5c). Mean and maximum soil temperatures (Fig. 5e) showed similar trends, differing only between 0 and 100% retention. Minimum air and soil temperatures (data not shown) and mean soil moisture (Fig. 5g) did not vary significantly with level of retention, contrary to expectation (Hypothesis 1b).

Within-treatment variability.— Patterns of within-treatment (plot-to-plot) variability in microclimate were not consistent with those predicted (Hypothesis 2): coefficients of variation (CVs) were not greatest at intermediate levels of retention. Instead, variability in PPFD exhibited a marginally significant increase (Fig. 5b), and variability in soil temperature, a marginally significant decrease with increasing levels of retention (Fig. 5f). Variability in air temperature and soil moisture showed no discernable trends among treatments. CVs for air temperature were considerably lower (<5%) than those for the other microclimatic variables.

Forest structure and understory conditions as predictors of microclimate.— Within a block, regression models for light and air temperature were generally stronger than those for soil temperature and soil moisture, consistent with expectation (Hypothesis 3a) (Table 2). Coefficients of determination ranged from 0.63 to 0.84 for PPFD, from 0.55 to 0.85 for mean/maximum air temperature, and from 0.25 to 0.61 for mean/maximum soil temperature. Models for minimum temperature explained less variation, but were comparable for air and soil (R^2 of 0.22 to 0.46 and 0.10 to 0.51, respectively). Models for soil moisture were consistently poor (R^2 of 0.11 to 0.28). Among blocks, models were consistently weaker for LWS than for BU or PH.

Consistent with expectation (Hypothesis 3b), aspect and one or at most two measures of overstory structure (canopy cover, SDI, basal area, or total tree height) yielded highly significant models for light and air temperature (Table 2). SDI was selected in all models of PPFD (canopy cover was not considered; see *Statistical analyses*). Canopy cover was the most frequent predictor of air temperature (7 of 9 models and all models of mean and maximum temperature). In contrast, models of soil temperature, which were poorer, consistently included cover of understory vegetation (and slash at BU) (Table 2). Neither canopy cover, nor vegetation cover were consistently included in models of soil moisture.

TABLE 2. Signs and *p* values of coefficients for significant predictors in multiple regression models of light (PPFD), temperature, and soil moisture.

Model/ Block	Slope (deg)	SWness[a]	Tree density (no. ha^{-1})[b]	Basal area (m^2 ha^{-1})	SDI	Overstory canopy cover (%)	Total tree height (m)[b]	Vegetation cover (%)	Slash cover (%)	R^2
PPFD (mols/m^2/day)										
BU	nc[c]	nc			- / <0.001	nc		nc	nc	0.84
LWS	nc	nc			- / <0.001	nc		nc	nc	0.63
PH	nc	nc			- / <0.001	nc	- / 0.021	nc	nc	0.82
Air temperature (C^o)										
Mean										
BU		+ / 0.002				- / <0.001		nc	nc	0.76
LWS						- / <0.001		nc	nc	0.69
PH		+ / 0.003		- / <0.001		- / <0.001		nc	nc	0.85
Maximum										
BU		+ / <0.001		- / 0.001		- / <0.001		nc	nc	0.78
LWS		+ / <0.001				- / <0.001		nc	nc	0.55
PH		+ / 0.005		- / <0.001		- / 0.001	+ / 0.023	nc	nc	0.83
Minimum										
BU					+ / <0.001			nc	nc	0.35
LWS	+ / <0.001			+ / <0.001				nc	nc	0.22
PH						+ / <0.001		nc	nc	0.46

TABLE 2. Continued.

Model/ Block	Slope (deg)	SWness	Tree density (no. ha^{-1})	Basal area (m^2 ha^{-1})	SDI	Overstory canopy cover (%)	Total tree height (m)	Vegetation cover (%)	Slash cover (%)	R^2
Soil temperature (C^o)										
Mean										
BU	+ / 0.036				- / <0.001			- / 0.001	- / 0.003	0.56
LWS						- / <0.001		- / 0.011		0.22
PH		+ / 0.019		- / 0.019		- / 0.003		- / 0.01		0.61
Maximum										
BU		+ / 0.015			- / <0.001			- / 0.001	- / 0.01	0.59
LWS		+ / 0.035				- / <0.001		- / 0.018		0.25
PH						- / 0.002	- / 0.039	- / 0.016		0.57
Minimum										
BU	+ / 0.012					- / <0.001		- / <0.001	- / 0.001	0.42
LWS						- / 0.003		- / 0.025		0.10
PH		+ / 0.004			- / <0.001			- / 0.001		0.51
Soil moisture (%)										
BU		+ / 0.036						+ / 0.019		0.11
LWS		- / 0.005			- / 0.005	+ / <0.001				0.28
PH				- / <0.001			+ / 0.03			0.17

[a] SWness = southwestness, computed as *cos* (*aspect - 225*°) with a range of –1.0 to 1.0
[b] Tree density and total tree height were log transformed
[c] nc = predictor was not considered for this model.

DISCUSSION

Effects of level of retention on mean responses

I hypothesized that with increases in overstory retention, light availability and mean and maximum temperatures would decline, but that minimum temperatures and soil moisture would increase (Hypothesis 1). Trends for transmitted light (PPFD) and for mean and maximum air and soil temperature were consistent with these predictions, although differences in temperature were surprisingly small and non-significant among most treatments. PPFD showed the strongest response to level of retention, declining more than three-fold across the treatment gradient. Nevertheless, light availability did not differ statistically between 40% retention and the control. This result is due, in large part, to trends at BU: here the combination of a more easterly aspect and shading by non-merchantable trees resulted in a relatively small difference (<30%) in light availability between these treatments. This contrasts with a >130% difference at LWS and PH. Clearly, light penetration to the understory can vary significantly at a given level of overstory retention depending on topography, initial forest structure, and treatment of sub-canopy trees during logging operations (Lieffers et al. 1999).

In contrast to light, differences in air and soil temperature among treatments were more difficult to detect. Even on warm sunny days, maximum air temperatures 1 m above the ground surface were comparable among harvest treatments (0-40%) and mean temperatures did not differ between 0 and 15 or 15 and 40% retention. Although these results do not point to a clear threshold, they do suggest that retention in excess of 15% is required to reduce average daytime temperatures from those in clearcut environments. These patterns are generally consistent with past work in the Pacific Northwest. In 60- to 70-yr-old coniferous forests in western Washington, Barg and Edmonds (1999) documented comparable summer maximum and mean air temperatures in clearcut and dispersed-retention sites (~30% of original basal area), as did Chen et al. (1999).

The implications of trends at higher levels of retention in my study are less clear. The absence of differences between 40 and 100% retention suggest that 60% of original basal area can be removed without affecting mean or maximum air temperatures in the understory. However, with relatively low replication of treatments, this result may also reflect the effects of topographic variation at BU (Table 1): 40%D faces eastward (rather than southward) and lies 200 m higher than the control resulting in noticeably cooler temperatures. This points to the broader challenge of detecting treatment effects in large-scale experiments in landscapes in which complex topography and variation in forest structure can interact with experimental responses.

Not surprisingly, soil temperatures at 15 cm below the surface differed less among treatments than did air temperatures, which averaged ~5°C greater. Although mean temperatures consistently declined with level of retention, significant differences were observed only between 0 and 100% retention. Yet, it is possible that greater differences existed at shallower depths and at the soil surface, particularly in areas of exposed soil. It is also likely that differences in temperature were greater immediately after harvest when mineral soils were first exposed and understory plant cover was markedly reduced by logging disturbance (Halpern and McKenzie 2001, Halpern et al. 2005). By contrast, regrowth of the understory was considerable after 6-7 yr and plant cover was actually greater in 0% than in control plots (Table 1), likely tempering the extreme differences in overstory shading between these treatments.

Level of retention had no detectable effect on minimum air or soil temperatures. This result is consistent with observations of Barg and Edmonds (1999) and with their conclusion that partial canopy retention reduces loss of long-wave radiation to a greater degree than it limits input of short-wave radiation. Treatment effects on minimum temperatures may be stronger in topographic settings where cold air has greater potential to accumulate (Williamson and Minore 1978, Groot and Carlson 1996), and in spring or fall when the potential for frost is greater.

Consistent with temporal trends for this region (Gray and Spies 1997), volumetric soil moisture (0-15 cm) was generally low in mid-August, yet there was little variation among treatments (14-17%). Barg and Edmonds (1999) were also unable to detect differences in soil moisture in late summer among clearcut, dispersed retention, and uncut forests. Two processes with opposing effects, may contribute to the small difference in soil moisture among stands of contrasting overstory structure. At lower levels of retention, greater heating of the soil surface should lead to greater evaporation; however, transpiration by trees should also be reduced due to lower tree densities. Rates of evaporation and transpiration are also likely to be affected by understory vegetation through variation in foliar cover, root system development, and water-use of plant species (Joffre and Rambal 1993, Breshears et al. 1998, Xu et al. 2002). A clearer picture of soil moisture dynamics would require a more complete understanding of these factors and their interactions.

Within-treatment variation in microclimate

I hypothesized that variability in overstory structure within treatments would lead to similar variability in understory microclimate. Specifically, I expected greater heterogeneity in microclimate (larger CVs among sample points) at intermediate levels of retention than in clearcut or undisturbed forests. However, I was unable to detect a significant effect for any of the variables considered. For air temperature, rapid mixing of air masses (Chen and Franklin 1997) is a likely explanation for the small variation (CVs <5%) among harvest treatments. Although not statistically significant, CVs for soil temperature showed an interesting and potentially relevant trend when considered together with treatment-scale differences. CVs for mean and maximum soil temperature increased with decreasing retention; thus, not only were average temperatures of treatment units greater at lower retention, but within-treatment variability was higher increasing the potential for unusually high temperatures at particular locations.

It is possible that the general absence of treatment effects on microclimatic variation among harvest units reflects the spatial scale of sampling. The distances between sample points (40 to >100 m) may be too large to capture the variation associated with overstory structure, particularly at higher levels of retention. Greater variability may instead be detected at finer spatial scales, e.g., associated with individual trees at the scale of meters (but see Barg and Edmonds 1999).

Predicting microclimate from attributes of forest structure

To what extent can variation in local microclimate among these retention treatments be predicted by residual forest structure? Multiple regression models illustrated that simple measures of overstory structure explained much of the variation in light availability and air temperature. Stand density index, which incorporates both the number and basal area of trees, emerged as the strongest predictor of light availability (PPFD) in all blocks, suggesting that both the density and size of trees contribute to light attenuation in the understory. This result is not particularly surprising, as light has been modeled with similar plot-scale measures of forest structure (e.g., basal area, stem density, or the summed diameters or heights of trees) in both coniferous and broadleaf forests (e.g., Palik et al. 1997, Comeau and Heineman 2003, Drever and Lertzman 2003). However, attempts to predict local variation in other characteristics of forest microclimate (e.g., air or soil temperature) are less common in the literature (but see Kang et al. 2000). My results suggest that mean and maximum air temperature (at least for warm summer days) can be predicted from forest structure and aspect. Canopy cover (estimated from hemispherical photographs) was a significant predictor in all blocks, reflecting the strong relationships among canopy cover, solar radiation, and energy balance at the forest floor (Yoshino 1975, Aussenac 2000). In contrast, I could explain considerably less variation in soil temperature and very little variation in soil moisture. Models for soil temperature included not only overstory attributes (canopy cover or SDI), but cover of understory plants, as shading by herbaceous and woody vegetation can contribute significantly to moderation of soil temperatures (Pierson and Wight 1991, Breshears et al. 1998, Buckley et al. 1998, Xu et al. 2002). Interestingly, cover of logging slash was a significant predictor of soil temperature at BU 7 yr after treatment. This suggests that its ameliorating effect was likely to have been stronger immediately after harvest when slash cover and depth were greater (Halpern and McKenzie 2001). In fact, moderate levels of slash were positively correlated to initial survival of shade-tolerant herbs in these sites (Nelson and Halpern 2005a). Clearly, however, factors other than overstory structure and understory cover contribute to local variation in soil microclimate. Models for soil temperature at LWS, and models for soil moisture at all blocks suggest that I was unable to account for most of this variation. Factors not sampled in this study may exert stronger controls on soil moisture; these include microtopography, soil texture, and organic matter content, which can vary considerably at small spatial scales (Beckett and Webster 1971, Robertson et al. 1993, Gray and Spies 1997).

Correspondence of microclimatic and biological responses

Are trends in microclimate consistent with the biological responses documented in other studies on these sites? Studies of vascular plants, bryophytes, and fungal sporocarps, groups that should be sensitive to changes in light and temperature (Renhorn et al. 1997, Jones et al. 2003, Fenton and Frego 2005), revealed initial (1-3 yr) responses that were largely consistent with patterns in light availability, and to some extent, air and soil temperature. For example, declines in cover of forest herbs were greater at lower levels of retention, and plants typically associated with late-seral forests were more frequently lost from “clearcut” plots (0% retention) than from those with residual trees (15 or 40% retention) (Halpern et al. 2005). For forest-floor bryophytes, however, increasing levels of retention did not mitigate loss of cover (C. Halpern, unpublished data) suggesting that declines were either induced by other factors (e.g., physical disturbance) or by environmental stresses that were not measured (Saunders et al. 1991, Renhorn et al. 1997, Fenton and Frego 2005). In studies of ectomycorrhizal fungi, sporocarp (mushroom and truffle) production was virtually eliminated in clearcut areas (0% retention) and was significantly reduced at 15% retention

(Luoma et al. 2004). At 40% retention, however, production of sporocarps was generally comparable to that in controls, consistent with trends in light and temperature.

Despite the many consistencies between microclimatic and biological responses, factors other than environmental changes can shape biological responses to overstory removal. For example, production of fungal sporocarps requires carbon subsidies from associated trees; greater retention may simply increase access to these subsidies. Variation in disturbance intensity also can play a critical role in the survival of understory plants (Halpern 1989, Haeussler et al. 2002, Roberts and Zhu 2002, Fenton and Frego 2005). Unfortunately, it is difficult to differentiate between the effects of disturbance and those resulting from physiological stress following timber harvest because they typically co-vary with level of retention (Halpern and McKenzie 2001, Halpern et al. 2005).

Management implications

Structural retention is now a standard practice in harvest of mature forests on federal lands within the range of the northern spotted owl. Current standards require managers to retain at least 15% of the original stand within each harvest unit, with 70% of this retention in aggregates of 0.2-1.0 ha (USDA and USDI 1994). Although this practice has been widely adopted, few data exist to evaluate whether this minimum retention standard is sufficient to achieve its intended goals. One mechanism by which overstory retention has been hypothesized to facilitate species' persistence and recovery is by moderating climate at the forest floor (Franklin et al. 1997). My research provides direct evidence that at 15% dispersed retention, the potential for ameliorating air or soil temperatures in harvest areas is very limited. Although average levels of light are reduced, air and soil temperatures are not, resulting in mean and maxima that are no different from those found in completely open environments. In operational applications of this minimum standard, where 70% of the tree cover must be aggregated, light and temperature across most of the harvest unit are likely to be even greater. Studies of understory response (Luoma et al. 2004, Halpern et al. 2005, Nelson and Halpern 2005a, b) and susceptibility of trees to wind-induced mortality (C. Halpern, unpublished data) further suggest that there may be few short-term benefits associated with this minimum standard. Yet, it is not clear at what point increases in retention provide microclimatic benefits. This may depend, in part, on the microclimatic variables of interest and how they mediate biological responses. For example, mean air temperatures were significantly cooler at 40 than at 15% retention, whereas maxima were similar. Thus, biological processes mediated by extremes in temperature would suggest a different retention threshold than those shaped by average conditions. On the other hand, changes in light availability at lower levels of retention indicate that small increases in canopy cover can yield large reductions in light. Thus, if sensitivity to excess solar radiation dictates biological responses (Svenning 2000, Coxson et al. 2003, Fenton and Frego 2005), small changes in canopy retention could yield large effects.

The results of this study and companion studies of ecological response suggest important relationships that warrant further investigation. For now, however, forest managers must continue to implement silvicultural approaches with incomplete knowledge of their ecological consequences. This study begins to fill some of these knowledge gaps: it provides strong evidence that current minimum standards for retention do not substantially moderate the effects of canopy removal on forest floor microclimates.

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APPENDIX I: PHOTOS OF RESEARCH METHODS AND SITES

Figure 6. Sampling soil moisture using time domain reflectometry (TDR).

Figure 7. Example of differences in pre-treatment forest structure between blocks at the same level of retention (100% - control); Paradise Hills at left, Little White Salmon at right.

Figure 8. Example of pre- and post-harvest stand structure in 0% retention at Little White Salmon (LWS), 7 years after harvest (large tree bole at center of post-harvest photo is a snag).

Figure 9. Sample plot in the 0% retention treatment at Butte (BU), showing woody debris, logging slash, and significant vegetation cover.

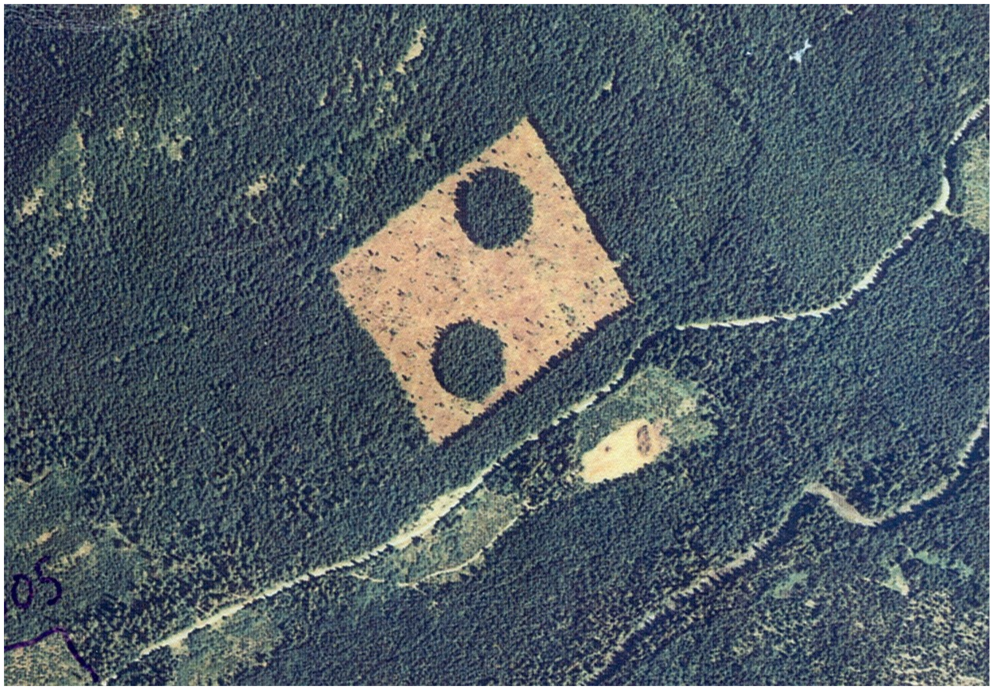

Figure 10. Aerial photograph of the 15% aggregated retention treatment at Butte (BU); the harvested area represents 0% retention for this study.

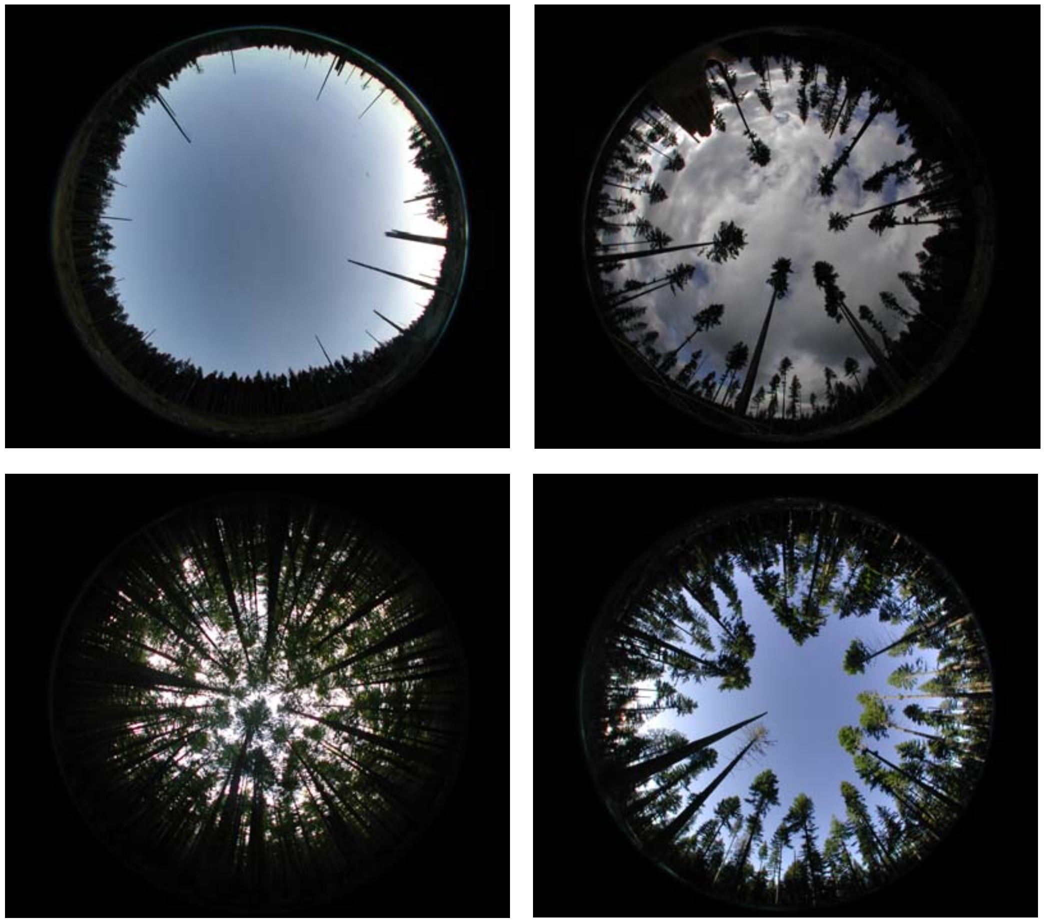

Figure 11. Hemispherical photographs representing four levels of retention at Paradise Hills (PH): 0, 15, 40, and 100% (clockwise from upper left).