An Ecological Restoration Experiment in the Cedar River Municipal Watershed

2008-2009 Progress Report

SPU Agreement No. DA2004-52

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1. Introduction and Purpose

The City of Seattle SPU Watershed Management Division manages the Cedar River Municipal Watershed under a Habitat Conservation Plan (HCP) approved in 2000. A goal of the HCP forest habitat restoration program is to improve habitat for federally listed species by achieving three goals in dense, young, second-growth forests: (1) accelerate development of ecological structures associated with older forests, (2) increase complexity of wildlife habitat, and (3) enhance biological diversity. As one of several strategies for achieving these goals, the SPU Watershed Management Division is collaborating with scientists from the College of Forest Resources on an ecological-restoration thinning experiment to guide broader application of restoration treatments within the watershed.

The objectives of this research are several-fold: (1) to characterize the structure and composition of the existing forests; (2) to quantify relationships among overstory structure, light availability, and understory development within these forests; (3) to design experimental treatments that are likely to accelerate development of forest structure and understory diversity; and (4) to implement the experimental treatments and assess short-term responses of the vegetation.

In previous reports we have addressed objectives 1 and 2 (see *Task 3 Report.pdf*, *Task 4 Report.pdf*, and *Task 4b Report.pdf*, submitted Feb-May 2006). The current report focuses on objectives 3 and 4. Its primary purpose is to provide detailed documentation on the experimental and sampling designs and on the structure and content of the core datasets. We provide detailed descriptions and schematic diagrams of experimental and sampling designs for the "main restoration experiment" and the "CWD experiment," summarize the timeline of field activities (past and future), document the structure and content of the core datasets (submitted to SPU electronically, as Excel files), and provide copies of field forms used in data collection. A future report will include data summaries.

2. Experimental and Sampling Designs

2.1. Main Restoration Experiment

2.1.1. Experimental design

Experimental sites.— The main restoration experiment consists of three treatments (two manipulations and a control) within 40 x 40 m experimental units at each of three study sites: Bear Creek (Bear), Pine Creek (Pine), and Pine Creek-North (Pine-N) (Fig. 1). Pine and Pine-N are adjacent, separated by a small stream. We used the following criteria to select these sites: dominance or a significant component of *Tsuga heterophylla* (western hemlock) in the main canopy, limited tree regeneration, and minimal development of understory vegetation. Forests at Bear and Pine/Pine-N are ca. 65 yr old, dominated by western hemlock and *Pseudotsuga menziesii* (Douglas-fir). Bear (47° 19'N, 121° 33'W) lies at an elevation of ca. 610 m on a gentle (0-10°) SW-facing slope; Pine (47° 21'N, 121° 38'W) lies at an elevation of ca. 740 m on a slightly steeper (0-30°) W-SW-facing slope.

Treatments.— Treatments were completed during fall/early winter 2006; felling and yarding occurred on snow at Bear (but not at Pine or Pine-N). Treatments include an unharvested control (C), a 20-m diameter gap (gap, G), and a "structured ecological thin" (thin, T). Harvest treatments were designed to increase both the magnitude and variation in understory light, as well as the heterogeneity of forest structure—changes that should presumably lead to greater diversity and abundance of understory plants. However, the treatments chosen to achieve these objectives differ greatly in the spatial distribution of residual trees.

Gaps were centered within the experimental unit. All trees, including subcanopy stems, were felled within a 10 m radius of the center (removing ca. 20% of the original basal area). Trees were yarded by cable through a narrow exit corridor to one edge of the experimental unit, then upslope through a corridor along the edges of the experimental units to a roadside landing.

The thin treatment was implemented as follows: The largest-diameter trees (comprising ca. 40% of the original basal area) were first reserved. Smaller trees were then marked for removal in 6 m radius circles. The centers of removal circles were located randomly with the condition that they lie outside previous removal circles. Circles were added until 30% of the original basal area was achieved. Trees were felled and yarded to the edges of experimental units, then upslope, as described above for gaps.

Treatment replication varies by site with 5 replicates at Bear and 4 replicates at both Pine and Pine-N. Two experimental units (thin and control) at the southern end of Pine-N (column 8; Fig. 1) are considered replicates of Pine for analytical purposes because of greater similarity in structure to forests at Pine (see stem maps in Appendix 4.1); assignment of treatments to these two experimental units was made randomly among the larger set of Pine experimental units. Accordingly, they are coded in all understory and light data files as belonging to the Pine site (i.e., Site = Pine). In the tree files used to create stem maps, however, they are coded as belonging to Pine-N (i.e., Tree-plot = Pine-N), as they are contiguous with the experimental units at Pine-N.

Targets for basal area removal were exceeded in all treatments at all sites (Table 1). This was due, in large part, to removal of trees from yarding corridors that bordered the relatively small experimental units.

Table 1. Summary of pre- and post-treatment stand basal area (m^2/ha) and basal area reductions (%). Values are the means of four or five experimental units per treatment.

		Basal area (m^2/ha)		
Treatment (target % reduction)	Site	Pre-treatment	Post-treatment	Basal area reduction (%)
Control (0% reduction)	Bear	74.4	68.4	8.3
	Pine	75.1	70.3	6.5
	Pine-N	76.3	70.4	7.5
Gap (20% reduction)	Bear	73.1	51.5	29.6
	Pine	75.3	53.8	28.5
	Pine-N	80.7	56.9	29.6
Thin (30% reduction)	Bear	76.2	47.1	38.2
	Pine	79.1	49.8	36.9
	Pine-N	79.6	48.9	38.6

Bear	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
Row 2		C	T		T	T	C	G	C	G
Row 1		C	C		G	G	T	T	G	

Pine	Col 1	Col 2	Col 3	Col 4	Col 5
Row 2	T	G	G	G	C
Row 1	G	T	C	T	C

Pine-N	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
Row 4		G	T					
Row 3			G	G	T	T	C	
Row 2				C	G	C	C	T (Pine)
Row 1						T		C (Pine)

Fig. 1. Layout of experimental treatments in the main restoration experiment. Treatments codes: C = control, G = gap, and T = thin. At Pine-N, experimental units in column 8 (rows 1 and 2) are considered replicates of the Pine site for analytical purposes and are coded as belonging to the Pine site in all data files. Black areas are not sampled.

2.1.2. Marking of experimental unit boundaries and internal grids

The boundaries of experimental units are permanently marked with PVC posts (Figs. 3 and 4). Posts are ca. 30 cm tall (except for occasional taller posts), spaced at 10 m intervals. Each post has one or more laminated labels attached at the base. Labels indicate treatment, row, column, distance (m) along the X axis (i.e., the experimental unit baseline that runs across the slope), and distance (m) upslope from the baseline. For example, the post in the upper left corner of the control treatment in row 1, column 2 at Bear is labeled “Cntrl, R1, C2, 0-40”. Because many of the experimental units share boundaries, PVC posts often hold more than one label. The azimuths of experimental unit boundaries (X and Y axes) at each site are documented in Table 2. In addition to these boundary markers, permanent PVC posts occur at 10-m intervals (in both directions) within each experimental unit. Posts are labeled in the same fashion as the boundary markers (e.g., "Cntrl, R1, C2, 10-10").

Table 2. Azimuths (in degrees) of experimental unit (EU) boundaries at each site. The X axis runs across the slope, the Y axis up/downslope. Azimuths are the same for both the main restoration experiment and the CWD experiment at Bear. Declination = 17.5 deg E.

Azimuth	Bear	Pine	Pine-N
X axis: 0 (origin) → maximum distance	130	160	163
X axis: maximum distance → 0 (origin)	310	340	343
Y axis: from EU baseline → upslope	40	70	73
Y axis: from EU topline → downslope	220	250	253

2.1.3. Tree maps and measurements

In 2005, mapped tree plots were established at each site using a combination of Nikon Total Station (model DTM-420), distance tapes, and a Haglöf Vertex III hypsometer. A reference transect (200 to 400 m long) was first surveyed with the Nikon Total Station; two transects were then established parallel to the first, 20 m upslope and 20 m downslope. For all trees and snags within 10 m of each transect (60-m total width), we recorded species, diameter at breast height (dbh), distance along the transect to a point perpendicular to the tree, and perpendicular distance from the transect to the tree. Distance data were then used to calculate the x-y locations of each tree and snag.

In 2007, plots were widened by 10 m along their upper and lower boundaries using similar mapping techniques; this provided for a full stem map of each experimental unit (80-m total width; e.g., Fig. 2). However, because these strips were mapped after treatment, some stems had already been cut. For these individuals, pre-treatment diameter was reconstructed using species- and site-specific regression equations of dbh vs. stump diameter. These equations were developed from paired measurements of diameter at breast height and stump height on ca. 20-25 live stems of each of the primary tree species (*Pseudotsuga menziesii*, *Thuja plicata*, and *Tsuga heterophylla*) at each site.

In addition, at Bear and Pine-N, portions of the original tree plot were subsequently determined to be unsuitable as experimental units based on forest composition, structure, or presence of old skid roads. These 40 x 40 m sections were abandoned (black cells in rows 1 and 2, Fig. 1). To achieve sufficient replication of treatments at Pine-N, seven additional experimental units were established upslope of the original rows (see rows 3 and 4 ; Fig. 1). Within each of these new experimental units, all trees were identified to species, measured for diameter, and spatially mapped (2006 and 2007). For stumps, pre-treatment diameters were reconstructed as described above for the 10-m strips.

After treatment implementation in 2007, all experimental units were revisited and stem maps were updated. The condition of each tree was noted (live; stump; standing dead; or live but prone, tipped, or topped). Appendix 4.1. contains a complete set of pre- and post-treatment stem maps for each site. Appendix 4.2. contains illustrations of the changes in size structure of tree populations for each experimental treatment at each site.

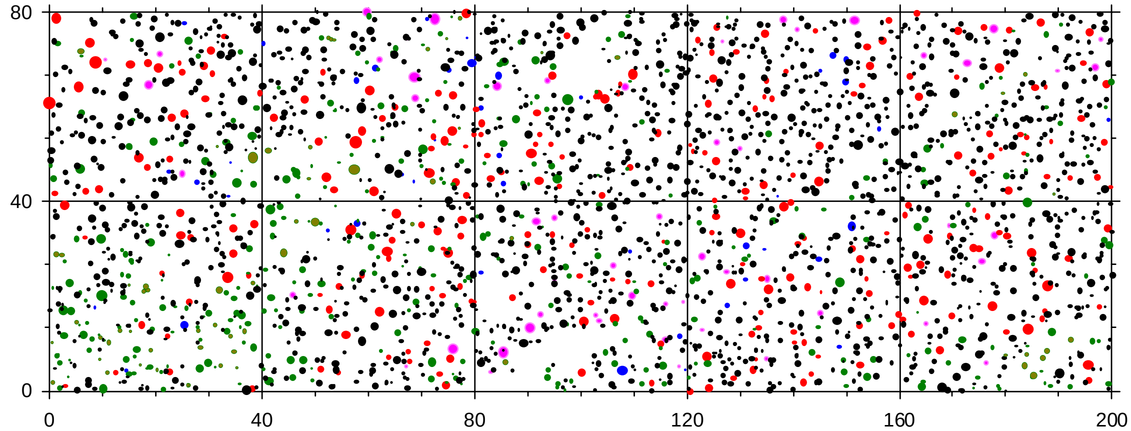


Fig. 2. Pre-treatment stem map of the Pine site. Species are: *Abies amabilis*, blue; *A. procera*, pink; *Pseudotsuga menziesii*, red; *Thuja plicata*, green; *Tsuga heterophylla*, black; and all hardwoods (*Alnus rubra*, *Populus trichocarpa*, and *Prunus emarginata*), yellow.

2.1.4. Hemispherical photographs

We estimated light availability at the forest floor after treatment (Sep 2007) from hemispherical photographs. Photos were taken in each experimental at multiple points along each understory transect (see section 2.1.5, below); however, the number and locations of photos varied by treatment. In the controls, where forest structure was most homogeneous, nine photos were taken—3 per transect at 10 m intervals. In the gap treatment, 21 photos were taken—at the gap center and at 2-4 m intervals along each of the four transects. In the thin treatments 27 photos were taken—9 per transect spaced at 4 m intervals.

Images were analyzed with the software, Gap Light Analyzer 2.0 (GLA; Frazer et al. 1999[1]) employing the standard overcast sky model (UOC). Direct, diffuse, and total transmitted light (or photosynthetic photon flux density, PPFD) were calculated for the period May through September.

2.1.5. Understory sampling: ground conditions, vascular plants, tree seedlings

Control and thin treatments.— In control and thin treatments, three understory transects are marked with PVC posts. Transects run up/downslope, spaced 10 m apart (Fig. 3; see Table 3 for transect orientations). Beginning at a center line 20 m upslope from the experimental unit baseline (see dashed line in Fig. 3), unmarked sample quadrats (1 x 1 m) are spaced at 1 m intervals (i.e., 0-1 m, 2-3 m … 18-19 m) in both directions yielding 20 quadrats per transect and 60 quadrats per experimental unit.

Gap treatments.— In the gap treatments, permanent posts are spaced on a grid at 10 m intervals (Fig. 4) and are labeled as in the control and thin treatments. Understory transects are oriented at 45 (NE), 135 (SE), 225 (SW), and 315 (NW) degrees (Table 3). A permanent post marks the center of each gap and 10 m intervals along each transect. Posts are labeled with treatment, row, column, transect, and distance from gap center (e.g., "Gap, R3, C3, SW10"). Unmarked sample quadrats (1 x 1 m) are spaced at 1 m intervals (i.e., 0-1 m, 2-3 m … 18-19 m) along each transect yielding 10 quadrats per transect (but 9 for the SE transect which shares the same first quadrat as the NE transect), and 39 quadrats per experimental unit (Fig. 4).

[1] Frazer, G. W., C. D. Canham, and K. P. Lertzman. 1999. Gap Light Analyzer (GLA), Ver. 2.0. Burnaby, B.C.

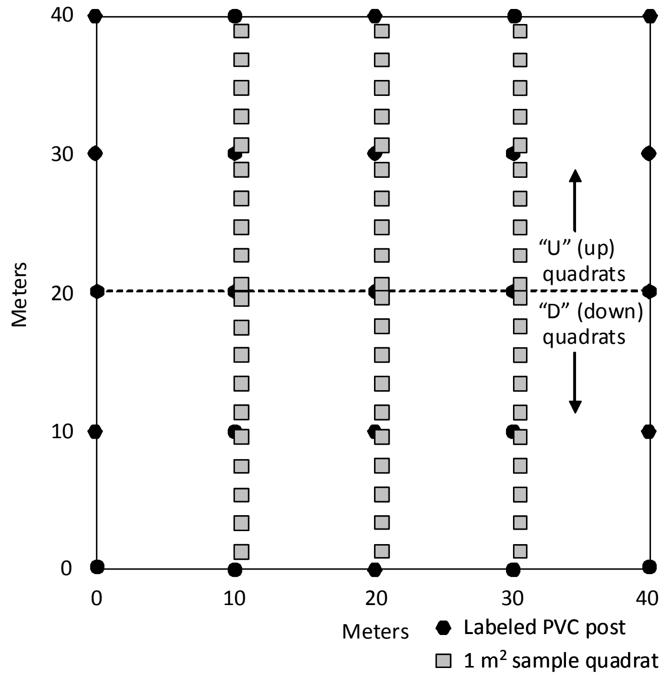


Fig. 3. Understory sampling design for control and thin treatments.

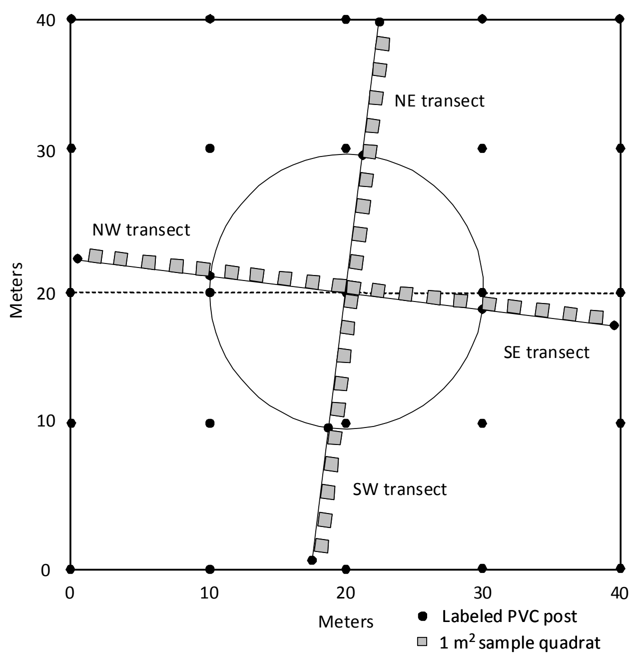


Fig. 4. Understory sampling design for gap treatments.

Understory measurements.—Understory measurements are similar in all treatments. In each quadrat the following variables were sampled before (2006) and after (2007) treatment: (1) cover of ground-surface characteristics (e.g., bare ground, fresh wood, decayed wood, fine litter, stumps, and post-treatment logging slash); (2) total cover of bryophytes; (3) cover of individual vascular plant species; and (4) counts of tree seedlings (≤1.4 m tall) by species and size class.

Table 3. Azimuth in degrees of understory transects in the main restoration experiment at each site. Declination = 17.5 deg E.

Azimuth	Bear	Pine	Pine-N
Thin and control treatments			
From 20 m midline → upslope	40	70	73
From 20 m midline → downslope	220	250	253
Gap treatments			
Center → NE	45	45	45
Center → SW	225	225	225
Center → NW	315	315	315
Center → SE	135	135	135

2.1.6. Understory sampling: bryophyte study (Bear)

Effects of experimental treatments on the composition and diversity of forest-floor bryophytes were studied only at the Bear site. Twelve of the 15 experimental units were sampled (i.e., 4 replicates of each treatment), each with 16-24 pairs of permanent quadrats (0.2 x 0.5 m). In the control and thin treatments, quadrat pairs were distributed across the entire experimental unit. In the gap treatments, half of the pairs were established within the gaps and half in the adjacent forest.

Two substrates were compared with paired quadrats: one quadrat was placed on a decayed log (decay class III-V); the other was established in close proximity to the first on the forest floor. Quadrat corners were marked with pink pin flags uniquely labeled with experimental unit (row and column), treatment, substrate type (CWD or forest floor), and sample number. To aid in relocation or reestablishment, quadrats are referenced by distance and direction to the center of each gap in gap treatments or by distance from the X and Y baselines of control and thin experimental units. Quadrats on CWD are also referenced to labeled nails on each log. In most instances, quadrats were easily relocated and reestablished after treatment. However, if one of a pair of quadrats was lost to disturbance, a new quadrat was established as close as possible to the second.

In each bryophyte quadrat the following variables were sampled before (2006) and after (2007) treatment: (1) cover of ground-surface characteristics (bare ground, fresh wood); (2) logging disturbance (e.g., cover of slash, percentage of CWD missing); (3) total cover of mosses, liverworts, and vascular plants; (4) presence of individual moss and liverwort species; and (5) counts of tree seedlings by species and size class.

2.2. CWD Experiment (Bear)

2.2.1. Experimental design

The CWD experiment was designed to compare the effects on understory vegetation of retaining vs. removing the down wood resulting from thinning. It was implemented only at the Bear site, uphill from the main experiment. The thinning prescription for this experiment was the same as in the main restoration experiment. Among eight, 40 x 60 m experimental units, CWD was removed from a randomly chosen set of four, and retained in the remainder (Fig. 5).

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6		Col 7	Col 8
- CWD	+ CWD	- CWD	- CWD	+ CWD	+ CWD		- CWD	+ CWD

Fig. 5. Layout of experimental units and assignment of treatments in the CWD experiment. Treatment codes: +CWD = CWD retained, -CWD = CWD removed.

2.2.2. Marking of experimental unit boundaries

The boundaries of each experimental unit are marked with PVC posts (Fig. 6). Posts are ca. 30 cm tall, spaced at 10-20 m intervals with one or more laminated labels attached at the base. Labels indicate treatment, column, distance (m) along the X axis (i.e., the experimental unit baseline that runs across the slope), and distance (m) upslope from the experimental unit baseline (e.g., "+CWD, C8, 0-40"). Because experimental units share boundaries, PVC posts often hold more than one label.

2.2.3. Tree measurements

Unlike the main restoration experiment, trees in the CWD experiment were not mapped nor were snags measured. In each experimental unit, trees were identified to species and measured for dbh.

2.2.4. Understory sampling: ground conditions, vascular plants, tree seedlings

Within each experimental unit, three understory sampling transects are marked with permanent PVC posts at 10 m intervals (Fig. 6); posts are labeled by treatment, column, transect #, and distance (m) along the X axis (e.g., "+CWD, C8, Trans 1, 10"). Transects are spaced 10 m apart (beginning 20 m upslope from the experimental unit baseline) and run across the slope (azimuth of 130 degrees). Unmarked sample quadrats (1 x 1 m) are spaced at 1-m intervals along each transect beginning at the 4 m mark and ending at 36 m (i.e., 4-5 m, 6-7 ... 36-37 m) yielding a total of 17 quadrats per transect and 51 quadrats per experimental unit.

Understory measurements.— In each quadrat the following variables were sampled before treatment (2006) and will be sampled in 2009, 3 years after treatment: (1) cover of ground-surface characteristics (bare ground, fresh and decayed wood, litter, stumps, and post-treatment logging slash); (2) total cover of bryophytes; (3) cover of individual vascular plant species; and (4) counts of tree seedlings ($\leq$1.4 m tall) by species and size class.

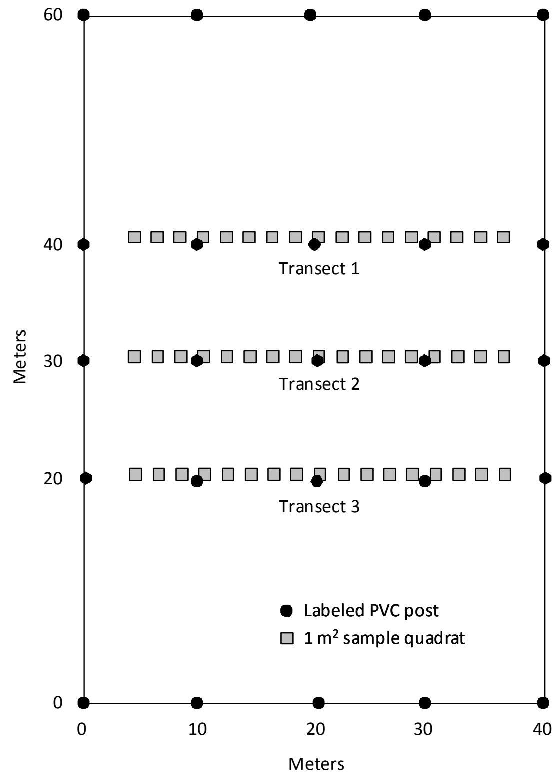


Fig. 6. Understory sampling design for the CWD experiment at Bear.

2.3. Timeline: Summary of Field Activities

Table 4 summarizes the history of plot establishment, treatment implementation, and sampling to date, as well as field activities planned for summer 2009 (year 3).

Table 4. Timeline of field activities in the experimental sites at Bear, Pine, and Pine-N.

	Pre-tmt		Post-tmt	
Field activity	2005	2006	2007	2009*
Plot establishment, treatment implementation				
Survey of initial transects, overstory tree maps and measurements	X	X		
Layout of experimental unit boundaries, tree marking for removal		X		
Establishment of understory sampling transects		X		
Implementation of experimental treatments		X		
Post-treatment reestablishment of experimental unit boundaries and understory sampling transects			X	
Vegetation measurements: Main restoration experiment				
Understory sampling (ground conditions, vascular plants, tree seedlings)		X	X	X
Bryophyte study (bryophyte species, tree seedlings)		X	X	X
Post-treatment updating of overstory tree maps			X	X
Hemispherical photographs (light availability)			X	
Vegetation measurements: CWD experiment (Bear)				
Understory sampling (ground conditions, vascular plants, tree seedlings)		X		X
Overstory tree measurements		X		

* Planned for Jun-Sep 2009

3. Data Files and Documentation

In the pages that follow, we provide detailed documentation about the core set of field data. All data are stored in Excel files containing one or more worksheets. Documentation tables for each data file or set of related files include brief descriptions of the types of data, file and worksheet names, variable names and definitions, meanings of coded values, and units of measurement. EU = experimental unit.

3.1. Data Files and Documentation for the Main Restoration Experiment

3.1.1. Main restoration experiment: Mapped overstory trees

Description: Species, DBH, spatial location (X,Y), and condition (e.g., live, dead, live but down) of all overstory trees (≥1.4 m tall) before and after treatment.

File Name(s): Bear complete tree data 2005-2007.xls
Pine complete tree data 2005-2007.xls
Pine-N complete tree data 2005-2007.xls

File Contents:

Worksheet 1: Bear (Pine or Pine-N) live trees in study EU's

Excel column	Variable name	Coded	Units	Definition
A	Tree-plot	No	—	Name of tree plot*
B	ID	No	—	Unique tree number identifier
C	Species	Yes	—	PNW species code
D	Sp.No.	Yes	—	Species number
E	DBH	No	cm	Diameter at breast height†
F	Plot X	No	m	Distance along X axis of full tree plot
G	Plot Y	No	m	Distance along Y axis of full tree plot
H	PostC	Yes	—	Post-treatment condition
I	Row	No	—	Row number of EU
J	Column	No	—	Column number of EU
K	Treatment	Yes	—	Type of treatment

* Differs from "Site" in that trees present in column 8 at Pine-N are coded as belonging to Pine-N.
† For trees with ID values >8000, DBH was calculated from stump diameter.

Coded Variables:

Variable: Species

ABAM	*Abies amabilis*	PREM	*Prunus emarginata*
ABIES	*Abies amabilis* or *A. procera*	PSME	*Pseudotsuga menziesii*
ABPR	*Abies procera*	TSHE	*Tsuga heterophylla*
ALRU	*Alnus rubra*	THPL	*Thuja plicata*
POTR2	*Populus trichocarpa*	HARDWOOD	Unknown hardwood
		UNKN	Unknown species

* Continued on next page *

3.1.1. Main restoration experiment: Mapped overstory trees (cont.)

File Contents: (cont.)

Worksheet 1: Bear (Pine or Pine-N) live trees in study EU's (cont.)

Coded Variables: (cont.)

Variable: Sp.No. (Note: there are no Sp.No. values of 3, 11-14, or 16 in these worksheets)

1	*Abies amabilis*
2	*Abies procera*
4	*Pseudotsuga menziesii*
5	*Thuja plicata*
6	*Tsuga heterophylla*
7	*Alnus rubra*
8	*Populus trichocarpa*
9	*Prunus emarginata*
10	*Abies amabilis* or *A. procera*
15	Unknown species
17	Unknown hardwood

Variable: PostC

0	Dead or snag
1	Alive
2	Prone, tipped, or topped
3	Stump

Variable: Treatment

C	Control
G	Gap
T	Thin

3.1.1. Main restoration experiment: Mapped overstory trees (cont.)

File Contents:

Worksheet 2: Bear (Pine or Pine-N) complete

Excel column	Variable name	Coded	Units	Definition
A	Tree-plot	No	—	Name of tree plot*
B	ID	No	—	Unique tree number identifier
C	Species	Yes	—	PNW species code
D	Sp.No.	Yes	—	Species number
E	DBH	No	cm	Diameter at breast height†
F	Plot X	No	m	Distance along X axis of full tree plot
G	Plot Y	No	m	Distance along Y axis of full tree plot
H	PreC	Yes	—	Pre-treatment condition
I	PostC	Yes	—	Post-treatment condition

* Differs from "Site" in that trees present in column 8 at Pine-N are coded as belonging to Pine-N.
† For trees with ID values >8000, DBH was calculated from stump diameter.

Coded Variables:

Variable: Species

ABAM	*Abies amabilis*	PSME	*Pseudotsuga menziesii*
ABIES	*Abies amabilis* or *A. procera*	TABR	*Taxus brevifolia*
ABPR	*Abies procera*	THPL	*Thuja plicata*
ACMA	*Acer macrophyllum*	TSHE	*Tsuga heterophylla*
ALRU	*Alnus rubra*	TSME	*Tsuga mertensiana*
POTR2	*Populus trichocarpa*	HARDWOOD	Unknown hardwood
PREM	*Prunus emarginata*	UNKN	Unknown species

Variable: Sp.No. (Note: there are no Sp.No. values of 3, 12, or 13 in these worksheets)

1	*Abies amabilis*	10	*Abies amabilis* or *A. procera*
2	*Abies procera*	11	*Acer macrophyllum*
4	*Pseudotsuga menziesii*	14	*Taxus brevifolia*
5	*Thuja plicata*	15	Unknown species
6	*Tsuga heterophylla*	16	*Tsuga mertensiana*
7	*Alnus rubra*		
8	*Populus trichocarpa*		
9	*Prunus emarginata*		

Variable: PreC

0	Dead
1	Alive

Variable: PostC

0	Dead or snag
1	Alive
2	Prone, tipped, or topped
3	Stump

3.1.2. Main restoration experiment: Post-treatment hemispherical photos

Description: Results of GLA analysis of post-treatment hemispherical photos.

File Name(s): All hemispherical photos 2007.xls

File Contents:

Worksheets 1, 3, and 5: Bear gaps, Pine gaps, and Pine-N gaps

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site*
B	Year	No	—	Photo year
C	Photopoint	Yes	—	Code for spatial location of photo derived from Treatment, Row, Column, Direction, Distance
D	Threshold	No	—	Threshold value selected in GLA program
E	Treatment	Yes	—	Type of treatment
F	Row	No	—	Row number of EU
G	Column	No	—	Column number of EU
H	Transect	Yes		Transect direction from gap center
I	Line	Yes	—	Integer code for SW-NE or SE-NW transects
J	+Distance	No	m	Distance from gap center (positive values only)
K	Distance	No	m	Distance along transect from gap center with negative numbers representing distances SW or SE of gap center, and positive numbers, distances NW or NE of gap center
L	X	No	m	Distance along X axis of full tree plot
M	Y	No	m	Distance along Y axis of full tree plot
N	% Cnpy Open	No	—	% canopy openness or % open sky
O	LAI 4Ring	No	—	Effective leaf area index integrated over zenith angles 0-60 degrees
P	LAI 5Ring	No	—	Effective leaf area index integrated over zenith angles 0-75 degrees
Q	Trans Dir	No	mols/m^2/day	Amount of direct solar radiation (May-Sep) transmitted by the canopy
R	Trans Dif	No	mols/m^2/day	Amount of diffuse solar radiation (May-Sep) transmitted by the canopy
S	Trans Tot	No	mols/m^2/day	Sum of Trans Dir and Trans Dif
T	% Trans Dir	No	%	% of above-canopy direct solar radiation (May-Sep) transmitted by the canopy
U	% Trans Dif	No	%	% of above-canopy diffuse solar radiation (May-Sep) transmitted by the canopy
V	% Trans Tot	No	%	% of above-canopy total solar radiation (May-Sep) transmitted by the canopy

* Site = Pine for EUs located in column 8 at Pine-N (see section 2.1.1)

* Continued on next page *

3.1.2. Main restoration experiment: Post-treatment hemispherical photos (cont.)

File Contents: (cont.)

Coded Variables:

Variable: Photopoint

Tmt-R#-C#-##-##	Treatment-Row #-Column #-Transect(X m)-Distance(Y m)

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: Transect

NE	transect runs NE from gap center (gaps)
NW	transect runs NW from gap center (gaps)
SE	transect runs SE from gap center (gaps)
SW	transect runs SW from gap center (gaps)

Variable: Line

1	transect runs from SW to NE through gap center
2	transect runs from SE to NW through gap center

3.1.2. Main restoration experiment: Post-treatment hemispherical photos (cont.)

File Contents:

Worksheets 2, 4, and 6: Bear C&T, Pine C&T, and Pine-N C&T

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site*
B	Year	No	—	Photo year
C	Photopoint	Yes	—	Code for spatial location of photo derived from Treatment, Row, Column, Transect, Distance
D	Threshold	No	—	Threshold value selected in GLA program
E	Treatment	Yes	—	Type of treatment
F	Row	No	—	Row number of EU
G	Column	No	—	Column number of EU
H	Transect	Yes	m	Transect number, i.e., distance along X axis of EU
I	Distance	No	m	Distance along Y axis of EU
J	X	No	m	Distance along X axis of full tree plot†
K	Y	No	m	Distance along Y axis of full tree plot
L	% Cnpy Open	No	—	% canopy openness or % open sky
M	LAI 4Ring	No	—	Effective leaf area index integrated over the zenith angles 0-60 degrees
N	LAI 5Ring	No	—	Effective leaf area index integrated over the zenith angles 0-75 degrees
O	Trans Dir	No	$mols/m^2/day$	Amount of direct solar radiation (May-Sep) transmitted by the canopy
P	Trans Dif	No	$mols/m^2/day$	Amount of diffuse solar radiation (May-Sep) transmitted by the canopy
Q	Trans Tot	No	$mols/m^2/day$	Sum of Trans Dir and Trans Dif
R	% Trans Dir	No	%	% of above-canopy direct solar radiation (May-Sep) transmitted by the canopy
S	% Trans Dif	No	%	% of above-canopy diffuse solar radiation (May-Sep) transmitted by the canopy
T	% Trans Tot	No	%	% of above-canopy total solar radiation (May-Sep) transmitted by the canopy

* Site = Pine for EUs located in column 8 at Pine-N (see section 2.1.1)

† For Pine EUs located in column 8 at Pine-N, distance is along X axis of full tree plot at Pine-N

Coded Variables:

Variable: Photopoint

Tmt-R#-C#-##-## Treatment-Row #-Column #-Transect(X m)- Distance(Y m)

Variable: Treatment

C	Control
G	Gap
T	Thin

* continued on next page *

3.1.2. Main restoration experiment: Post-treatment hemispherical photos (cont.)

Coded Variables: (cont.)

Variable: Transect

10	transect at 10-m along X axis of EU
20	transect at 20-m along X axis of EU
30	transect at 30-m along X axis of EU

3.1.3. Main restoration experiment: Ground conditions

Description: Pre- and post-treatment cover of ground characteristics, logging slash, and bryophytes.

File Name(s): Bear ground cover 2006-2007.xls
Pine ground cover 2006-2007.xls
Pine-N ground cover 2006-2007.xls

File Contents:

Worksheet 1: Ground 2006 (pre-treatment)
Worksheet 2: Ground 2007 (post-treatment)

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site*
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	U/D	Yes	—	Up or downslope from 20-m midline of EU (controls, thins)
G	Transect	Yes	—	Transect designation on field form: distance along X axis of EU (controls, thins) or orientation from gap center (gaps)
H	Quadrat #	No	m	Distance from 0-m mark on Transect to closest post of sample quadrat
I	Line	Yes	—	Transect designation for analysis: distance (m) along baseline of EU (controls, thins) or integer code for SW-NE or SE-NW transects (gaps)
J	Distance	No	m	Distance along Y axis from baseline of EU to mid-point of quadrat edge (controls, thins); or along transect from gap center to midpoint of quadrat edge (gaps), with negative numbers representing distances SW or SE of gap center, and positive numbers, distances NW or NE of gap center
K	X	No	m	Distance along X axis of full tree plot†
L	Y	No	m	Distance along Y axis of full tree plot
M	BARE	No	%	Cover of bare ground (mineral soil)
N	FRESH	No	%	Cover of fresh wood (decay classes I and II, $\geq$10 cm diameter)
O	DECAY	No	%	Cover of decayed wood (decay classes III-V, $\geq$10 cm diameter)
P	LITTER	No	%	Cover of fine litter (foliage or wood <10 cm diameter)
Q	TBASE	No	%	Cover of tree bases (live or dead)
R	STUMP	No	%	Cover of stumps
S	SLASH	No	%	Cover of logging slash (<10 cm diameter)
T	BRYOP	No	%	Cover of bryophytes (total)

* Continued on next page *

3.1.3. Main restoration experiment: Ground characteristics (cont.)

Excel column	Variable name	Coded	Units	Definition
U	Comments	No	—	Comments

* Site = Pine for EUs located in column 8 at Pine-N (see section 2.1.1)

† For Pine EUs located in column 8 at Pine-N, distance is along X axis of full tree plot at Pine-N

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: U/D

D	transect runs downslope from 20-m midline of EU
U	transect runs upslope from 20-m midline of EU

Variable: Transect

10	transect at 10-m along X axis of EU (controls, thins)
20	transect at 20-m along X axis of EU (controls, thins)
30	transect at 30-m along X axis of EU (controls, thins)
NE	transect runs NE from gap center (gaps)
NW	transect runs NW from gap center (gaps)
SE	transect runs SE from gap center (gaps)
SW	transect runs SW from gap center (gaps)

Variable: Line

10	transect runs upslope from 10-m mark along baseline of EU (controls, thins)
20	transect runs upslope from 20-m mark along baseline of EU (controls, thins)
30	transect runs upslope from 30-m mark along baseline of EU (controls, thins)
1	transect runs from SW to NE through gap center (gaps)
2	transect runs from SE to NW through gap center (gaps)

3.1.4. Main restoration experiment: Understory plant composition

Description: Pre- and post-treatment cover of vascular plant species including simple summaries of species richness and total cover by site and treatment.

File Name(s): Bear understory species 2006-2007.xls
Pine understory species 2006-2007.xls
Pine-N understory species 2006-2007.xls

File Contents:

Worksheet 1: Species 2006 (pre-treatment)
Worksheet 2: Species 2007 (post-treatment)

Excel column	Variable name	Coded	units	Definition
A	Site	No	—	Study site*
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	U/D	Yes	—	Up or downslope from 20-m midline of EU (controls, thins)
G	Transect	Yes	—	Transect designation on field form: distance along X axis (controls, thins) or orientation from gap center (gaps)
H	Quadrat	No	m	Quadrat number, i.e., distance from 0-m mark on Transect to closest post of sample quadrat
I	Line	Yes	—	Transect designation for analysis: distance (m) along baseline of EU (controls, thins) or integer code for SW-NE or SE-NW transects (gaps)
J	Distance	No	m	Distance along Y axis from baseline of EU to mid-point of quadrat edge (controls, thins); or along transect from gap center to midpoint of quadrat edge (gaps), with negative numbers representing distances SW or SE of gap center, and positive numbers, distances NW or NE of gap center
K	X	No	m	Distance along X axis of full tree plot†
L	Y	No	m	Distance along Y axis of full tree plot
M → CV	Species cover	No	%	Projected canopy cover of species listed in column heading
CW	—	—	—	Blank column
CX	Richness	—	no./quadrat	Number of species in the quadrat
CY	% cover	—	%	Summed cover of all species in the quadrat

* Site = Pine for EUs located in column 8 at Pine-N (see section 2.1.1)

† For Pine EUs located in column 8 at Pine-N, distance is along X axis of full tree plot at Pine-N

* Continued on next page *

3.1.4. Main restoration experiment: Understory plant composition (cont.)

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: U/D

D	downslope from 20-m midline of EU
U	upslope from 20-m midline of EU

Variable: Transect

10	transect runs up/downslope at 10-m along X axis (controls, thins)
20	transect runs up/downslope at 20-m along X axis (controls, thins)
30	transect runs up/downslope at 30-m along X axis (controls, thins)
NE	transect runs NE from gap center (gaps)
NW	transect runs NW from gap center (gaps)
SE	transect runs SE from gap center (gaps)
SW	transect runs SW from gap center (gaps)

Variable: Line

10	transect runs upslope from 10-m mark along baseline of EU (controls, thins)
20	transect runs upslope from 20-m mark along baseline of EU (controls, thins)
30	transect runs upslope from 30-m mark along baseline of EU (controls, thins)
1	transect runs from SW to NE through gap center (gaps)
2	transect runs from SE to NW through gap center (gaps)

Variable: Species cover (column headings are species codes; data cells are cover)

See Table 5, next page, for a full list of species codes and scientific names

3.1.4. Main restoration experiment: Understory plant composition (cont.)

Coded Variables: (cont.)

Table 5. PNW codes and scientific names of vascular plant species recorded in quadrats at Bear, Pine, and Pine-N. Tree species are not included (not sampled for cover). Nomenclature follows Hitchcock, C. L., and A. Cronquist. 1973. *Flora of the Pacific Northwest*. University of Washington Press, Seattle, WA.

Code	Scientific name	Code	Scientific name
ACCI	*Acer circinatum*	LUZUL	*Luzula* species
ACER	*Acer* species	LYCL	*Lycopodium clavatum*
ACRU	*Actaea rubra*	MADI2	*Maianthemum dilatatum*
ACTR	*Achlys triphylla*	MEFE	*Menziesia ferruginea*
ANMA	*Anaphalis margaritacea*	OPHO	*Oplopanax horridus*
ASCA3	*Asarum caudatum*	OSCH	*Osmorhiza chilensis*
ATFI	*Athyrium filix-femina*	PLMA	*Plantago major*
BENE	*Berberis nervosa*	POLYPO	*Polypodiaceae* species
BLSP	*Blechnum spicant*	POMU	*Polystichum munitum*
CHLE2	*Chrysanthemum leucanthemum*	PTAQ	*Pteridium aquilinum*
CHME	*Chimaphila menziesii*	PYCH	*Pyrola chlorantha*
CIAL	*Circaea alpina*	PYROL	*Pyrola* species
CIVU	*Cirsium vulgare*	PYSE	*Pyrola secunda*
CLUN	*Clintonia uniflora*	PYUN	*Pyrola uniflora*
COCA	*Cornus canadensis*	RIBES	*Ribes* species
COME	*Corallorhiza mertensiana*	ROGY	*Rosa gymnocarpa*
DIFO	*Dicentra formosa*	RUBUS	*Rubus* species
DIPU	*Digitalis purpureum*	RULA	*Rubus lasiococcus*
DISPO	*Disporum* species	RULE	*Rubus leucodermis*
DRAU2	*Dryopteris austriaca*	RUPE	*Rubus pedatus*
EPAN	*Epilobium angustifolium*	RUUR	*Rubus ursinus*
EPILO	*Epilobium* species	SADO	*Satureja douglasii*
EPWA	*Epilobium watsonii*	SARA	*Sambucus racemosa*
EQUIS	*Equisetum* species	SESY	*Senecio sylvaticus*
GASH	*Gaultheria shallon*	SMST	*Smilacina stellata*
GATR	*Galium triflorum*	SOSC	*Sorbus scopulina*
GOOB	*Goodyera oblongifolia*	STAM	*Streptopus amplexifolius*
GRAMIN#	Unknown graminoid species	TITR	*Tiarella trifoliata*
GYDR	*Gymnocarpium dryopteris*	TRCA3	*Trautvetteria caroliniensis*
HAOR	*Habenaria orbiculata*	TROV	*Trillium ovatum*
HODI	*Holodiscus discolor*	UNKN#	Uknown species
HYMO	*Hypopitys monotropa*	VACCI	Vaccinium species
LAMU	*Lactuca muralis*	VAPA	*Vaccinium parvifolium*
LIBO2	*Linnaea borealis*	VIGL	*Viola glabella*
LICA3	*Listera caurina*	VIOLA	*Viola* species
LICO3	*Listera cordata*	VISE	*Viola sempervirens*
LUPA	*Luzula parviiflora*		

3.1.5. Main restoration experiment: Tree seedling counts

Description: Pre- and post-treatment counts of tree seedlings (<1.4 m tall) by height class including simple summaries of species richness and total counts by site and treatment.

File Name(s): Bear tree seedlings 2006-2007.xls
Pine tree seedlings 2006-2007.xls
Pine-N tree seedlings 2006-2007.xls

File Contents:

Worksheet 1: Seedlings 2006 (pre-treatment)
Worksheet 2: Seedlings 2007 (post-treatment)

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site*
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	U/D	Yes	—	Up or downslope from 20-m midline of EU (controls, thins)
G	Transect	Yes	—	Transect designation on field form: distance along X axis (controls, thins) or orientation from gap center (gaps)
H	Quadrat	No	m	Quadrat number, i.e., distance from 0-m mark on Transect to closest post of sample quadrat
I	Line	Yes	—	Transect designation for analysis: distance (m) along baseline of EU (controls, thins) or integer code for SW-NE or SE-NW transects (gaps)
J	Distance	No	m	Distance along Y axis from baseline of EU to mid-point of quadrat edge (controls, thins); or along transect from gap center to midpoint of quadrat edge (gaps), with negative numbers representing distances SW or SE of gap center, and positive numbers, distances NW or NE of gap center
K	X	No	m	Distance along X axis of full tree plot†
L	Y	No	m	Distance along Y axis of full tree plot
M → BH	Count	No	no./quadrat	Seedling count by species and height class or total of all height classes for the species and height class listed in the column heading
BI	—	—	—	Blank column

* Continued on next page *

3.1.5. Main restoration experiment: Tree seedling counts (cont.)

Excel column	Variable name	Coded	Units	Definition
BJ	Tree seedling richness	—	no./quadrat	Number of tree seedling species in the quadrat
BK	Tree seedling count	—	no./quadrat	Summed count of tree seedlings in the quadrat

* Site = Pine for EUs located in column 8 at Pine-N (see section 2.1.1)

† For Pine EUs located in column 8 at Pine-N, distance is along X axis of full tree plot at Pine-N

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: U/D

D	downslope from 20-m midline of EU
U	upslope from 20-m midline of EU

Variable: Transect

10	transect runs up/downslope at 10-m mark along X axis (controls, thins)
20	transect runs up/downslope at 20-m mark along X axis (controls, thins)
30	transect runs up/downslope at 30-m mark along X axis (controls, thins)
NE	transect runs NE from gap center (gaps)
NW	transect runs NW from gap center (gaps)
SE	transect runs SE from gap center (gaps)
SW	transect runs SW from gap center (gaps)

Variable: Line

10	transect runs upslope from 10-m mark along baseline of EU (controls, thins)
20	transect runs upslope from 20-m mark along baseline of EU (controls, thins)
30	transect runs upslope from 20-m mark along baseline of EU (controls, thins))
1	transect runs from SW to NE through gap center
2	transect runs from SE to NW through gap center

Variable: Count (column headings are species x height class codes; data cells are counts)

Species		**Ht class**	
ABAM	*Abies amabilis*	0	1 or 2-yr old
ABIES	*Abies amabilis* or *A. procera*	1	≥3-yr old and ≤10 cm tall
ABPR	*Abies procera*	2	11-25 cm tall
ALRU	*Alnus rubra*	3	26-50 cm tall
PSME	*Pseudotsuga menziesii*	4	51-140 cm tall
TABR	*Taxus brevifolia*	T	all classes combined
TSHE	*Tsuga heterophylla*		
UNKN	Unknown species		

3.2. Data Files and Documentation for the Bryophyte Study (Bear)

3.2.1. Bryophyte study: Quadrat locations, growth-form cover data

Description: Survey data for relocating/reestablishing sample quadrats; total cover of mosses, liverworts, and vascular plants.

File Name(s): Bryophyte quadrat attributes 2006-2007.xls

File Contents:

Worksheet 1: Bryophyte attributes 2006 (pre-treatment)
Worksheet 2: Bryophyte attributes 2007 (post-treatment)

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	Sample #	No	—	Quadrat sample number
G	S-Type	Yes	—	Quadrat sample type (substrate type)
H	Decay Class	No	—	Log decay class (III-V) (2006 worksheet only)
I	New	Yes	—	Indicator variable for quadrats lost during logging and reestablished in a new location in 2007 (2007 worksheet only)
J	Nail to Flag	No	deg	Azimuth from aluminum reference nail with tag to flag on the same short side of the quadrat but at the opposite end; nail with tag was placed near the flag closest to gap center in gap treatments, or near the flag closest to the X baseline in control and thin treatments (2007 worksheet only)
K	U/D/G/F	Yes	—	General location within EU
L	Down	No	m	General location (distance) from top of 10-m strip (controls, thins)
M	Across	No	m	General location (distance) from left edge of 10-m strip (controls, thins)
N	Dist	No	m	Distance from quadrat to gap center (gaps)
O	Deg	No	deg	Azimuth from aluminum reference nail with tag to gap center (gaps)
P	MOSS	No	%	Total cover of mosses
Q	LIVER	No	%	Total cover of liverworts
R	VASCUL	No	%	Total cover of vascular plant species
S	Comments	—	—	Comments

* Continued on next page *

3.2.1. Bryophyte study: Quadrat locations, growth-form cover data (cont.)

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: S-Type

Floor	forest floor
CWD	coarse woody debris (decay class III-V)

Variable: U/D/G/F

D	located downslope from 20-m midline of EU (controls, thins)
U	located upslope from 20-m midline of EU (controls, thins)
F	located in forest adjacent to gap
G	located in gap

Variable: New

blank	no change in quadrat location
X	new quadrat established after treatment (location may differ from pre-treatment)

3.2.2. Bryophyte study: Disturbance

Description: Disturbance and slash cover data (2007, post-treatment only).

File Name(s): Bryophyte disturbance 2007.xls

File Contents:

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	Sample #	No	—	Quadrat sample number
G	S-Type	Yes	—	Quadrat sample type (forest floor or CWD)
H	U/D/G/F	Yes	—	General location within EU
I	BARE	No	%	Cover of bare ground/mineral soil (forest floor quadrats only)
J	FRESH	No	%	Cover of fresh wood (new, $\geq$ 10cm diameter)
K	SLASH	No	%	Cover of logging slash (<10 cm diameter)
L	%MISS	No	%	Percentage of CWD quadrat missing (removed) due to logging disturbance
M	Comments			Comments

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: S-Type

Floor	forest floor
CWD	coarse woody debris (decay class III-V)

Variable: U/D/G/F

D	located downslope from central sampling transect
U	located upslope from central sampling transect
F	located in forest adjacent to gap
G	located in gap

* Continued on next page *

3.2.3. Bryophyte study: Bryophyte species

Description: Presence of all moss and liverwort species within each bryophyte quadrat.

File Name(s): Bryophyte species.xls

File Contents:

Worksheet 1: Bryophyte species 2006 (pre-treatment)

Worksheet 2: Bryophyte species 2007 (pre-treatment)

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	Sample #	No	—	Quadrat sample number
G	S-Type	Yes	—	Quadrat sample type (forest floor or CWD)
H	Species	Yes	—	Code of species present in the quadrat
I	Comments	No	—	Comments

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: S-Type

Floor	forest floor
CWD	coarse woody debris (decay class III-V)

* Continued on next page *

3.2.3. Bryophyte study: Bryophyte species (cont.)

Coded Variables:

Variable: Species

(See Table 6, below, for a full list of species codes and scientific names)

Table 6. Codes and scientific names of bryophyte species recorded in quadrats at the Bear site.

Code	Scientific name	Code	Scientific name
BAZAMB	*Bazzania ambigua*	LEPREP	*Lepidozia reptans*
BLETRI	*Blepharostoma trichophyllum*	LOPHET	*Lophocolea heterophylla*
BRAHYL	*Brachythecium hylotapetum*	LOPHET	*Lophocolea heterophylla*
CALMUE	*Calypogeia muelleriana*	NECDOU	*Neckera douglasii*
CALSUE	*Calypogeia suecica*	ORTLYE	*Orthotrichium lyellii*
CALYP	*Calypogeia* species	PLAUND	*Plagiothecium undulatum*
CEPHA	*Cephalozia* species*	PLESCH	*Pleurozium schreberi*
DICFUS	*Dicranum fuscescens*	PSEELE	*Pseudotaxiphyllum elegans*
DIPALB	*Diplophyllum albicans*	PTICAL	*Ptilidium californicum*
EURORE	*Eurhynchium oreganum*	RHIGLA	*Rhizomnium glabrescens*
HOMMEG	*Homalothecium megaptilum*	RHYLOR	*Rhytidiadelphus loreus*
HYLSPL	*Hylocomium splendens*	RHYROB	*Rhytidiopsis robusta*
HYPCIR	*Hypnum circinale*	RICCA	*Riccardia* species
ISOSTO	*Isothecium stoloniferum*	SCABOL	*Scapania bolanderi*

* includes *C. lunulifolia* and *C. bicuspidata*

3.2.4. Bryophyte study: Tree seedling counts

Description: Tree seedling counts within bryophyte quadrats.

File Name(s): Bryophyte tree seedlings.xls

File Contents:

Worksheet 1: Bryophyte tree seedlings 2006 (pre-treatment)

Worksheet 2: Bryophyte tree seedlings 2007 (post-treatment)

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Row	No	—	Row number of EU
D	Column	No	—	Column number of EU
E	Treatment	Yes	—	Type of treatment
F	Sample #	No	—	Quadrat sample number
G	S-Type	Yes	—	Quadrat sample type (forest floor or CWD)
H	Species	Yes	—	PNW species code
I	Ht class	Yes	—	Height class
J	Count	No	no./quadrat	Number of seedlings in the quadrat
K	Comments	No	—	Comments

Coded Variables:

Variable: Treatment

C	Control
G	Gap
T	Thin

Variable: S-Type

Floor	forest floor
CWD	coarse woody debris (decay class III-V)

Variable: Species

ABAM	*Abies amabilis*
ABIES	*Abies amabilis* or *A. procera*
ABPR	*Abies procera*
ALRU	*Alnus rubra*
PREM	*Prunus emarginata*
TSHE	*Tsuga heterophylla*

Variable: Ht class

0	1 or 2-yr old
1	≥3-yr old and ≤10 cm tall
2	11-25 cm tall

3.3. Data Files and Documentation for the Bear CWD Experiment

3.3.1. Bear CWD experiment: Overstory trees

Description: Diameters (dbh) of all overstory trees ($\geq$1.4 m tall) before treatment.

File Name(s): Bear CWD complete tree data 2006.xls

File Contents:

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Column	No	—	Column number of EU
D	Treatment	Yes	—	Type of treatment (CWD retained or removed)
E	Species	Yes	—	PNW species code
F	DBH	No	cm	Tree diameter at breast height

Coded Variables:

Variable: Treatment

+CWD	CWD retained
-CWD	CWD removed

Variable: Species

ABAM	*Abies amabilis*
ALRU	*Alnus rubra*
PSME	*Pseudotsuga menziesii*
THPL	*Thuja plicata*
TSHE	*Tsuga heterophylla*

3.3.2. Bear CWD experiment: Ground characteristics

Description: Cover of ground characteristics and bryophytes (pre-treatment data only to date).

File Name(s): Bear CWD ground cover 2006.xls

File Contents:

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Column	No	—	Column number of EU
D	Treatment	Yes	—	Type of treatment (CWD retained or removed)
E	Transect	No	—	Transect number (1 is highest on the slope, 2 is midslope, 3 is lowest on the slope)
F	Quadrat	No	—	Quadrat number, i.e., distance from 0-m mark on Transect to closest post of sample quadrat
G	Ground type	Yes	—	Code for ground-surface variable or total bryophytes
H	Cover	No	%	Cover
I	Comments	No	—	Comments

Coded Variables:

Variable: Treatment

+CWD	CWD retained
-CWD	CWD removed

Variable: Ground type

BARE	bare ground (mineral soil)
FRESH	fresh wood (decay classes I and II, ≥ 10 cm diameter)
DECAY	decayed wood (decay classes II-V, ≥ 10 cm diameter)
TBASE	tree base (live or dead)
LITTER	fine litter (foliage and wood <10 cm diameter)
STUMP	stump
BRYOP	bryophytes (mosses and liverworts)

3.3.3. Bear CWD experiment: Understory plant composition

Description: Cover of vascular plant species (pre-treatment data only to date).

File Name(s): Bear CWD understory species 2006.xls

File Contents:

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Column	No	—	Column number of EU
D	Treatment	Yes	—	Type of treatment (CWD retained or removed)
E	Transect	No	—	Transect number (1 is highest on the slope, 2 is midslope, 3 is lowest on the slope)
F	Quadrat	No	—	Quadrat number, i.e., distance from 0-m mark on Transect to closest post of sample quadrat
G	Species	Yes	—	PNW species code
H	Cover	No	%	Projected canopy cover
I	Comments	No	—	Comments

Coded Variables:

Variable: Treatment

+CWD	CWD retained
-CWD	CWD removed

Variable: Species

See Table 5 (above) for a full list of species codes and scientific names

3.3.4. Bear CWD experiment: Tree seedling counts

Description: Counts of tree seedlings (<1.4 m tall) by height class (pre-treatment data only to date).

File Name(s): Bear CWD tree seedlings 2006.xls

File Contents:

Excel column	Variable name	Coded	Units	Definition
A	Site	No	—	Study site
B	Year	No	—	Sampling year
C	Column	No	—	Column number of EU
D	Treatment	Yes	—	Type of treatment (CWD retained or removed)
E	Transect	No	—	Transect number (1 is highest on the slope, 2 is midslope, 3 is lowest on the slope)
F	Quadrat	No	—	Quadrat number, i.e., distance from 0-m mark on Transect to closest post of sample quadrat
G	Species	Yes	—	PNW species code
H	Ht class	Yes	—	Height class
I	SppHt	Yes	—	Combined species x height-class code
J	Count	No	no./quadrat	Number of seedlings in the quadrat
K	Comments	No	—	Comments

Coded Variables:

Variable: Treatment

+CWD	CWD retained
-CWD	CWD removed

Variable: Species

ABAM	*Abies amabilis*
ABIES	*Abies amabilis* or *A. procera*
ABPR	*Abies procera*
PSME	*Pseudotsuga menziesii*
TSHE	*Tsuga heterophylla*
UNKN	Unknown species

Variable: Ht class

0	1 or 2-yr old
1	≥3-yr old and ≤10 cm tall
2	11-25 cm tall
3	26-50 cm tall
4	51-140 cm tall

Variable: SppHt

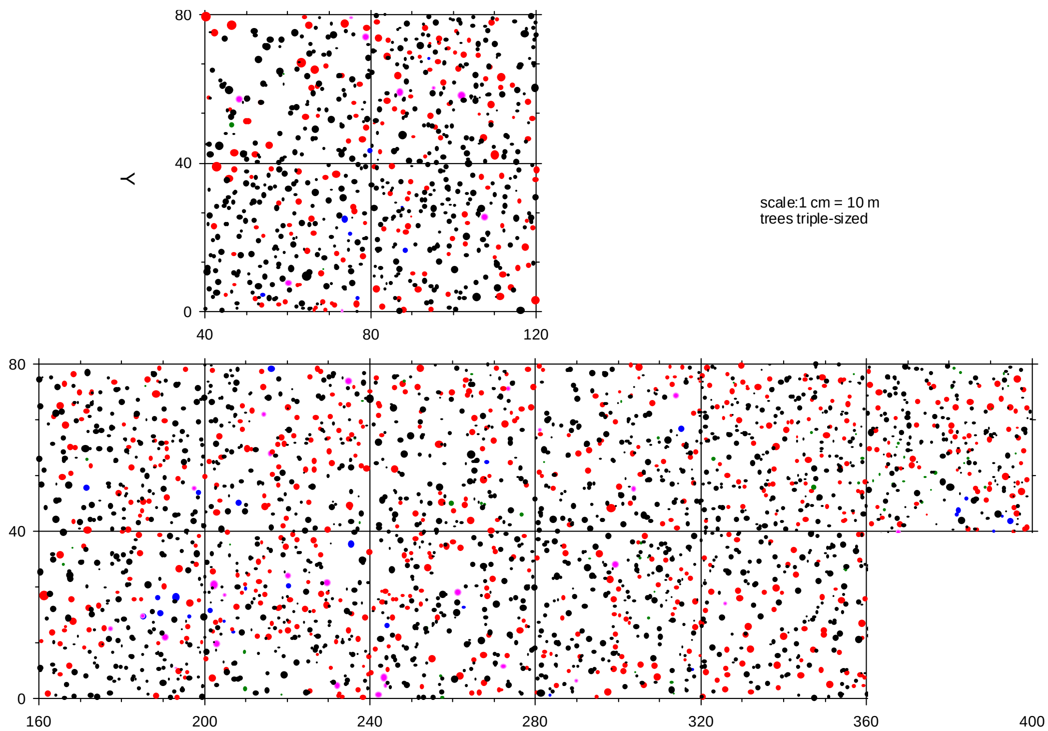
Defined by combining the variables Species and Ht class (see above)

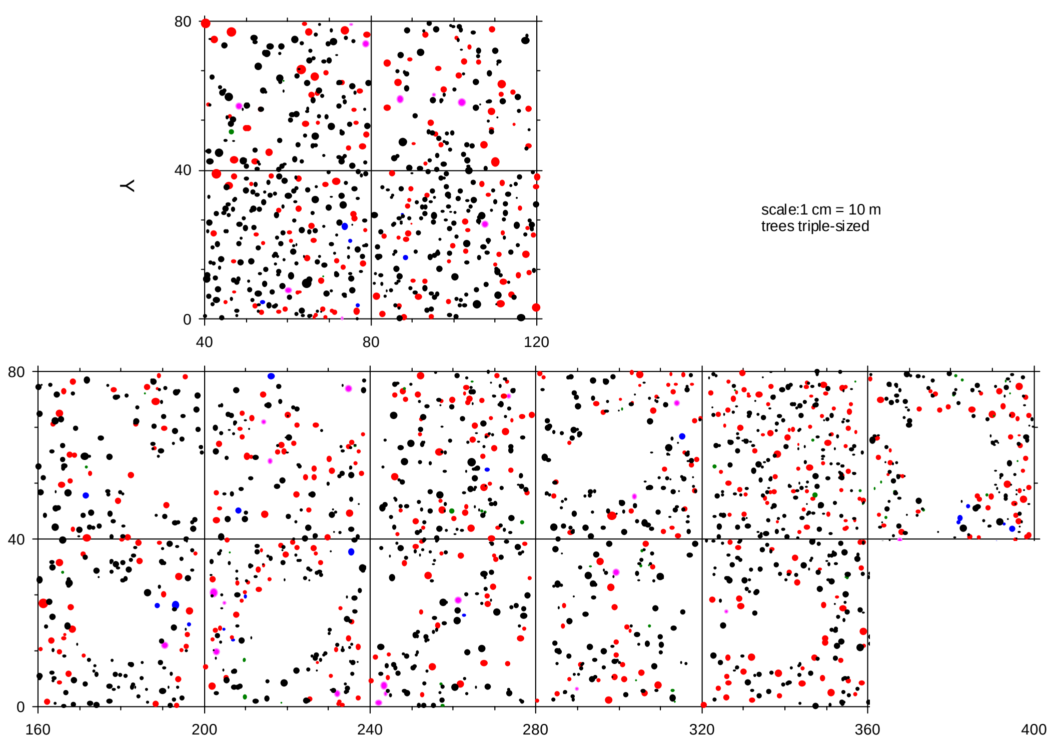
4. Appendices

4.1. Stem Maps of Pre- and Post-treatment Stands

4.1.1. Bear: Pre- and Post-treatment Stem Maps (split along X axis to allow for enlargement)

Species are: *Abies amabilis*, blue; *A. procera*, pink; *Pseudotsuga menziesii*, red; *Thuja plicata*, green; *Tsuga heterophylla*, black; and all hardwoods (*Alnus rubra*, *Populus trichocarpa*, and *Prunus emarginata*), yellow.

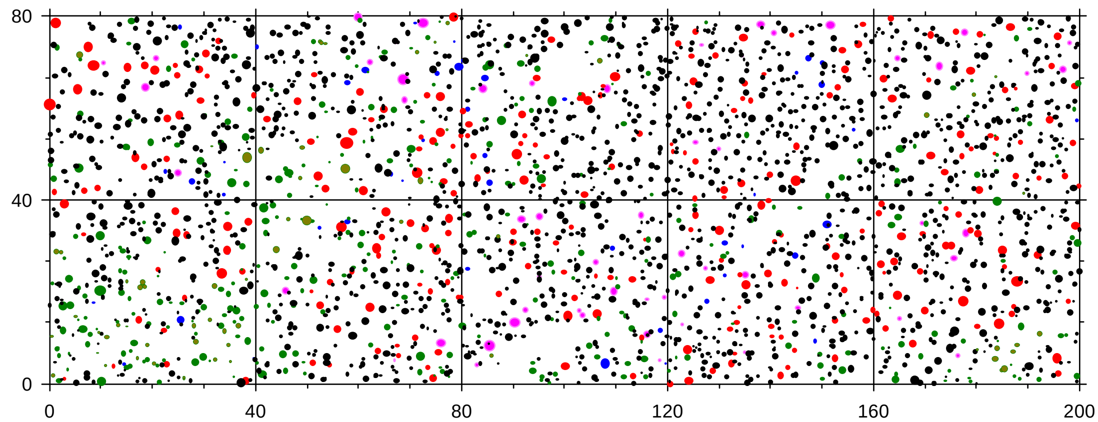


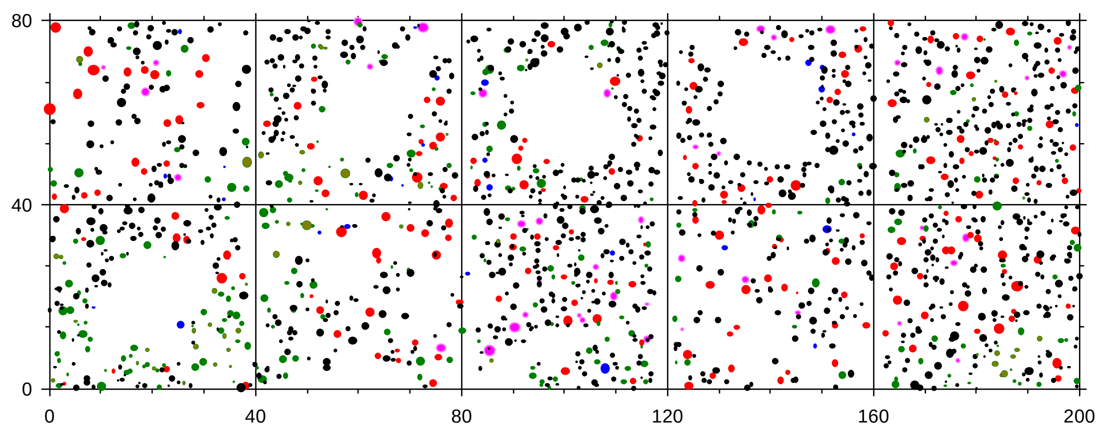


4.1. Stem Maps of Pre- and Post-treatment Stands (cont.)

4.1.2. Pine: Pre- and Post-treatment Stem Maps

Species are: *Abies amabilis*, blue; *A. procera*, pink; *Pseudotsuga menziesii*, red; *Thuja plicata*, green; *Tsuga heterophylla*, black; and all hardwoods (*Alnus rubra*, *Populus trichocarpa*, and *Prunus emarginata*), yellow.

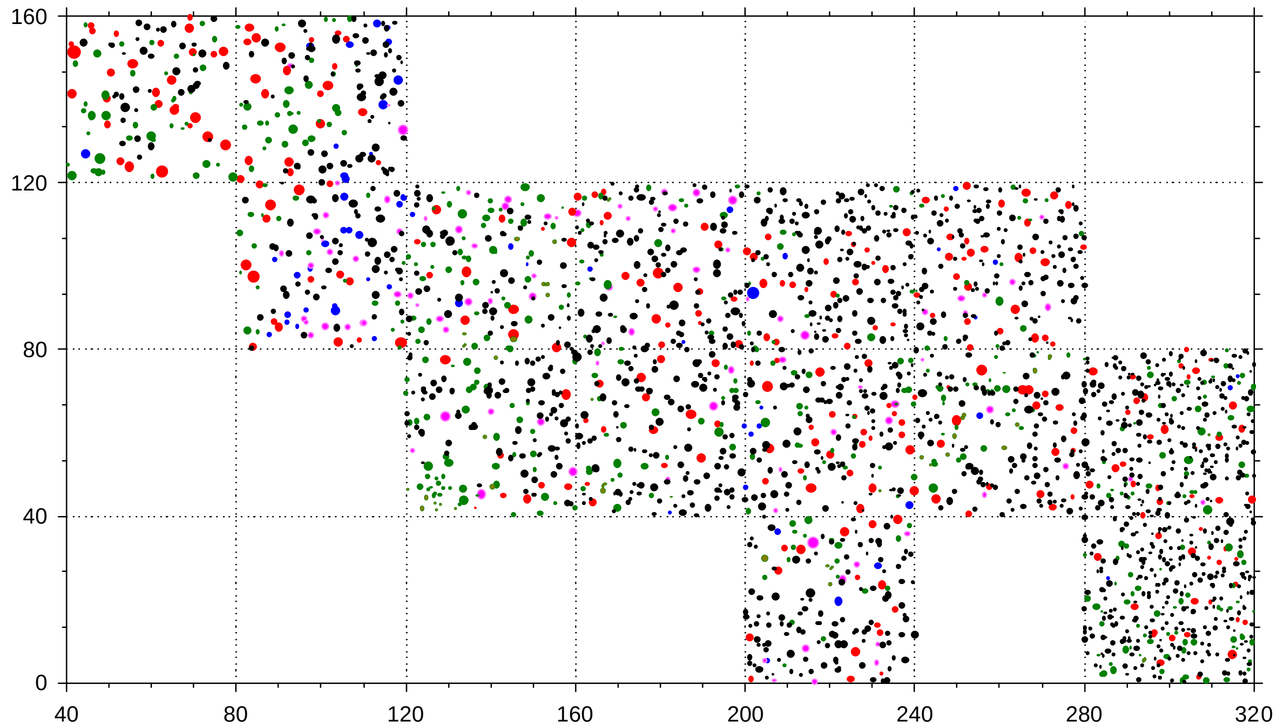


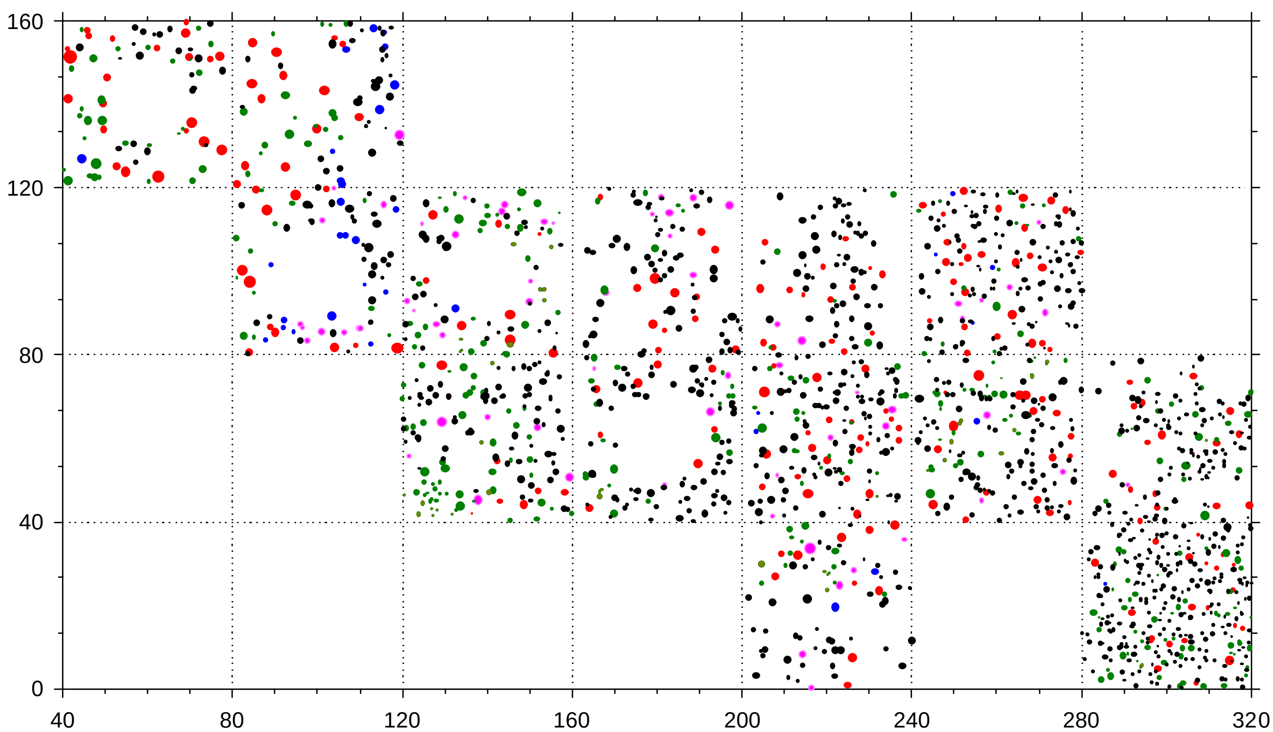


4.1. Stem Maps of Pre- and Post-treatment Stands (cont.)

4.1.3. Pine-N: Pre- and Post-treatment Stem Maps

Species are: *Abies amabilis*, blue; *A. procera*, pink; *Pseudotsuga menziesii*, red; *Thuja plicata*, green; *Tsuga heterophylla*, black; and all hardwoods (*Alnus rubra*, *Populus trichocarpa*, and *Prunus emarginata*), yellow.

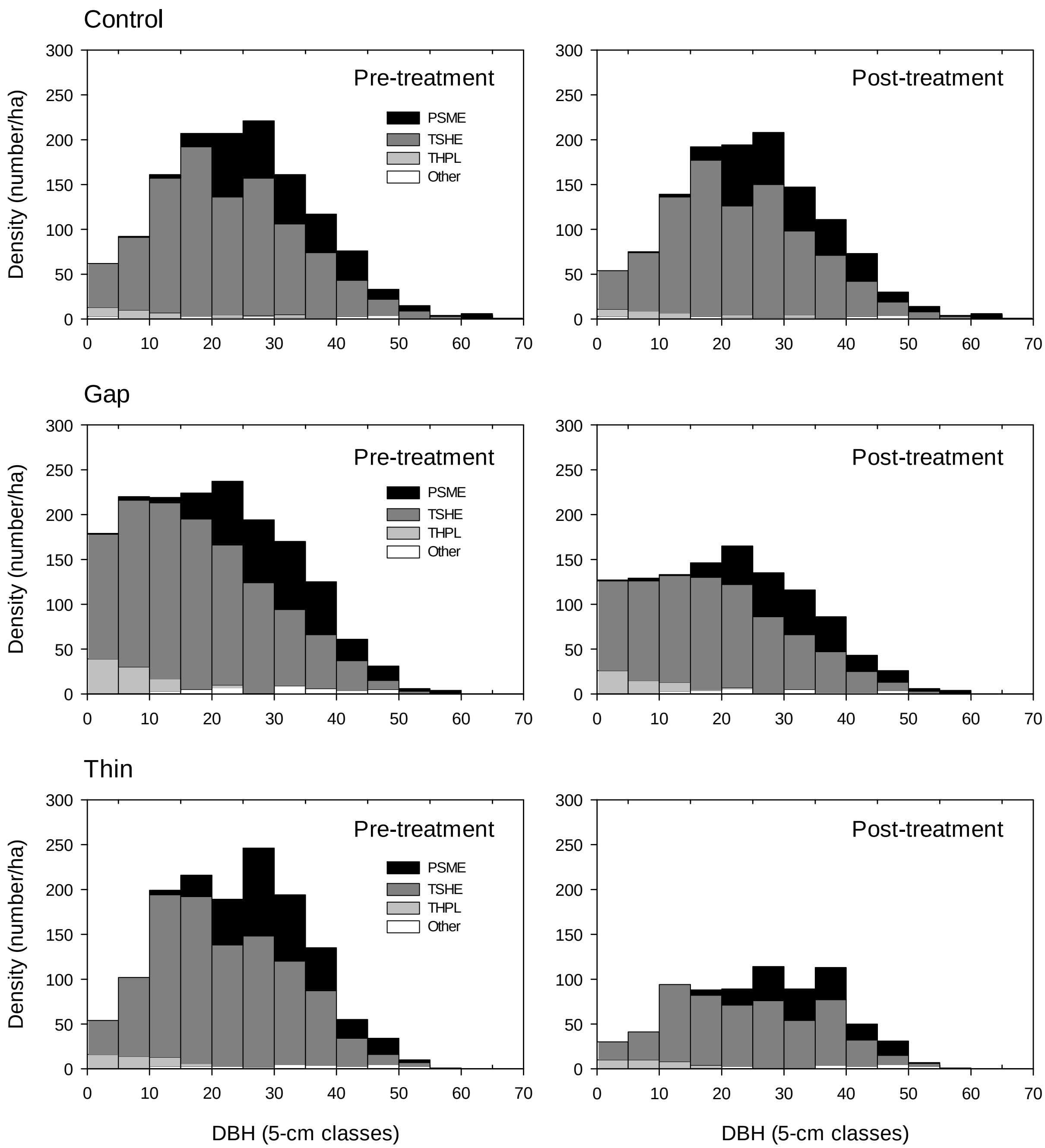




4.2. Pre- and Post-treatment Size Structures of Major Tree Species

4.2.1. Bear: Pre- and Post-treatment Size Structures

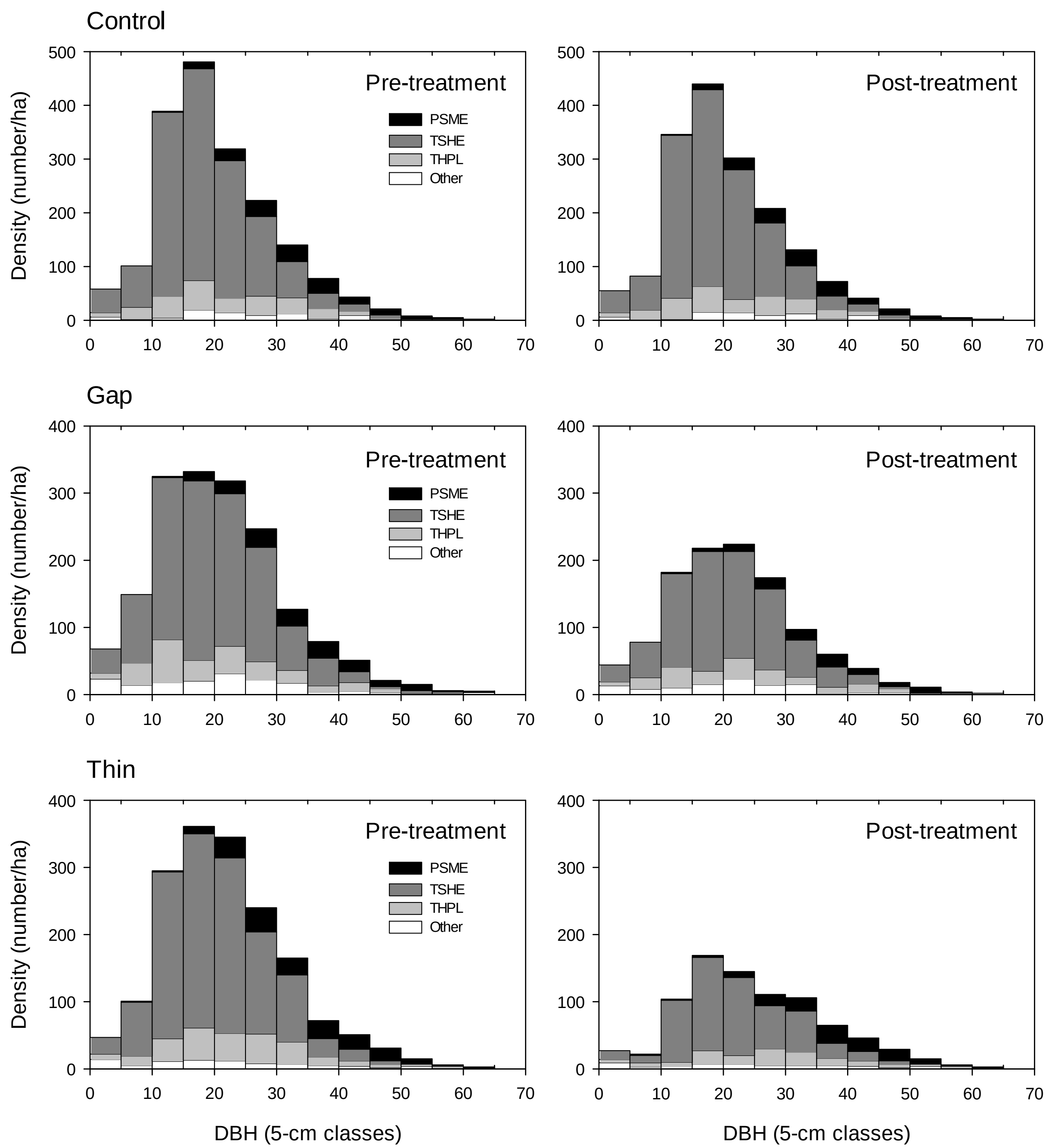
Tree species codes are: PSME, *Pseudotsuga menziesii*, TSHE = *Tsuga heterophylla*, THPL = *Thuja plicata*, and Other = all other species combined



4.2. Pre- and Post-treatment Size Structures of Major Tree Species (cont.)

4.2.2. Pine: Pre- and Post-treatment Size Structures

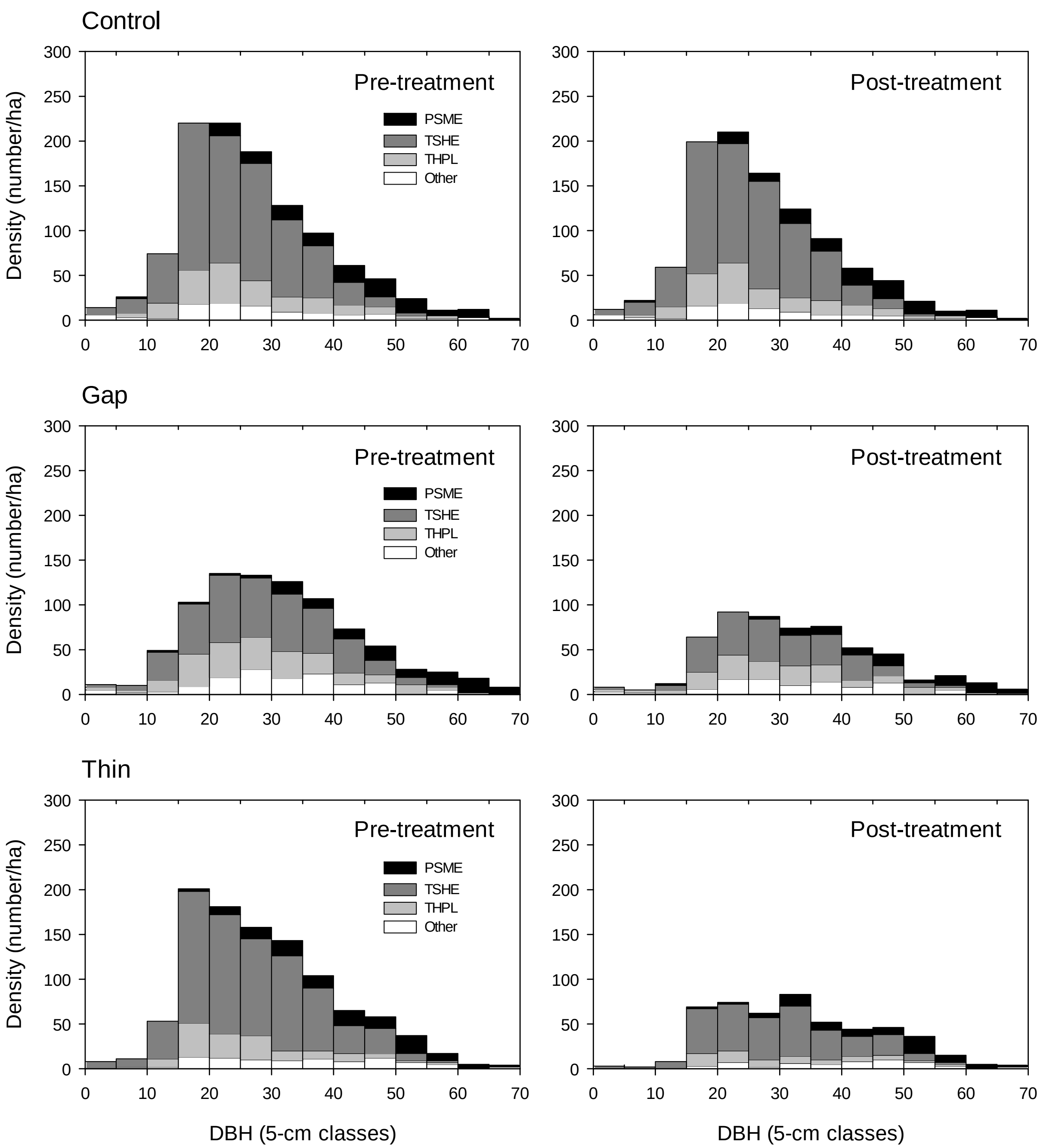
Tree species codes are: PSME, *Pseudotsuga menziesii*, TSHE = *Tsuga heterophylla*, THPL = *Thuja plicata*, and Other = all other species combined



4.2. Pre- and Post-treatment Size Structures of Major Tree Species (Cont.)

4.2.3. Pine-N: Pre- and Post-treatment Size Structures

Tree species codes are: PSME, *Pseudotsuga menziesii*, TSHE = *Tsuga heterophylla*, THPL = *Thuja plicata*, and Other = all other species combined



4.3. Data Forms for Pre-and Post-treatment Sampling

Forms are ordered as follows:

Pre-treatment forms

1. 2005 Pre-treatment Tree Location, Diameter, and Condition
2. 2006 Pre-treatment Understory Sampling (Control and Thin Treatments)
3. 2006 Pre-treatment Understory Sampling (Gap Treatments)
4. 2006 Pre-treatment Understory Sampling (CWD Experiment at Bear)
5. 2006 Pre-treatment Tree Diameters (CWD Experiment at Bear)
6. 2006 Pre-treatment Bryophyte Sampling (Control and Thin Treatments)
7. 2006 Pre-treatment Bryophyte Sampling (Gap Treatments)

Post-treatment forms

1. 2007 Post-treatment Understory Sampling (Control and Thin Treatments)
2. 2007 Post-treatment Understory Sampling (Gap Treatments)
3. 2007 Post-treatment Bryophyte Sampling (Control and Thin Treatments)
4. 2007 Post-treatment Bryophyte Sampling (Gap Treatments)

Cedar River Watershed – 2005 Pre-treatment Tree Location, Diameter, and Condition

Personnel ___________________________________ **Date:** 2005 (mm) ____ (dd) ___

Site ______ Pine, Pine-N, or Bear (500/600-Rd) **Transect #** _____ Upslope / Downslope (circle 1)

Distance along transect (m)	Distance from transect (m)	Azimuth (°)	Species	Diameter (cm)	A/D (alive/ dead)
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Distance along transect (m)	Distance from transect (m)	Azimuth (°)	Species	Diameter (cm)	A/D (alive/ dead)
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Cedar River Watershed – 2006 Pre-treatment Understory Sampling — CONTROL and THIN Treatments Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2006 (mm) ___ (dd) ___ **Personnel** ______________________________

Treatment (C or T) ___ **Row** (1-3) ___ **Column** (1-10) ___ **Up- or Down-slope** (U or D)___ **X meters** (10, 20, or 30) ___

Quadrat starting meter mark (m): even #s only (**0** = 0-1 m, **2** = 2-3 m) ___ Check if comment made on back of form (record quadrat #)

Ground surface types: sums to 100%; **Bryophytes** (max. 100%); **Cover precision**: 0-2% (by 0.1%), 2-15% (by 1%), 15-100% (by 5%)

Cover of Ground Surface Types and Bryophytes

Quadrat starting meter mark (m)		0	2	4	6	8	10	12	14	16	18
Bare ground	BARE	.	.	.	.	.	.	.	.	.	.
Fresh CWD (I-II)	FRESH	.	.	.	.	.	.	.	.	.	.
Decayed CWD (III-V)	DECAY	.	.	.	.	.	.	.	.	.	.
Fine Litter (<10 cm)	LITTER	.	.	.	.	.	.	.	.	.	.
Tree base (live/dead)	TBASE	.	.	.	.	.	.	.	.	.	.
Stump	STUMP	.	.	.	.	.	.	.	.	.	.
Bryophyte total	BRYOP	.	.	.	.	.	.	.	.	.	.

Tally of Understory Trees by Height Class (**0** = 1-2 yr; **1** = 3+ yr and ≤10 cm; **2** = 11-25 cm; **3** = 26-50 cm; **4** = 51-140 cm)

#	Species full name	Code	Ht	0	2	4	6	8	10	12	14	16	18
1													
2													
3													
4													
5													
6													

Cover of Vascular Plants (%) Quadrat cont. ____

#	Species full name	Code	0	2	4	6	8	10	12	14	16	18
1			.	.	.	.	.	.	.	.	.	.
2			.	.	.	.	.	.	.	.	.	.
3			.	.	.	.	.	.	.	.	.	.
4			.	.	.	.	.	.	.	.	.	.
5			.	.	.	.	.	.	.	.	.	.
6			.	.	.	.	.	.	.	.	.	.
7			.	.	.	.	.	.	.	.	.	.
8			.	.	.	.	.	.	.	.	.	.
9			.	.	.	.	.	.	.	.	.	.
10			.	.	.	.	.	.	.	.	.	.
11			.	.	.	.	.	.	.	.	.	.
12			.	.	.	.	.	.	.	.	.	.
13			.	.	.	.	.	.	.	.	.	.
14			.	.	.	.	.	.	.	.	.	.
15			.	.	.	.	.	.	.	.	.	.
16			.	.	.	.	.	.	.	.	.	.

Cedar River Watershed – 2006 Pre-treatment Understory Sampling — GAP Treatments Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2006 (mm) ___ (dd) ___ **Personnel**_______________________________
Treatment _G_ **Row** (1-3) ___ **Column** (1-10) ___ **Transect** (NE, SW, NW, SE) ___

Quadrat starting meter mark (m): even #s only (**0** = 0-1 m, **2** = 2-3 m). ***Don't sample "SE0"**. ___ Check if comment made on back of form (record quadrat #)

Ground surface types: sums to 100%; **Bryophytes** (max. 100%); **Cover precision**: 0-2% (by 0.1%), 2-15% (by 1%), 15-100% (by 5%)

Cover of Ground Surface Types and Bryophytes											
Quadrat starting meter mark (m)		*0	2	4	6	8	10	12	14	16	18
Bare ground	BARE	.	.	.	.	.	.	.	.	.	`
Fresh CWD (I-II)	FRESH	.	.	.	.	.	.	.	.	.	.
Decayed CWD (III-V)	DECAY	.	.	.	.	.	.	.	.	.	.
Fine Litter (<10 cm)	LITTER	.	.	.	.	.	.	.	.	.	.
Tree base (live/dead)	TBASE	.	.	.	.	.	.	.	.	.	.
Stump	STUMP	.	.	.	.	.	.	.	.	.	.
Bryophyte total	BRYOP	.	.	.	.	.	.	.	.	.	.

Tally of Understory Trees by Height Class (**0** = 1-2 yr; **1** = 3+ yr and ≤10 cm; **2** = 11-25 cm; **3** = 26-50 cm; **4** = 51-140 cm)													
#	Species full name	Code	Ht	0	2	4	6	8	10	12	14	16	18
1													
2													
3													
4													
5													
6													

Cover of Vascular Plants (%) Quadrat cont. ____												
#	Species full name	Code	0	2	4	6	8	10	12	14	16	18
1			.	.	.	.	.	.	.	.	.	.
2			.	.	.	.	.	.	.	.	.	.
3			.	.	.	.	.	.	.	.	.	.
4			.	.	.	.	.	.	.	.	.	.
5			.	.	.	.	.	.	.	.	.	.
6			.	.	.	.	.	.	.	.	.	.
7			.	.	.	.	.	.	.	.	.	.
8			.	.	.	.	.	.	.	.	.	.
9			.	.	.	.	.	.	.	.	.	.
10			.	.	.	.	.	.	.	.	.	.
11			.	.	.	.	.	.	.	.	.	.
12			.	.	.	.	.	.	.	.	.	.
13			.	.	.	.	.	.	.	.	.	.
14			.	.	.	.	.	.	.	.	.	.
15			.	.	.	.	.	.	.	.	.	.
16			.	.	.	.	.	.	.	.	.	.

Cedar River Watershed – 2006 Pre-treatment Understory Sampling — ±CWD Experiment at Bear Page ___ of ___

Site __Bear__ **Date:** 2006 (mm) ___ (dd) ___ **Personnel** ____ Cont. _____

CWD (Y or N) ___ **Column** (1-10) ___ **Transect** (1-3) ___

Quadrat starting meter mark (m): even #s only (e.g., **4** = 4-5 m; **4** through **36**, only) ___ Check if comment made on back of form (record quadrat #)
Ground surface types: sums to 100%; **Bryophytes** (max. 100%); **Cover precision**: 0-2% (by 0.1%), 2-15% (by 1%), 15-100% (by 5%)

Cover of Ground Surface Types and Bryophytes											
Quadrat starting meter mark (m)		___	___	___	___	___	___	___	___	___	___
Bare ground	BARE	.	.	.	.	.	.	.	.	.	.
Fresh CWD (I-II)	FRESH	.	.	.	.	.	.	.	.	.	.
Decayed CWD (III-V)	DECAY	.	.	.	.	.	.	.	.	.	.
Fine Litter (<10 cm)	LITTER	.	.	.	.	.	.	.	.	.	.
Tree base (live/dead)	TBASE	.	.	.	.	.	.	.	.	.	.
Stump	STUMP	.	.	.	.	.	.	.	.	.	.
Bryophyte total	BRYOP	.	.	.	.	.	.	.	.	.	.

Tally of Understory Trees by Height Class (**0** = 1-2 yr; **1** = 3+ yr and ≤10 cm; **2** = 11-25 cm; **3** = 26-50 cm; **4** = 51-140 cm)													
#	Species full name	Code	Ht	___	___	___	___	___	___	___	___	___	___
1													
2													
3													
4													
5													

Cover of Vascular Plants (%)										Quadrat cont. ____		
#	Species full name	Code	___	___	___	___	___	___	___	___	___	___
1			.	.	.	.	.	.	.	.	.	.
2			.	.	.	.	.	.	.	.	.	.
3			.	.	.	.	.	.	.	.	.	.
4			.	.	.	.	.	.	.	.	.	.
5			.	.	.	.	.	.	.	.	.	.
6			.	.	.	.	.	.	.	.	.	.
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12			.	.	.	.	.	.	.	.	.	.
13			.	.	.	.	.	.	.	.	.	.
14			.	.	.	.	.	.	.	.	.	.
15			.	.	.	.	.	.	.	.	.	.
16			.	.	.	.	.	.	.	.	.	.

Cedar River Watershed – 2006 Pre-treatment Tree Diameters — ±CWD Experiment at Bear Page ___ of ___

CWD (Y or N) ___ **Column** (1-8) ___ **Personnel** ____

Live trees only **Date:** 2006 (mm) ___ (dd) ___

Species	DBH (cm)	Species	DBH (cm)	Species	DBH (cm)	Species	DBH (cm)	Species	DBH (cm)	Species	DBH (cm)
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Cedar River Watershed – 2006 Pre-treatment Bryophyte Sampling — Control and Thin Treatments

Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2006 (mm) ___ (dd) ___ **Personnel** ________________________________

Treatment (C or T) ___ **Row** (1-3) ___ **Column** (1-10) ___

Sample # (consecutive #s in each EU)		___		___		___		___		___		___	
Sample type - CWD decay class (3-5) Upslope or downslope X distance (nearest m) Y distance (nearest m)		**Floor** U/D ____ X _____ Y _____	**CWD** ___ U/D ____ X _____ Y _____	**Floor** U/D ____ X _____ Y _____	**CWD** ___ U/D ____ X _____ Y _____	**Floor** U/D ____ X _____ Y _____	**CWD** ___ U/D ____ X _____ Y _____	**Floor** U/D ____ X _____ Y _____	**CWD** ___ U/D ____ X _____ Y _____	**Floor** U/D ____ X _____ Y _____	**CWD** ___ U/D ____ X _____ Y _____	**Floor** U/D ____ X _____ Y _____	**CWD** ___ U/D ____ X _____ Y _____
		Moss, Liverwort, and Herb + Shrub Cover (%)											
Total moss cover (%)	MOSS	.	.	.	.	.	.	.	.	.	.	.	.
Total liverwort cover (%)	LIVER	.	.	.	.	.	.	.	.	.	.	.	.
Total herb + shrub cover (%)	VASCUL	.	.	.	.	.	.	.	.	.	.	.	.

#	Species full name	Code	Ht	**Tally of Tree Seedlings by Height Class** (**0 =** 1-2 yr; **1** = 3+ yr and ≤10 cm)											
1															
2															
3															
4															
5															

Sample # (consecutive #s in each EU)			___		___		___		___		___		___	
#	Species full name	Code	**Individual Bryophyte Species** (**1** = present, **blank** = absent) Sample cont. ____											
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														

Version: 12 May 2006

Cedar River Watershed – 2006 Pre-treatment Bryophyte Sampling — Gap Treatments Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2006 (mm) ___ (dd) ___ **Personnel** ____________________________

Treatment _ G _ **Row** (1-3) ___ **Column** (1-10) ___

Sample # (consecutive #s in each EU)		___		___		___		___		___		___	
Sample type - CWD decay class (3-5) Gap or Forest Distance (nearest m) Azimuth **to** gap center (deg)		**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____
		Moss, Liverwort, and Herb + Shrub Cover (%)											
Total moss cover (%)	MOSS	.	.	.	.	.	.	.	.	.	.	.	.
Total liverwort cover (%)	LIVER	.	.	.	.	.	.	.	.	.	.	.	.
Total herb + shrub cover (%)	PLANT	.	.	.	.	.	.	.	.	.	.	.	.

#	Species full name	Code	Ht	**Tally of Tree Seedlings by Height Class** (**0 =** 1-2 yr; **1** = 3+ yr and ≤10 cm)											
1															
2															
3															
4															
5															

Sample # (consecutive #s in each EU)			___		___		___		___		___		___	
#	Species full name	Code	**Individual Bryophyte Species** (**1** = present, **blank** = absent) Sample cont. ____											
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														
11														

Version: 2 June 2007

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Site _____ (Bear, Pine, or PineN) **Date:** 2007 (mm) ___ (dd) ___ **Personnel** ______________________________

Treatment (C or T) ___ **Row** (1-3) ___ **Column** (1-10) ___ **Up- or Down-slope** (U or D)___ **X meters** (10, 20, or 30) ___

Quadrat starting meter mark (m): even #s only (**0** = 0-1 m, **2** = 2-3 m, etc). ___ Check if comment on back of form (record quadrat #)

Ground surface types sum to 100%. **Fresh and Decayed CWD** are ≥10 cm diam. **Slash** (0-100%) = logging slash (foliage/branches) <10 cm diam.

Bryophytes: 0- 100%. **Cover precision**: 0-2% (by 0.1%), 2-15% (by 1%), 15-100% (by 5%)

Cover of Ground-surface Types, Slash, and Bryophytes

Quadrat starting meter mark (m)		0	2	4	6	8	10	12	14	16	18
Bare ground	BARE	.	.	.	.	.	.	.	.	.	.
Fresh CWD (I-II)	FRESH	.	.	.	.	.	.	.	.	.	.
Decayed CWD (III-V)	DECAY	.	.	.	.	.	.	.	.	.	.
Fine litter (<10 cm)	LITTER	.	.	.	.	.	.	.	.	.	.
Tree base (live/dead)	TBASE	.	.	.	.	.	.	.	.	.	.
Stump	STUMP	.	.	.	.	.	.	.	.	.	.
Slash (<10 cm)	SLASH	.	.	.	.	.	.	.	.	.	.
Bryophyte total	BRYOP	.	.	.	.	.	.	.	.	.	.

Tally of Understory Trees by Height Class (Ht: 0 = 1-2 yr; **1** = 3+ yr and ≤10 cm; **2** = 11-25 cm; **3** = 26-50 cm; **4** = 51-140 cm)

#	Species full name	Code	Ht	0	2	4	6	8	10	12	14	16	18
1													
2													
3													
4													

Cover of Vascular Plants (%) Quadrat cont. ____

#	Species full name	Code	0	2	4	6	8	10	12	14	16	18
1			.	.	.	.	.	.	.	.	.	.
2			.	.	.	.	.	.	.	.	.	.
3			.	.	.	.	.	.	.	.	.	.
4			.	.	.	.	.	.	.	.	.	.
5			.	.	.	.	.	.	.	.	.	.
6			.	.	.	.	.	.	.	.	.	.
7			.	.	.	.	.	.	.	.	.	.
8			.	.	.	.	.	.	.	.	.	.
9			.	.	.	.	.	.	.	.	.	.
10			.	.	.	.	.	.	.	.	.	.
11			.	.	.	.	.	.	.	.	.	.
12			.	.	.	.	.	.	.	.	.	.
13			.	.	.	.	.	.	.	.	.	.
14			.	.	.	.	.	.	.	.	.	.
15			.	.	.	.	.	.	.	.	.	.

Cedar River Watershed – 2007 Post-treatment Understory Sampling — GAP Treatments Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2007 (mm) ___ (dd) ___ **Personnel**_______________________________

Treatment _G_ **Row** (1-3) ___ **Column** (1-10) ___ **Transect** (NE, SW, NW, SE) ___

Quadrat starting meter mark (m): even #s only (**0** = 0-1 m, **2** = 2-3 m, etc). *Don't sample "**SE0**". ___ Check if comment on back of form (record quadrat #)

Ground surface types sum to 100%. **Fresh and Decayed CWD** are ≥10 cm diam. **Slash** (0-100%) = logging slash (foliage/branches) <10 cm diam.

Bryophytes: 0- 100%. **Cover precision**: 0-2% (by 0.1%), 2-15% (by 1%), 15-100% (by 5%)

Cover of Ground-surface Types, Slash, and Bryophytes											
Quadrat starting meter mark (m)		*0	2	4	6	8	10	12	14	16	18
Bare ground	BARE	.	.	.	.	.	.	.	.	.	.
Fresh CWD (I-II)	FRESH	.	.	.	.	.	.	.	.	.	.
Decayed CWD (III-V)	DECAY	.	.	.	.	.	.	.	.	.	.
Fine litter (<10 cm)	LITTER	.	.	.	.	.	.	.	.	.	.
Tree base (live/dead)	TBASE	.	.	.	.	.	.	.	.	.	.
Stump	STUMP	.	.	.	.	.	.	.	.	.	.
Slash (<10 cm)	SLASH	.	.	.	.	.	.	.	.	.	.
Bryophyte total	BRYOP	.	.	.	.	.	.	.	.	.	.

Tally of Understory Trees by Height Class (**Ht: 0** = 1-2 yr; **1** = 3+ yr and ≤10 cm; **2** = 11-25 cm; **3** = 26-50 cm; **4** = 51-140 cm)													
#	Species full name	Code	Ht	*0	2	4	6	8	10	12	14	16	18
1													
2													
3													
4													

Cover of Vascular Plants (%) Quadrat cont. ____												
#	Species full name	Code	*0	2	4	6	8	10	12	14	16	18
1			.	.	.	.	.	.	.	.	.	.
2			.	.	.	.	.	.	.	.	.	.
3			.	.	.	.	.	.	.	.	.	.
4			.	.	.	.	.	.	.	.	.	.
5			.	.	.	.	.	.	.	.	.	.
6			.	.	.	.	.	.	.	.	.	.
7			.	.	.	.	.	.	.	.	.	.
8			.	.	.	.	.	.	.	.	.	.
9			.	.	.	.	.	.	.	.	.	.
10			.	.	.	.	.	.	.	.	.	.
11			.	.	.	.	.	.	.	.	.	.
12			.	.	.	.	.	.	.	.	.	.
13			.	.	.	.	.	.	.	.	.	.
14			.	.	.	.	.	.	.	.	.	.
15			.	.	.	.	.	.	.	.	.	.

Cedar River Watershed – 2007 Post-treatment Bryophyte Sampling — Control and Thin Treatments Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2007 (mm) ___ (dd) ___ **Personnel** ______________________________

Treatment (C or T) ___ **Row** (1-3) ___ **Column** (1-10) ___ Enter **X** & **Y** only if sample plot is missing and has to be reestablished

Sample # (consecutive #s in each EU)		___		___		___		___		___		___	
Sample type - CWD decay class (3-5) Upslope or downslope X distance (nearest m) Y distance (nearest m)		**Floor** U/D ___ X ____ Y ____	**CWD___** U/D ___ X ____ Y _____	**Floor** U/D ___ X ____ Y ____	**CWD___** U/D ___ X ____ Y _____	**Floor** U/D ___ X ____ Y ____	**CWD___** U/D ___ X ____ Y _____	**Floor** U/D ___ X ____ Y ____	**CWD___** U/D ___ X ____ Y _____	**Floor** U/D ___ X ____ Y ____	**CWD___** U/D ___ X ____ Y _____	**Floor** U/D ___ X ____ Y ____	**CWD___** U/D ___ X ____ Y _____
		Disturbance and Slash (%)											
Bare ground (disturbance)	BARE	.	.	.	.	.	.	.	.	.	.	.	.
Fresh CWD (new, ≥10 cm)	FRESH	.	.	.	.	.	.	.	.	.	.	.	.
Slash (<10 cm)	SLASH	.	.	.	.	.	.	.	.	.	.	.	.
% missing log (**CWD only**)	%MISS	.	.	.	.	.	.	.	.	.	.	.	.
		Moss, Liverwort, and Herb + Shrub Cover (%)											
Total moss cover (%)	MOSS	.	.	.	.	.	.	.	.	.	.	.	.
Total liverwort cover (%)	LIVER	.	.	.	.	.	.	.	.	.	.	.	.
Total herb + shrub cover (%)	VASCUL	.	.	.	.	.	.	.	.	.	.	.	.

#	Species full name	Code	Ht	**Tally of Tree Seedlings by Height Class** (**Ht: 0 =** 1-2 yr; **1** = 3+ yr and ≤10 cm)											
1															
2															
3															

Sample # (consecutive #s in each EU)			___		___		___		___		___		___	
#	Species full name	Code	**Individual Bryophyte Species** (**1** = present, **blank** = absent) Sample cont. ____											
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														

Cedar River Watershed – 2007 Post-treatment Bryophyte Sampling — Gap Treatments Page ___ of ___

Site _____ (Bear, Pine, or PineN) **Date:** 2007 (mm) ___ (dd) ___ **Personnel** ______________________________

Treatment _ G_ **Row** (1-3) ___ **Column** (1-10) ___ Enter **X** & **Y** only if sample plot is missing and has to be reestablished

# (consecutive #s in each EU)		___		___		___		___		___		___	
Sample type - CWD decay class (3-5) Gap or Forest Distance (nearest m) Azimuth **to** gap center (deg)		**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____	**Floor** G/F ____ Dist ____ Deg ____	**CWD** ___ G/F____ Dist ____ Deg ____
		Disturbance and Slash (%)											
Bare ground (disturbance)	BARE	.	.	.	.	.	.	.	.	.	.	.	.
CWD (new, ≥10 cm)	FRESH	.	.	.	.	.	.	.	.	.	.	.	
Slash (<10 cm)	SLASH	.	.	.	.	.	.	.	.	.	.	.	.
% missing log (**CWD only**)	%MISS	.	.	.	.	.	.	.	.	.	.	.	.
		Moss, Liverwort, and Herb + Shrub Cover (%)											
Total moss cover (%)	MOSS	.	.	.	.	.	.	.	.	.	.	.	.
liverwort cover (%)	LIVER	.	.	.	.	.	.	.	.	.	.	.	
Total herb + shrub cover (%)	VASCUL	.	.	.	.	.	.	.	.	.	.	.	.

#	Species full name	Code	Ht	**Tally of Tree Seedlings by Height Class** (**Ht: 0 =** 1-2 yr; **1** = 3+ yr and ≤10 cm)											
1															
2															
3															

# (consecutive #s in each EU)			___		___		___		___		___		___	
#	Species full name	Code	**Individual Bryophyte Species** (**1** = present, **blank** = absent) Sample cont. ____											
1														
2														
3														
4														
5														
6														
7														
8														
9														
10														

4.4. Written Products: Manuscripts Published and in Review

4.4.1. Spatially explicit modeling of overstory manipulations in young forests: effects on stand structure and light. Sprugel, D. G., K. A. Grieve, R. Gersonde, M. Dovčiak, J. A. Lutz, and C. B. Halpern. *In review* in Ecological Modelling.

Spatially explicit modeling of overstory manipulations in young forests: effects on stand structure and light

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Abstract: Young forests can be manipulated in diverse ways to enhance their ecological values. We used stem maps from dense, second-growth stands in western Washington and a spatially explicit light model to simulate effects of different silvicultural manipulations on stand structure and light availability. All treatments removed 30% of basal area, but differed in how trees were selected. Thin from below (removing the smallest trees) greatly reduced the range of tree sizes, decreased abundance of shade-tolerant species, increased regularity of tree spacing, and more than doubled forest floor light availability. Random thin (removing trees randomly) and random ecological thin (retaining the largest trees but randomly removing smaller ones) had little effect on forest structure, but increased light to levels similar to those in thin from below. Gap creation greatly increased spatial heterogeneity and the mean and range of light values. Structured ecological thin (retaining the largest trees and removing smaller trees in clumps) created a more heterogeneous spatial pattern and increased the mean and range of light values more than thin from below, but less than gap creation. Stem maps, simulated thinning, and a light model provide useful planning tools for predicting initial effects of silvicultural manipulations on forest structure and resource availability.

Key words: forest gaps, forest restoration, forest thinning, light model, spatial analysis, stand structure, tRAYci.

Introduction

Silvicultural thinning has long been used in young, managed forests to improve timber production and quality. Increasingly, however, forest managers are using thinning and other silvicultural manipulations to enhance the ecological values of managed forests, and in particular to accelerate the development of characteristics associated with late-successional forests (Thysell and Carey 2001; Davis et al. 2007; Fahey and Puettmann 2007). These characteristics include large trees, snags, and coarse woody debris; high foliage-height diversity; horizontal heterogeneity (e.g., canopy gaps and tree clumps); and high abundance and diversity of shade-tolerant plant species (Halpern and Spies 1995; Franklin et al. 2002; Franklin and Van Pelt 2004). Numerous processes, including self-thinning, differential growth and reproduction, and gap-forming disturbance contribute to the development of these characteristics in old natural stands (Spies and Franklin 1991; Franklin et al. 2002; Lutz and Halpern 2006; Hanson and Lorimer 2007). Thus, it can be challenging to design manipulations that achieve similar outcomes in young managed stands.

The metrics commonly used to prescribe silvicultural manipulations may not be appropriate when the goals of thinning are primarily ecological. Thinning targets are traditionally framed with respect to stand density or site occupancy, i.e., trees per acre, basal area, or stand density index (Reinecke 1933). However, when management goals are primarily ecological, changes to the structural and functional attributes of forests may be of greater interest (e.g., Larson and Churchill, *in press*). These attributes include vertical stratification of the canopy, heterogeneity of tree species and sizes, spatial patterns, habitat diversity, and richness of the understory (O'Hara 2001). Clearly it is more difficult to prescribe a treatment that will elicit a specific ecological response than to prescribe a specific change in basal area, if only because the desired changes in structure and function may require several to many years to develop. However, it is possible to predict the immediate effect of silvicultural manipulations on metrics that characterize spatial structure and resource availability, and these in turn can serve as reasonable surrogates for longer term changes in forest structure and function. We focus on four such metrics in the current paper:

1. *Size structure*. Size structure provides an index of canopy complexity and habitat diversity for birds and other canopy-dwelling organisms (e.g., Brokaw and Lent 1999). Direct measures of canopy complexity such as foliage height diversity (MacArthur and MacArthur 1961) would be ideal, but are difficult to measure. However, tree height and vertical foliage distribution are correlated with tree diameter (Curtis 1967; Ritchie and Hann 1987; Maguire et al. 2007; but see Garber and Maguire 2005), thus a treatment that leaves a greater range of tree diameters is also likely to yield greater vertical complexity.

2. *Species composition.* Tree species can differ in their effects on soil chemistry and nutrient cycling (Kiilsgaard et al. 1987; Reich et al. 2005) and on habitat quality or food resources. As a consequence, tree species may support different communities of vertebrates (Holmes and Robinson 1981; Gabbe et al. 2002) or invertebrates (Wiezik et al. 2007). Thus, a greater diversity of tree species can be expected to promote greater diversity of other organisms.

3. *Spatial pattern*. The spatial distributions of trees (i.e., clumpiness vs. regularity) can be indicative of habitat diversity and of the rates at which canopies will close after treatment. Spatial patterning can also influence rates of growth and regeneration as tree spacing influences competition for light and soil resources (Peterson and Squiers 1995a; Canham et al. 2004). Consequently, spatial patterning can have direct effects on future stand dynamics (Peterson and Squiers 1995b; Dovčiak et al. 2001) and understory development (McKenzie et al. 2000).

4. *Light distribution.* In dense forests where light is limiting and understories are poorly developed, the distribution of light after thinning or gap creation may shape the future distribution and performance of understory plants and regenerating trees (Kobe et al. 1995; Gray and Spies 1997; Reich et al. 1998; Coates et al. 2003, Fahey and Puettmann 2007). One plausible mechanism for the greater diversity of species in old-growth forests is the greater heterogeneity, or patchiness, of resources, including light (Halpern and Spies 1995). Thus, treatments that increase not only the amount, but the range, of light at the forest floor should lead to greater diversity of understory species and to greater variation in plant performance (e.g., height growth, morphology, or flowering).

In this paper, we use stem maps of dense coniferous forests in western Washington and a spatially explicit light attenuation model, tRAYci (Brunner 2004), to predict the effects of different approaches to thinning and gap creation on forest structure and composition, spatial patterning, and light distribution. We apply a wide range of silvicultural manipulations, from traditional silvicultural approaches that emphasize increased tree size and volume growth to more novel approaches that enhance species, structural, and habitat diversity. Our analyses are limited to the immediate effects of treatments, although we recognize that stand structure and associated ecological functions will change over time. Nevertheless, initial differences in spatial structure and resource availability should be indicative of longer term differences in forest development and biological response (e.g., Coates et al. 2003), and may aid managers in developing treatment plans aimed at specific ecological goals.

Methods

Study area

Stand maps were constructed for two second-growth sites (Bear and Pine) in the Cedar River Municipal Watershed, approximately 50 km southeast of Seattle, Washington. Both are ~65 yr old stands dominated by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco *var. menziesii*) (nomenclature follows Hitchcock and Cronquist 1973). Bear (47° 19'N, 121° 33'W) lies at ~610 m elevation on a gentle (0-10°) slope that faces southwest. Pine (47° 21'N, 121° 38'W) lies at ~740 m elevation on a somewhat steeper (0-30°) slope that faces west-southwest. Both sites are in the *Tsuga heterophylla* zone (Franklin and Dyrness 1988). Climate is maritime, with cool wet winters and warm, dry summers. Mean annual temperature is ~8.6° C, and annual precipitation averages 260 cm, of which 70% falls between October and March (climate-station data from Cedar Lake, WA, elevation 475 m; 1931-2006; http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wa1233).

Stem maps

At each site, a 1.2 ha (60 x 200 m) study plot was established using a combination of a Nikon Total Station (model DTM-420; Nikon Corporation, Tokyo, Japan), distance tapes, and a Haglöf Vertex III hypsometer (Haglöf Sweden AB, Långsele, Sweden). A reference transect was surveyed with the Nikon Total Station, then two more transects were established parallel to the first, one 20 m up-slope and one 20 m down-slope. For all trees within 10 m of each transect, we recorded species, diameter at breast height (dbh), distance along the transect to a point perpendicular to the tree, and perpendicular distance from the transect to the tree. Distance data were used to calculate x-y locations for all trees, referenced to the lower left corner of the mapped area (Fig. 1a). The mapped area for these simulations included 1788 live trees at Bear and 2001 at Pine.

At each site, ~20 individuals (5-8 trees per primary species) were selected for measurement of height and crown characteristics. Individuals were stratified by crown class (dominant, co-dominant, intermediate, and overtopped). Each was measured for height, height to live crown (lowest node with three live branches), and two crown radii (south and north). Heights were determined with a Haglöf Laser Vertex Hypsometer, and crown radii were measured to the nearest 15 cm using a clinometer to determine the vertical projection of the crown edge.

Treatments

Five types of simulated treatments were applied to the mapped plot at each site. The first three represent different but basic approaches to stand manipulation, while the remaining two represent combinations of these approaches. Our primary goal was to quantify responses to the spatial and structural distribution of thinning; thus, we held the level of basal area removal constant at 30% (a level of removal comparable to current practices in the region), and removed trees without regard to species. Treatments were implemented as follows:

1. *Thin from below.* Trees were removed starting with the smallest stems until 30% of the basal area had been removed (Fig. 1b). This approach is commonly used by silviculturists to allocate more growing space to larger individuals, and to remove those most likely to die through competition. Its objective is to accelerate development of a single layer of large, productive trees. Thinning from below may produce a forest structure similar to that resulting from natural self-thinning, but much more rapidly, as greater resources are released by the synchronous removal of smaller stems.

2. *Random thin*. Trees were randomly removed without regard to size or location until 30% of the basal area was removed (Fig. 1c). This treatment is akin to proportional thinning, where trees are removed in proportion to their frequencies within size classes, without changing the size distribution. As such, this represents the most "neutral" treatment, and serves as a baseline against which other treatments can be compared.

3. *Gap creation.* All trees were removed from 27.5 m diameter gaps (~1 tree height) arranged in a regular hexagonal pattern throughout the stand (Fig. 1d). This gap size was chosen so that an integral number of gaps would remove 30% of the basal area. Gaps are commonly created in young, managed stands to increase spatial heterogeneity and habitat diversity; similar gaps can occur naturally as a result of wind, snow-loading, or other forms of mechanical damage (e.g. Lutz and Halpern 2006).

4. *Random ecological thin*. Random ecological thin is a combination of random thinning (which removes trees irrespective of size) and thinning from below (which removes all trees below a specified diameter and none above it). The largest trees (40% of the basal area or ~15% of the stems) were reserved, and smaller trees were removed randomly until 30% of the total basal area was removed (Fig. 1e). This approach preserves the largest trees, but retains some variety of tree diameters and heights to maintain structural diversity.

5. *Structured ecological thin.* Structured ecological thin represents a combination of thinning from below and gap creation. As in the random ecological thin, the largest trees (40% of the basal area) were reserved. However, smaller trees were removed in circles of 6 m radius rather than randomly (Fig. 1f). The centers of circles were located randomly, with the stipulation that they lie outside a previous removal circle; additional circles were added until 30% of the basal area was removed. Thus, tree removal was concentrated among smaller stems (as in thin from below), but some spatial heterogeneity was created, as in gap creation.

Prior to each thinning simulation (but not gap creation), plots were divided in thirds (67 x 60 m) and each third was treated separately to reduce the effect of spatial variation in tree size distribution within the larger plot. There is a substantial stochastic component in the structured ecological thin because of the random placement of a limited number of removal circles; thus, five replicates of this treatment were run and mean statistics are reported. For the spatially explicit tree stem and light maps, we illustrate the first of the five runs.

Size structure and species composition

Five measures of forest structure and composition were computed before and after each treatment: stem density and basal area (by species); and the mean, coefficient of variation (CV), and skewness of tree diameters (dbh).

Spatial pattern

We characterized the spatial distributions of trees before and after treatment with Morisita's index of dispersion (I_δ), a ratio of the variance to the mean of stem density from plots of increasing size (Morisita 1959). Morisita's index was computed for quadrats of 2 to 3000 m^2. At each spatial scale, the index reflects the degree of spatial regularity of trees: $I_\delta = 0$ indicates a completely uniform spatial pattern; $I_\delta = 1$, complete spatial randomness (CSR); and $I_\delta > 1$, an aggregated or clumped pattern. Confidence intervals for CSR were calculated using a Monte Carlo technique with 1001 replicates of 2000 randomly located points in a 60 x 200 m plot.

The light model

We simulated light distribution on the forest floor before and after each treatment using tRAYci, a spatially-explicit light modeling program that applies a reverse ray-tracing algorithm and Beer's law to calculate light attenuation through the foliated canopy to a series of grid points in a simulated forest stand (Brunner 1998, 2004). To construct the simulated canopy, tRAYci combines a method for describing three-dimensional canopy space developed in the growth and yield model TASS (Mitchell 1975) with a method for describing individual crown shapes (Koop 1989). From each grid point, 1296 rays are traced, each representing a 5° x 5° section of the hemisphere.

Input to the model included species, dbh, and x-y location of each tree, as well as estimated tree height, height to live crown, crown length, and crown radii (derived from the west-side Cascades variant of the Forest Vegetation Simulator, FVS Version 6.21; Donnelly and Johnson 1997; Dixon 2003). Crown-shape parameters were estimated visually in the field for each species. All coniferous species were assigned a leaf area density (LAD) of 2 m^2/m^3 and all broadleaved species a LAD of 0.5 or 1 m^2/m^3 (Table A1; for details see Brunner 2004 and Gersonde et al. 2004). Initial estimates of height and height to live crown were adjusted by a constant percentage (-10% for tree height, +10% for height to live crown) to better approximate relationships with dbh for trees measured at Bear and Pine. Additional inputs to the model included latitude, plot orientation relative to north, and the estimated proportion of diffuse light (set at 50%).

In the simplest implementation of tRAYci tree crowns are circular, leaving many gaps between trees while creating extremely dense canopies where individuals are close together. In fact, forest trees typically have asymmetric crowns because branches grow slowly in areas shaded by other trees and rapidly where light is available (Sprugel et al. 1991). To simulate this asymmetry, we modified the pre-treatment crown radii estimated by FVS depending on distances to nearest neighbors. Polygons were constructed around each tree to delineate an area that was closer to the tree of interest than to any other tree. These Voronoi polygons (or Dirichlet tessellations) were computed with the Lee-Schachter algorithm (Lee and Schachter 1980) in the *deldir* package in R (http://www.r-project.org). For each tree, the distance to the edge of its polygon in each of the cardinal directions was computed. Finally, for each cardinal direction, the maximum of the FVS-estimated radius and the radius computed from the polygon was used as the crown radius. This allowed tRAYci to fill the crown area more realistically with asymmetrically shaped trees

We used tRAYci to simulate percent of above-canopy light (PACL) from April 1 to September 30 at

1 m above the forest floor. For each treatment, PACL was computed at the center of each 1 x 1 m grid cell resulting in a total of 12,000 data points per simulation. To minimize edge effects we embedded each 200 x 60 m modeled stand in the center of a 600 x 180 m plot (i.e., at the center of a 3 x 3 array). For the control and thinned treatments, the larger array was constructed by flipping the mapped and treated plot in each direction over its edge with corner cells in the array flipped across the corners. For the gap treatment, the full array was first constructed from the pre-treatment map; gaps were then created uniformly across the array to ensure uniform spacing between gaps in adjacent cells.

tRAYci has not been validated in the particular forest type simulated here, but it has been validated in other western coniferous forests (Gersonde et al. 2004). Thus, we do not focus on the precise estimates of light produced by the model, but instead on the ways in which treatments affect light distribution (range and frequency of values) and spatial arrangement.

Results

Size structure

Before treatment, total stem density was ~1500 stems/ha at Bear and 1670 at Pine; basal area was 75 m^2/ha at both sites. Mean stem diameter was ~22 cm at both sites (Table 1), but the size distribution of stems was much more positively skewed at Pine (Table 1; Fig. 2).

Treatments produced three types of size structures. Thin from below, which removed all trees smaller than a specific size, sharply increased mean diameter and skewness, and reduced the variation in stem diameters (Table 1; Fig. 3). Density was reduced by ~64% at both sites (Table 1; Figs. 1 and 3). Random ecological thin and structured ecological thin, which preserved the largest 40% of the basal area, then removed smaller trees to achieve a total of 30% basal area reduction, increased mean diameter slightly, but did not change the coefficient of variation and actually decreased skewness (Table 1). Density was reduced by about 42% at both sites. Random thin and gap creation, which removed trees irrespective of size, reduced density by 30% but did not significantly change size distribution (Table 1; Fig. 3).

Species composition

Before treatment, both sites were dominated by western hemlock in most size classes and co-dominated in larger size classes by Douglas-fir (Fig. 2). Western redcedar (*Thuja plicata* Donn.) was also well represented in all size classes at Pine. Other common species included Pacific silver fir (*Abies amabilis* (Dougl.) Forbes) and noble fir (*A. procera* Rehder) at both sites, and at Pine, small numbers of red alder (*Alnus rubra* Bong.), black cottonwood (*Populus trichocarpa* T. & G.), and bitter cherry (*Prunus emarginata* (Dougl.) Walp.) (Table 2, Fig. 2).

Changes in species composition were dictated by the effects of treatments on size structure. Thin from below substantially decreased the importance of hemlock, which was more prevalent among smaller stems, and increased the proportion of Douglas-fir (Table 2). However, it did not affect the representation of redcedar, which was equally distributed among size classes (at Pine). The two ecological thin treatments also increased the importance of Douglas-fir, but to a lesser degree than thin from below. Random thin and gap creation had little effect on species composition.

Spatial pattern

Prior to treatment, stems at Bear were clumped at most spatial scales, but significantly so only in quadrats smaller than 25 m^2. In contrast, stems at Pine were distributed regularly in quadrats smaller than 25 m^2 (Fig. 4). Despite these initial differences, effects of treatments were essentially the same at both sites. Thin from below resulted in a strongly regular pattern at all spatial scales. Random ecological thin also produced a more regular distribution of stems, but less so than thin from below. Random thin had little effect on spatial pattern. Structured ecological thin and gap creation both resulted in a high degree of clumping at all spatial scales.

Light distribution

Prior to treatment, modeled light transmittance (PACL) was consistently very low at both sites (Figs. 5a and 6): mean transmittance was 5-6% at Bear (98% of points <10%) and 7-8% at Pine (~80% of points <10%). Thin from below more than doubled mean PACL at Bear (to ~13%), but the range of values remained relatively narrow, with >80% of points between 8 and 18% (Figs. 5b and 6). Patterns were similar at Pine, with mean PACL more than doubled (to ~18%) and ~75% of points between 13 and 23% (Fig. 6). Patches with higher light were typically 10-15 m wide in a north-south direction, but much longer east to west (Fig. 5b) due to the long days and low morning and afternoon solar angles at 47°N.

Random thin produced a light distribution very similar to that in thin from below (Figs. 5c and 6). Mean light was virtually identical to thin from below at Bear, and ~2% lower at Pine, with similar ranges in both cases (Fig. 6).

Gap creation produced a very broad and nearly bimodal light distribution. Compared with random thin and thin from below, it produced a similar proportion of low-light values (PACL <10%), fewer intermediate-light values (PACL 10-25%), and many more high-light values (PACL >25%). Mean light was also much greater (~20% at Bear, ~22% at Pine; Fig. 6). PACL averaged ~33% inside the gaps, with large areas receiving lower, but still elevated light levels along the margins of gaps, particularly along east and west edges (Fig. 5d). Areas of higher light extended 5-10 m under the canopy along the northern, but not the southern edges of gaps.

Random ecological thin produced light distributions very similar to random thin and thin from below at both sites (Figs. 5e and 6).

The structured ecological thin generally produced a much broader distribution of light values than did any of the other thinning treatments, but not as broad as gap creation (Figs. 5f and 6). Structured ecological thin produced about the same proportion of low-light points as unstructured thins, but fewer intermediate-light points and more high-light points. In addition, high-light patches in the structured ecological thin (Fig. 5f) tended to be wider and more continuous than in unstructured thins (Figs. 5b, c, and e). Because the number of removal circles was relatively small, there was a substantial stochastic element to the structured ecological thin. Although the overall light distribution was similar among the five runs at each site, each run had a unique spatial pattern.

Discussion

Our simulations illustrate how different approaches to thinning, applied alone or in combination, change stand structure and light availability in young forests. Some of these changes, particularly structural responses to more traditional approaches to thinning, were anticipated. However, effects on the amount and distribution of understory light were less intuitive, and thus informative, given the paucity of studies that have similarly modeled changes in light following silvicultural manipulation (Coates et al. 2003). Changes in the amount and spatial distribution of light may provide a stronger mechanistic basis than changes in structure for understanding subsequent patterns of regeneration and growth of understory plants. Before we discuss the results and implications of our models, however, we acknowledge several limitations.

First, our simulations predict only the immediate effects of treatments on stand structure and light. Clearly, these will change over time as trees grow laterally or vertically to fill canopy openings. Nevertheless, treatments that initially create greater and more variable light are likely to yield more rapid and spatially heterogeneous responses in the understory than those that create a more uniform light regime. Likewise, treatments that create larger canopy openings are likely to close more slowly, yielding a more prolonged response. Second, our simulations do not account for factors such as damage to tree boles (Moore et al. 2002), soil disturbance (e.g., Halpern and McKenzie 2001), and changes in microclimate (e.g., Heithecker and Halpern 2006; Weng et al. 2007), although these may also influence initial responses to treatments. Finally, our simulations were applied at a relatively small spatial scale — one appropriate to assessing variation in understory vegetation. In practice, thinning to enhance habitat diversity is often implemented at larger spatial scales to create a mosaic of stand densities (e.g., Carey et al. 1999; Wilson and Puettmann 2007). Under these circumstances, greater variation in structure and light are achieved, but at spatial scales larger than those examined in these simulations.

These caveats notwithstanding, our simulations highlight the similarities, as well as the substantial differences, among approaches in their immediate effects on stand structure and light availability:

Thin from below. Thin from below sharply decreased the diversity of tree sizes, reduced the representation of shade-tolerant subcanopy tree species, and created a more regular spatial structure. These changes were largely predictable because thin from below removed all smaller trees, and in stands undergoing self-thinning, larger trees tend to be distributed regularly (Kenkel 1988; He and Duncan 2000; Harris 2004). The strength of thin from below is that, more than other treatments, it retains the largest trees that are potentially valuable for timber (e.g., Marshall and Curtis 2002) or as eventual old-growth dominants. However, in most ecological applications, reductions in vertical and horizontal complexity and in the importance of late-successional species are significant weaknesses.

Random thin. As expected, random thin had little effect on the diameter distribution, species composition, or spatial pattern of stems; it simply reduced stand density. This may be the greatest strength of this approach: unlike most other approaches to thinning, it does not decrease canopy complexity or spatial heterogeneity because trees are removed from all size classes equally. Surprisingly, however, greater canopy complexity and spatial heterogeneity did not lead to a patchier distribution of light; in fact, random thin produced a light distribution whose mean and variation were very similar to thin from below. Simulations with lower (20%) to significantly greater (60%) basal area removal yielded similar outcomes, suggesting comparable responses to these treatments over a substantial range of thinning intensities. This points to a weakness of random thinning in many applications: because all sizes of trees are removed proportionally, it removes more large trees (potential dominants in older stands) than thin from below, with little difference in post-treatment light availability.

Gap creation. As expected, creation of circular gaps did not change forest size structure or species composition, but did increase spatial heterogeneity, average light levels, and the range of light values at the forest floor. Light availability at the centers of gaps was higher than in all other treatments, occasionally exceeding 40% of above-canopy light. Our simulations are thus consistent with empirical measurements of light in experimental gaps in both young and older forests of this region (e.g., Gray et al. 2002; Fahey 2005). Increases in light of this magnitude are likely to elicit growth releases or flowering of existing plants (e.g., Gray and Spies 1996; Van Pelt and Franklin 1999; Lindh et al. 2003; Fahey and Puettmann 2007), which may also extend into adjacent forest (Gray and Spies 1996; Gray et al. 2002; Kayler et al. 2005; Fahey and Puettmann 2007). However, they may also lead to less desirable outcomes, stimulating germination of early seral (and potentially exotic) species from the seed bank (e.g., Halpern et al. 1999; Fahey 2005; Fahey and Puettmann 2007).

In addition to the significant increase in light and its spatial variation, circular gaps should close more slowly than irregularly shaped openings of smaller or equivalent area (e.g., those created by structured ecological thin). As a result, biological responses to gap creation — at least where resources are sufficiently elevated — are likely to be more persistent. On the other hand, gap creation can have disadvantages for forest structure, including the loss of substantial numbers of large, potentially dominant trees from future stands and the potential for additional mortality along new, unstable edges (Harcombe et al. 2004; Lutz and Halpern 2006).

Random ecological thin. Random ecological thin combined elements of random thinning and thinning from below. Not surprisingly, its potential advantages and disadvantages are similar to those inherent in these approaches: it preserved all of the largest trees, but because many small trees were also retained, effects on size structure and species composition were muted, as were changes in spatial pattern. Resulting light distributions were similar to those produced by random thin and thin from below. Given these similarities, the benefits of retaining the largest trees without unduly homogenizing stand structure may outweigh the additional complexity of implementing this treatment.

Structured ecological thin. The structured ecological thin combined elements of thinning from below and gap creation, with gaps formed by removing groups of smaller, subdominant trees. The strength of this approach is that it maintains a diverse size structure and increases spatial heterogeneity, while preserving most large trees. Dominants are also likely to be released from competition with adjacent co-dominants, facilitating future crown development and greater vertical complexity. Structured ecological thin also increased the mean and variation in forest floor light more than all other approaches except for gap creation. A weakness may be that, as with most compromises, it may not achieve any goal as completely as its components: it removes a greater number of large trees than does thinning from below, but does not create openings as large, or edges as distinct, as does gap creation. On the other hand, if disturbance and resource enhancement in canopy gaps yield undesirable effects (e.g., promotion of weedy species), this compromise may be an advantage.

Management implications

Using a forest stand map and a light attenuation model we have illustrated how different approaches to removing the same basal area can have a broad range of effects on ecologically important aspects of the post-harvest environment. We did not attempt to be exhaustive in our choice of treatments, but instead explored treatments that represent a diversity of strategies — from traditional silvicultural approaches that aim to enhance timber production to more novel, ecologically based methods that emphasize variability of tree size and spatial structure. Model results could vary with treatment intensity, initial structure, or species compositions, but the fact that responses to treatments were generally similar at Bear and Pine, despite differences in pre-treatment size distribution, species composition, and spatial patterning, suggests that the basic patterns resulting from our simulations are fairly robust.

Our results suggest that if the primary goal of thinning is to increase long-term growth of the most productive trees, thin from below preserves the greatest proportion of large trees and removes smaller trees that can compete for below-ground resources. However, random and structured ecological thin also preserve the largest trees, and may be equally effective in enhancing growth of dominant trees by removing a larger proportion of co-dominants in close proximity. In contrast, if immediate improvement in understory diversity and wildlife habitat are the primary motivations for thinning, gap creation is the most obvious approach: it creates the widest diversity of light environments and the greatest spatial heterogeneity. Gap creation is also appropriate if the goal is to maximize the length of time over which forest organisms can respond to increases in resources, because larger circular openings are likely to fill more slowly than the smaller openings created by other types of thinning. Finally, if thinning is driven by multiple objectives that include improving wildlife habitat in the short term and accelerating growth of dominant trees in the long term, a structured ecological thin may be most appropriate: it retains the largest trees, but also creates significant variation in understory structure and light by removing subcanopy trees in moderate-sized patches.

Our simulations illustrate that different approaches to thinning can yield very different stand structures and resource distributions in the short term that should extend to distinctly different patterns of forest development in the long term. However, they also illustrate that treatments with contrasting stand structures may exhibit only subtle differences in light distribution. These model outcomes underscore the importance of defining management objectives prior to implementing silviculturally or ecologically based thinning prescriptions. Used in concert, stem maps and a light model provide valuable tools for managers and researchers to explore, before costly implementation, the effects of any number of thinning alternatives on forest structure and understory light. As long-term experiments provide insights into the relationships between changes in forest structure and biological responses, these tools will become increasingly valuable for management.

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Table 1. Basic attributes of stand structure before (untreated) and after the five simulated treatments at Bear and Pine.

	Density (stems/ha)	Basal area (m^2/ha)	Diameter (cm) Mean	CV (%)	Skewness
Bear					
Untreated	1489	73.7	22.5	50	0.22
Thinned from below	531	51.5	34.6	17	0.75
Random thin	1028	51.5	22.7	49	0.19
Gap creation	1061	52.6	22.4	51	0.19
Random ecological thin	864	51.5	24.8	48	0.08
Structured ecological thin (mean)	866	51.4	24.9	49	0.10
Pine					
Untreated	1668	76.0	21.7	48	0.70
Thinned from below	611	53.3	32.4	24	1.32
Random thin	1173	53.2	21.7	48	0.71
Gap creation	1186	53.7	21.6	49	0.69
Random ecological thin	958	53.2	23.9	49	0.55
Structured ecological thin (mean)	938	53.2	24.0	49	0.54

Table 2. Species composition before (untreated) and after the five simulated treatments at Bear and Pine. Minor species are not included (Bear: western redcedar, Pacific silver fir, and noble fir; Pine: Pacific silver fir, noble fir, red alder, black cottonwood, and bitter cherry).

	Density (% of total)						Basal area (% of total)					
	Untreated	Thin from below	Random thin	Gap creation	Random ecol. thin	Structured ecol. thin	Untreated	Thin from below	Random thin	Gap creation	Random ecol. thin	Structured ecol. thin
Bear												
W. hemlock	72	56	71	71	70	70	60	54	62	59	59	58
Douglas-fir	23	40	23	23	25	25	35	41	34	36	36	37
Pine												
W. hemlock	70	57	70	69	65	66	56	47	57	56	49	49
Douglas-fir	11	23	10	11	14	14	22	30	21	23	28	28
W. redcedar	13	12	13	13	15	13	13	13	13	13	14	13

Figure captions

Fig. 1. Stem maps of the Bear plot before and after treatment. Open circles are trees ≥25 cm dbh; smaller filled circles are <25 cm dbh.

Fig. 2. Diameter distributions of the primary species at Bear and Pine prior to treatment. "Other" includes Pacific silver fir, noble fir, black cottonwood, red alder, and bitter cherry.

Fig. 3. Diameter distributions of untreated and treated stands at Bear and Pine. Diameters are means of 5-cm dbh classes.

Fig. 4. Effects of the simulated treatments on Morisita's index. The dotted lines indicate the 95% confidence interval for a spatially random distribution. See section *2.5. Spatial pattern* for details.

Fig. 5. Light distribution maps of Bear before and after treatment. Values are percent of above canopy light (PACL).

Fig. 6. Frequency distribution of light (PACL) at Bear and Pine before and after treatment.

Figure 1

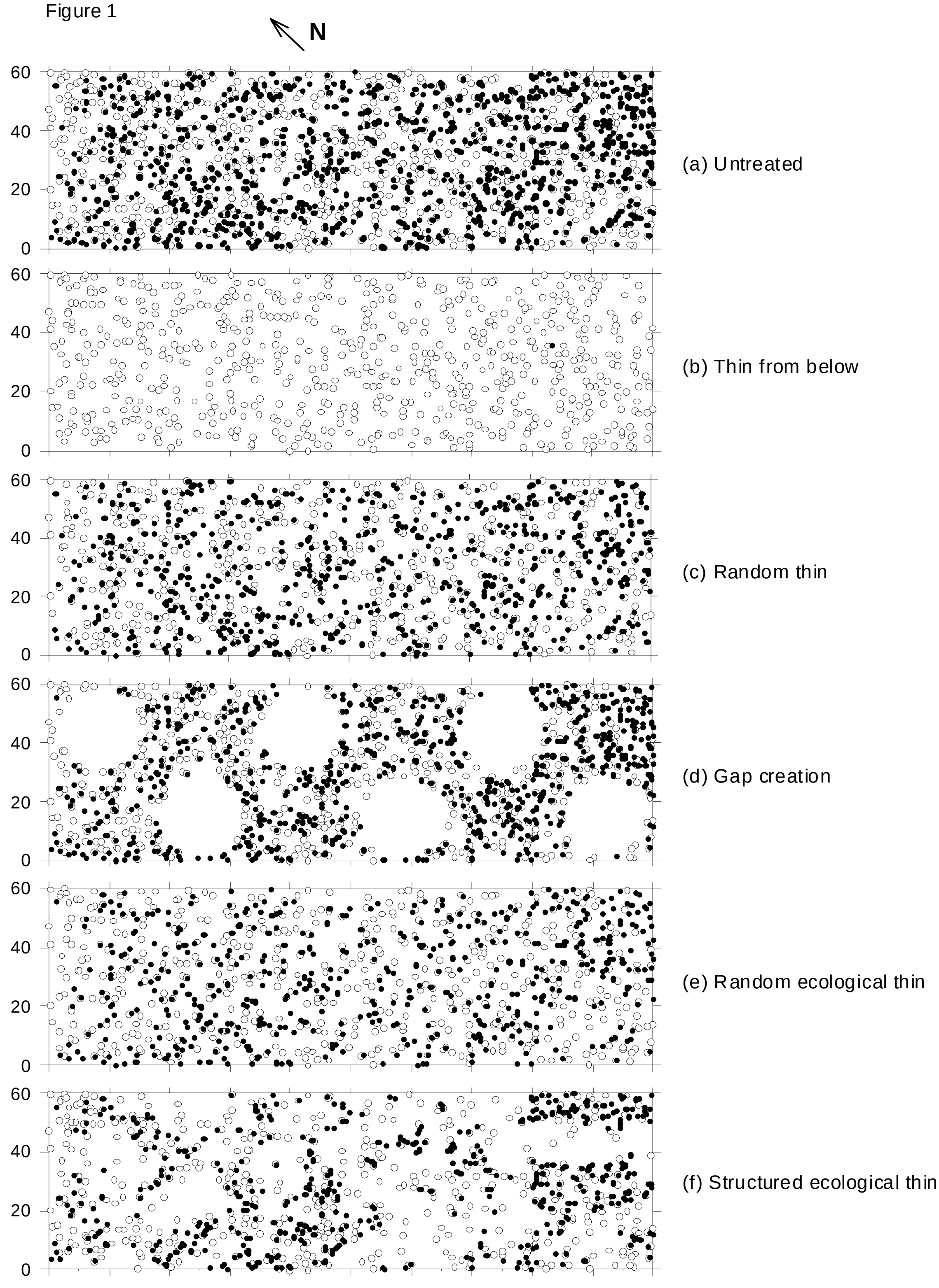

N
60
40
20
0
(a) Untreated
(b) Thin from below
(c) Random thin
(d) Gap creation
(e) Random ecological thin
(f) Structured ecological thin
0
20
40
60
80
100
120
140
160
180
200

Figure 2

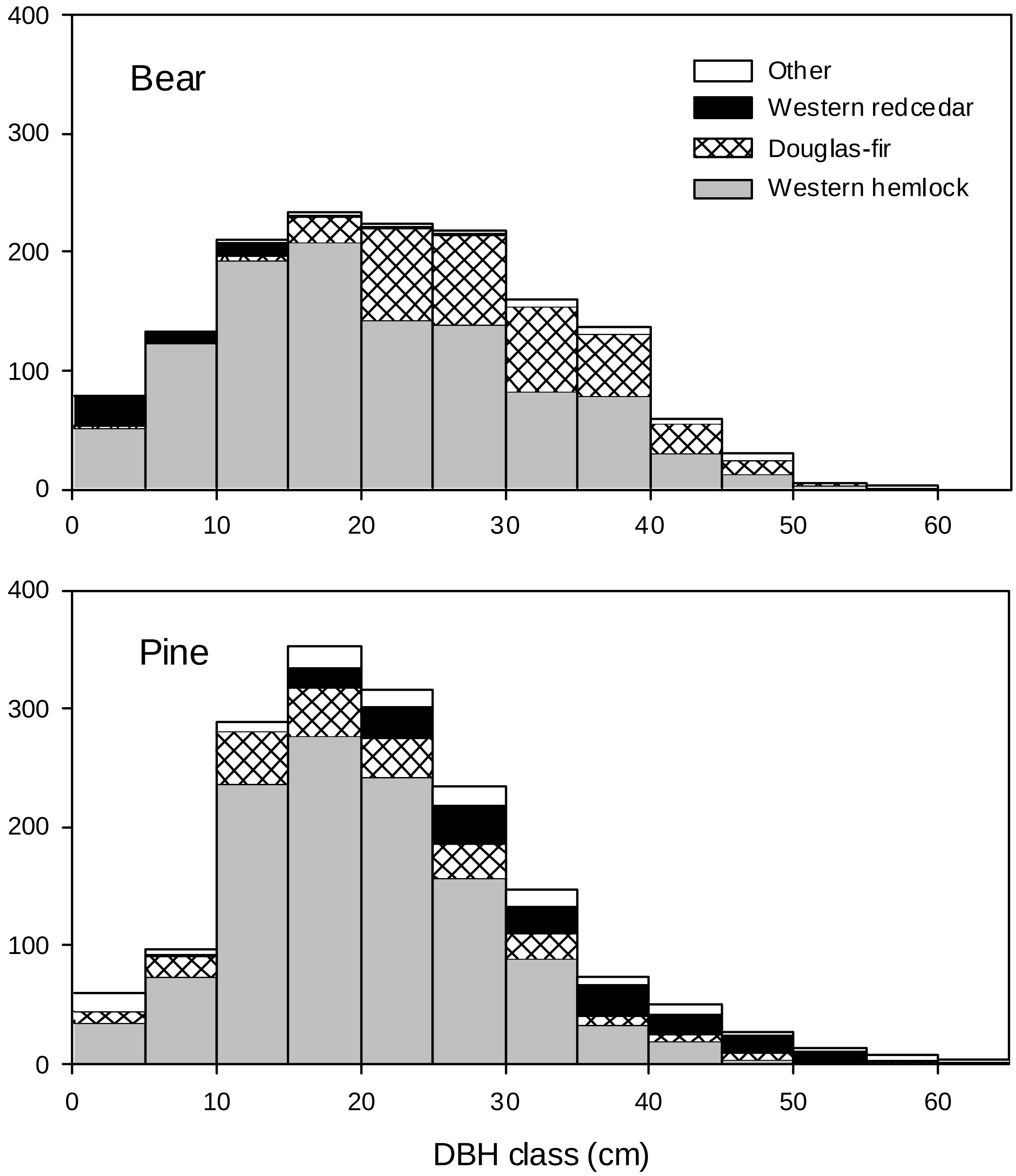
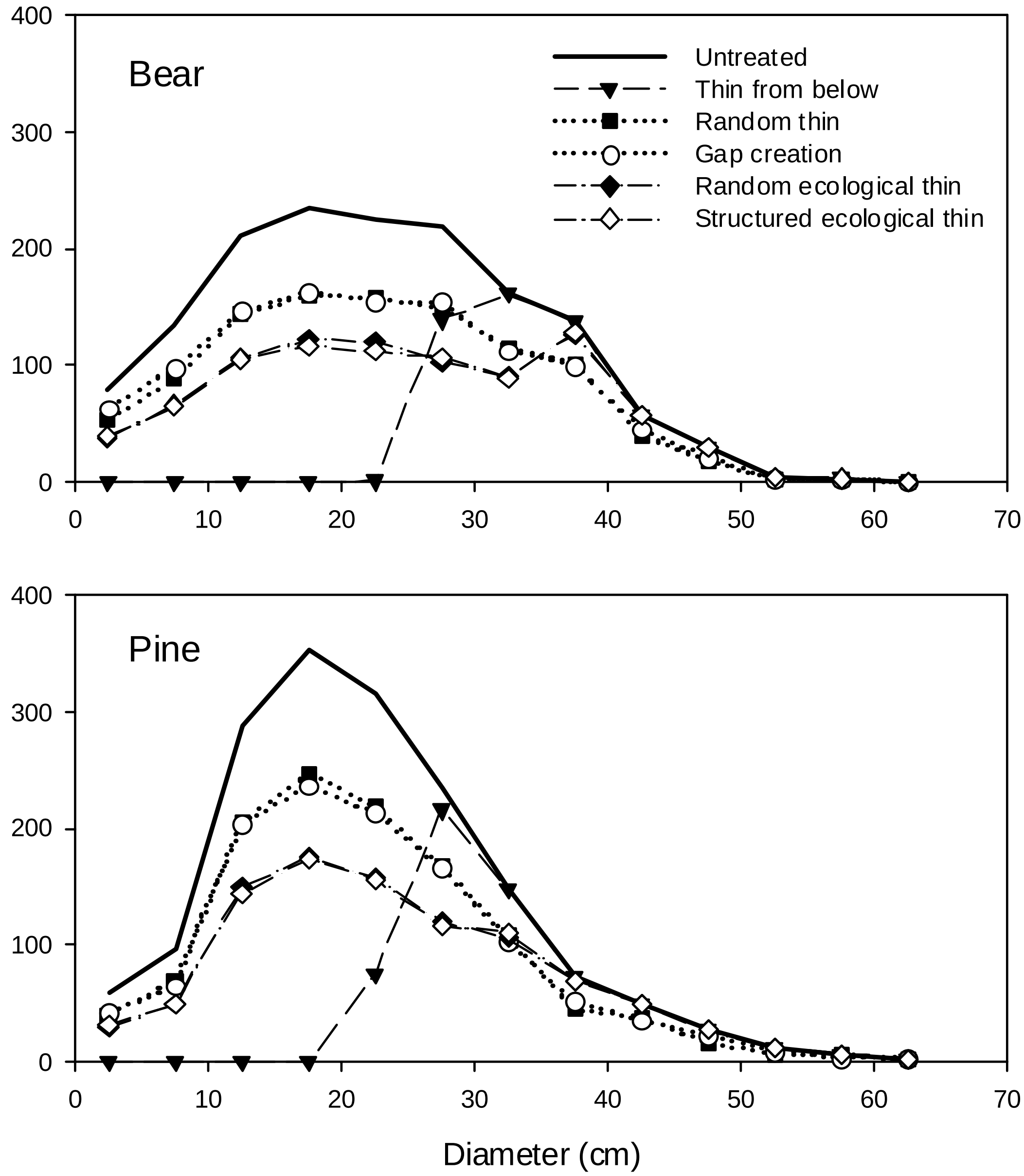

Bear
Pine
Other
Western redcedar
Douglas-fir
Western hemlock
0
100
200
300
400
0
10
20
30
40
50
60
DBH class (cm)

Figure 3



Bear
Pine
Untreated
Thin from below
Random thin
Gap creation
Random ecological thin
Structured ecological thin
400
300
200
100
0
0
10
20
30
40
50
60
70
Diameter (cm)

Figure 4

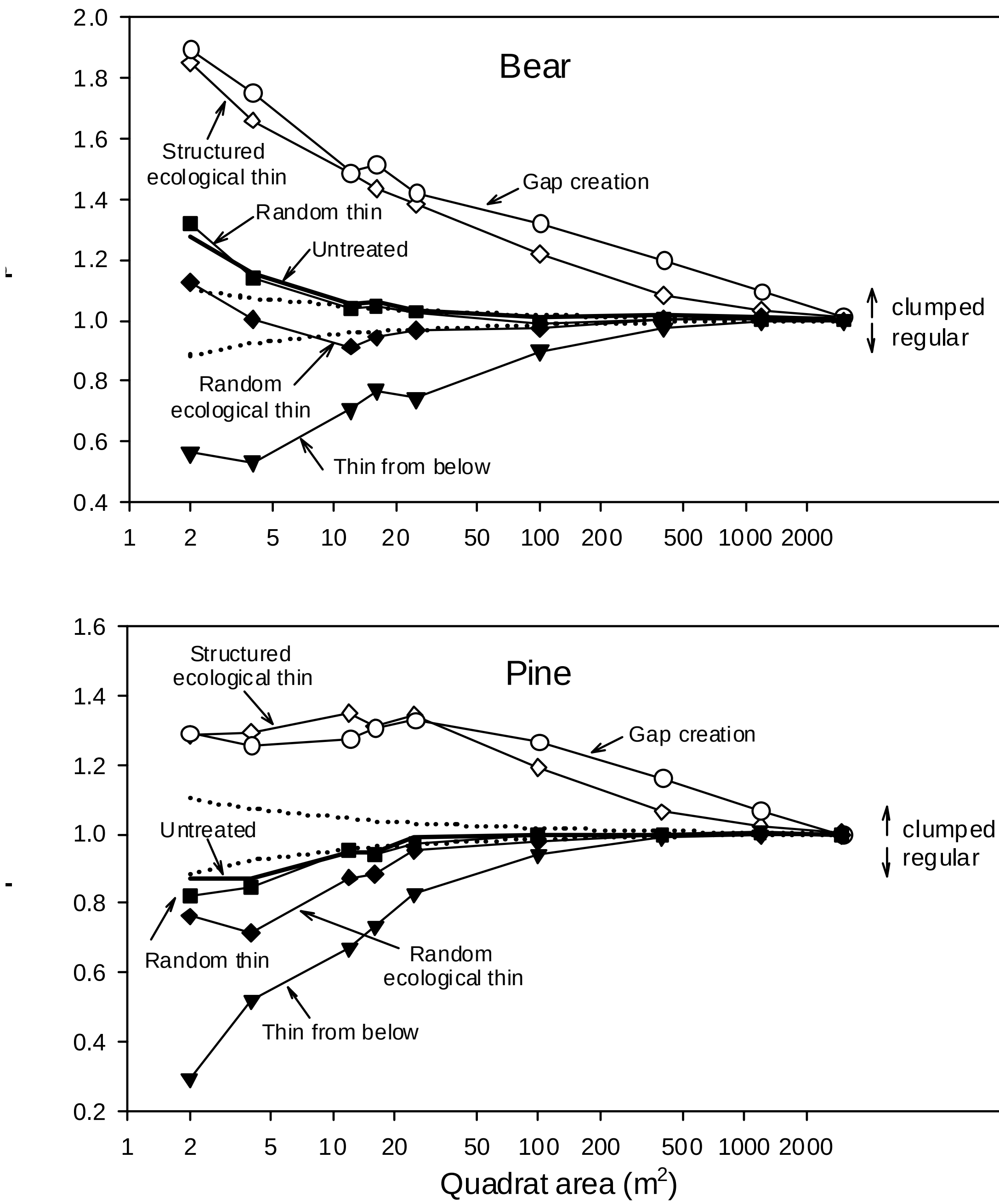

Bear
Structured
ecological thin
Gap creation
Random thin
Untreated
Random
ecological thin
Thin from below
clumped
regular
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
1 2 5 10 20 50 100 200 500 1000 2000
Pine
Structured
ecological thin
Gap creation
Untreated
Random thin
Random
ecological thin
Thin from below
clumped
regular
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
1 2 5 10 20 50 100 200 500 1000 2000
Quadrat area (m2)

Figure 5

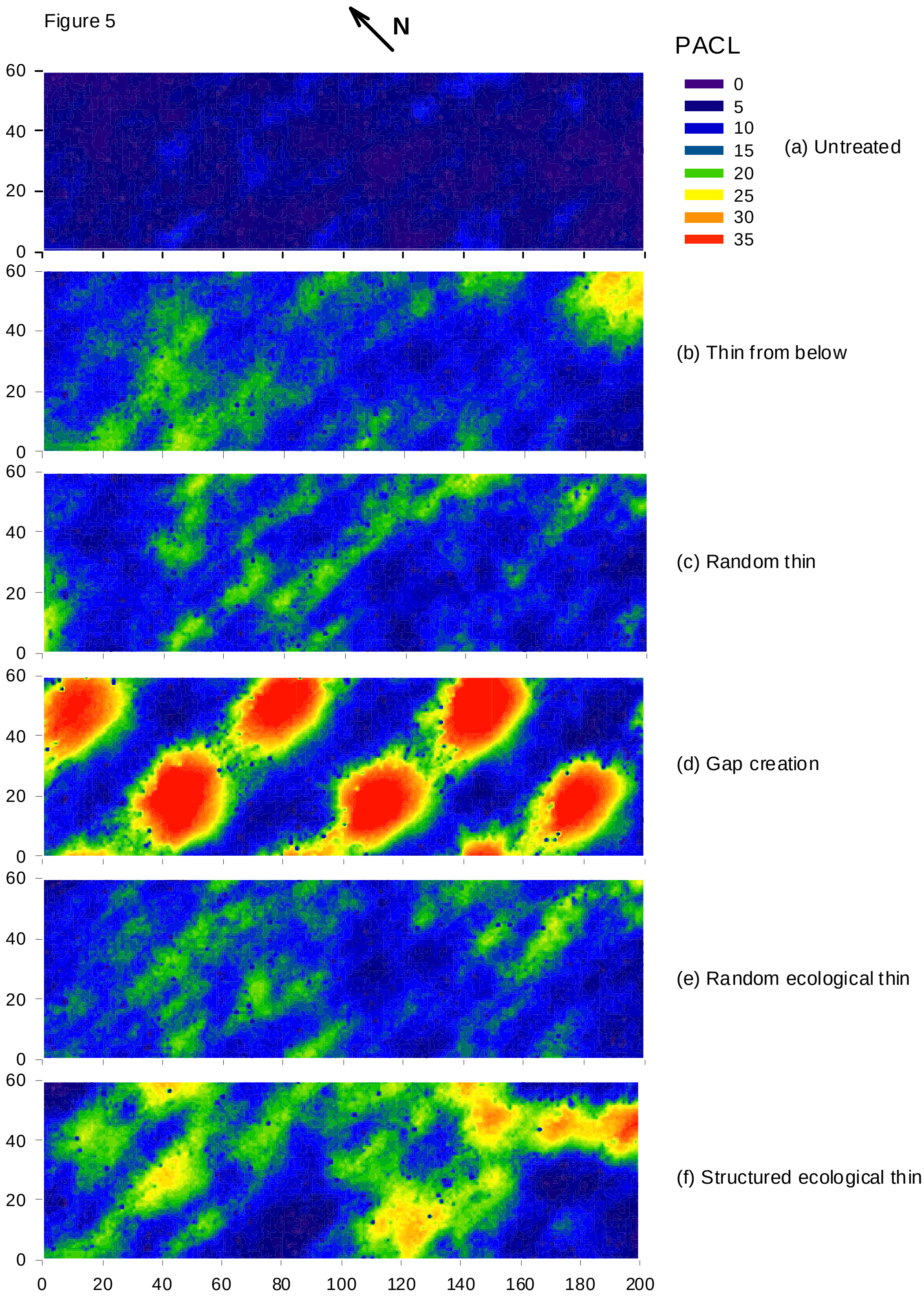
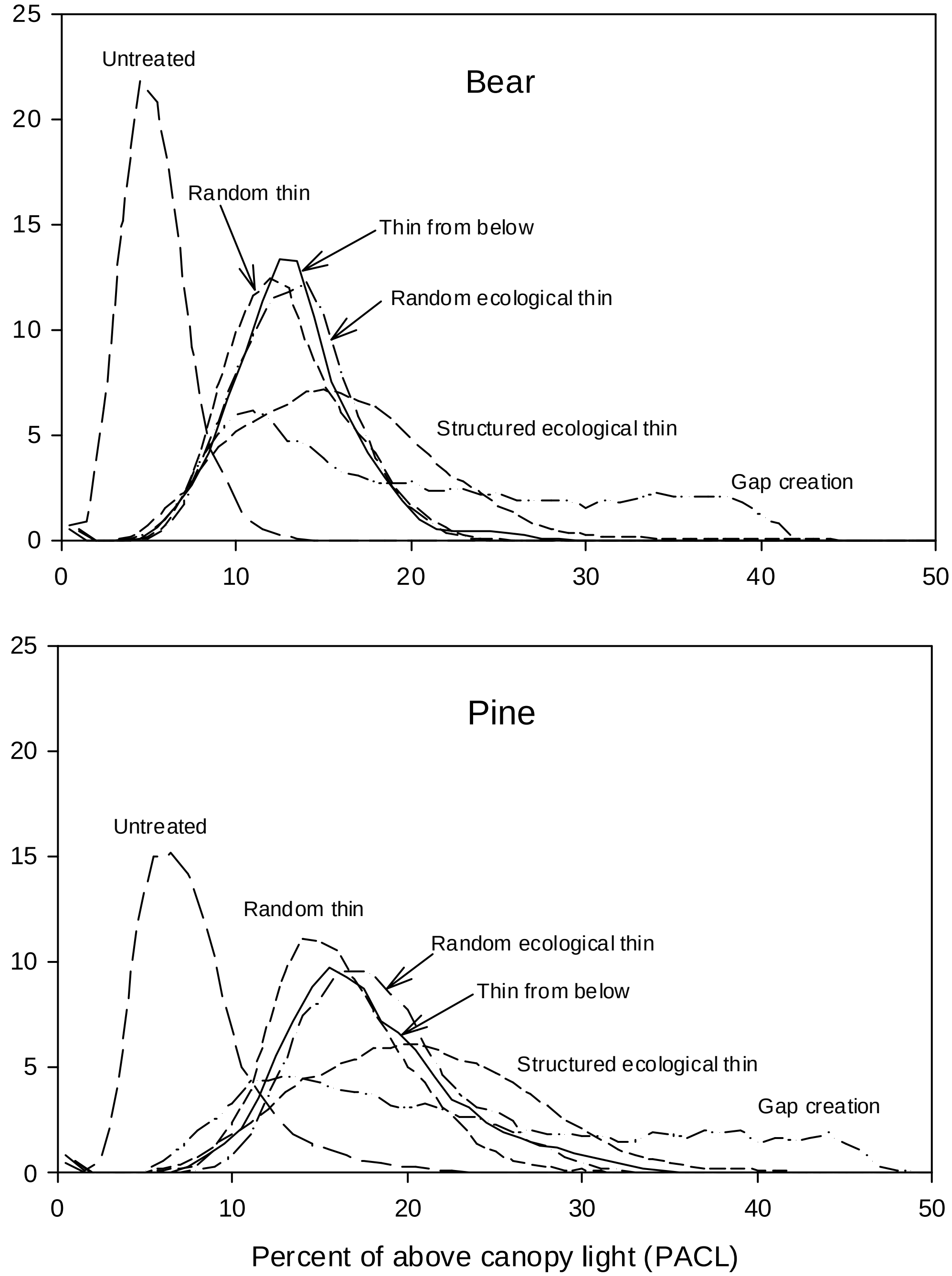

N
PACL
0
5
10
15
20
25
30
35
(a) Untreated
(b) Thin from below
(c) Random thin
(d) Gap creation
(e) Random ecological thin
(f) Structured ecological thin
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200

Figure 6


Bear
Untreated
Random thin
Thin from below
Random ecological thin
Structured ecological thin
Gap creation
Pine
Untreated
Random thin
Random ecological thin
Thin from below
Structured ecological thin
Gap creation
0
5
10
15
20
25
0
10
20
30
40
50
Percent of above canopy light (PACL)