An Ecological Restoration Experiment in the Cedar River Municipal Watershed

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1. Background, Objectives, and Purpose

The Seattle Public Utilities (SPU) Watershed Management Division manages the Cedar River Municipal Watershed under a Habitat Conservation Plan (HCP) approved in 2000. A primary goal of the HCP is to improve habitat for federally listed species in a watershed dominated by dense, young, second-growth forests. Three goals for improving habitat quality have been identified: (1) accelerate development of ecological structures associated with late seral forests, (2) increase habitat complexity, and (3) enhance biological diversity. As one of several strategies to achieve these goals, in particular, the enhancement of biological diversity—ecologists with the Watershed Management Division of SPU have collaborated with faculty, staff, and students from the School of Forest Resources (UW) to implement an ecological-restoration experiment in young, second growth forests at multiple sites in the watershed. The results of this experiment are intended to guide broader application of forest restoration treatments throughout the watershed.

This report serves two primary purposes. First, it provides a summary and synthesis of results from this ecological restoration experiment. Second, it contains metadata describing the structure and content of all databases associated with this project.

The original Memorandum of Agreement between SPU and UW established several objectives for this collaborative research, to be staged over time. We addressed the first three objectives in full in earlier *reports (Task 3 Report.pdf*, *Task 4 Report.pdf*, *Task 4b Report.pdf*, *and Establishment report_2009.pdf).*

1. Characterize the structure and composition of these young, second-growth forests. This provided a baseline assessment of the structure and composition of the forests of interest.

2. Quantify the relationships among overstory structure, light availability, and understory development within these forests. Light is assumed to be the primary limiting resource in these dense, young stands. These preliminary analyses provided insights into the extent to which current understory development reflected variation in overstory structure and light vs. other resources (notably, soil moisture) that could affect responses to structural manipulations.

3. Design experiments at multiple sites to test the potential to enhance understory structure and diversity by altering overstory structure. The need for restoration thinning is predicated on the assumptions that (1) light availability limits understory development in these forests, and (2) biological diversity will be enhanced by greater heterogeneity of forest structure and light. Our experiments were designed to test both assumptions. They contrast unmanipulated forests with two contrasting treatments: (i) gap creation, intended to increase light, but leave unchanged the structure of the surrounding forest, and (ii) "structured ecological thinning," intended to increase light, but in a patchy fashion by creating heterogeneity in residual forest structure. It was not our intention for these to represent narrowly defined operational treatments, but to provide sufficient contrasts in approach that managers could revise, adapt, or combine elements of these treatments to meet a diversity of restoration objectives across the landscape. Methods for sampling vegetation response were designed to capture not only mean responses of treatments, but to measure the spatial distribution and diversity of responses within them.

4. Implement the experiments and assess short-term responses of the vegetation to these manipulations. We address this final objective in the current report, which describes effects on forest structure and light, as well as first- and third-year responses of the vegetation.

We first review basic elements of the experimental design and methods for sampling to provide the context for these results.

2. Experimental Design, Field Sampling, and Response Variables

We designed two experiments to support three principal studies. The first, the "Main Restoration Experiment," compares vegetation responses to experimental treatments (control, thinned, and gap creation) at each of three locations. Much of this report focuses on this experiment. Within the context of this design, we established a smaller study that explores the responses of bryophytes to these treatments and how these responses are mediated by substrate (decayed wood and forest floor). We refer to this as "The Bryophyte Study." A second experiment, implemented at a single location, was designed to assess the consequences for vegetation of retaining vs. removing trees following thinning. We refer to this as "The Coarse Woody Debris (CWD) Experiment."

2.1. Main Restoration Experiment

Sites.— The main restoration experiment, our primary study, was implemented at three locations: Bear Creek (Bear), Pine Creek (Pine), and Pine Creek-North (Pine-N). Bear (47° 19'N, 121° 33'W) lies at an elevation of ~610 m on a gentle (0-10°) SW-facing slope; Pine and Pine-N (47° 21'N, 121° 38'W) lie at an elevation of ~740 m on a slightly steeper (0-30°) W/SW-facing slope. Pine and Pine-N are adjacent (separated by a stream), but differ in structure (see **Fig. 1,** Results). Two experimental units (EUs) at the southern end of Pine-N were grouped with Pine for analytical purposes because of greater similarity in structure to forests at Pine (see establishment report, Halpern et al. 2009).

We used three criteria to select sites: dominance by, or a significant component of, *Tsuga heterophylla* (western hemlock) in the main canopy; limited tree regeneration; and minimal development of understory vegetation. Forest stands were ~65 yr old at the time of treatment, dominated by *Tsuga* and *Pseudotsuga menziesii* (Douglas-fir).

Experimental treatments.— Treatments (control, structured ecological thin, and gap creation; see **Plate 1**, next page) were assigned randomly to 40 x 40 m experimental units (EUs) at each site with EUs arranged in two (Bear and Pine) or four (Pine-N) rows (see light maps in **Figs. 2 and 3**, Results). Levels of treatment replication were five at Bear and four at Pine and Pine-N.

Gaps were centered within the 40 x 40 m experimental unit. All trees, including subcanopy stems, were felled within a 10 m radius of the center (removing ~20% of the original basal area). From each gap. trees were yarded by cable through an exit corridor to one edge of the experimental unit, then upslope through a corridor to a roadside landing. Structured ecological thin (henceforth, thinned) was implemented as follows: the largest-diameter trees (~40% of the original basal area) were first reserved. Smaller trees were then marked for removal in 6-m radius circles. The centers of these circles were located randomly with the condition that they lie outside of previous circles. Circles were added until 30% of the original basal area was achieved. Trees were felled and yarded to the edge of each experimental unit, then upslope through a corridor to a roadside landing. Treatments were implemented during fall/early winter 2006. Felling and yarding occurred on snow at Bear, but not at Pine or Pine-N.

Tree maps and overstory structure.— Trees were measured and mapped at each site to facilitate the design and implementation of thinning prescriptions and to predict effects of treatments on forest-floor light levels. Prior to treatment (2005 and 2006), live and dead stems (≥1.4 m tall) were identified to species, measured for diameter, and spatially mapped. For a subset of trees, heights and heights to live crown were determined. Details on the surveying of plot boundaries and tree mapping procedures can be found in our earlier establishment report (Halpern et al. 2009).

Plate 1. Examples of control, thinned, and gap treatments (top to bottom).

After treatment (2007), all experimental units were revisited and stem maps were updated. This survey was used to determine which trees had been removed during gap creation and thinning. Standing trees were not systematically assessed for mortality, but dead stems were noted when they were encountered. We also noted live stems that were tipped, prone, or snapped (e.g., **Plate 2**). Control treatments were revisited along yarding corridors only. All experimental units were revisited in summer 2009 to document post-harvest treefall and to determine the conditions of trees previously noted as tipped, prone, or snapped. As in 2007, dead standing trees were noted when they were encountered.

Plate 2. Post-harvest windthrow in a gap treatment

Light modeling. A spatially explicit light model, tRAYci (Brunner 2004), parameterized for these forests (Sprugel et al. 2009), was used with the stem maps to model direct, diffuse, and total light at Pine and Bear before and after treatment. Percentage of above-canopy light (PACL) was modeled for the period 1 Apr through 30 Sep at 1 m above the forest floor across a 1 x 1 m grid (yielding 32000 light estimates at Bear and 16000 at Pine). Direct, diffuse, and total light were also modeled for each of the vegetation and bryophyte sampling locations.

Hemispherical photographs.— In addition to modeling post-treatment light availability (see section **3.1.2. Light distributions**), we used hemispherical photographs. We do not present these data here, but we briefly describe the field methods because they are included among the documented databases.

Photos were taken at multiple points in each EU corresponding to the locations of understory quadrats (see below). However, the number and locations of photos varied by treatment. In the controls, where forest structure was most homogeneous, nine photographs were taken: three per transect at 10 m intervals. In the thin treatments, 27 photographs were taken: 9 per transect spaced at 4 m intervals. In the gap treatments, 21 photographs were taken: at the gap center and at 2-4 m intervals along each of the four radial transects.

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

Sampling of ground-surface characteristics and understory vegetation.— Within each EU, ground conditions and understory vegetation were sampled with a series of 1 x 1 m quadrats arrayed along transects (**Plate 3**). In control and thinned treatments, three permanent transects are oriented up/downslope, spaced 10 m apart. Beginning at a center line 20 m upslope from baseline of each EU, sample quadrats are spaced at 1-m intervals up- and downslope, yielding 20 quadrats per transect (60 quadrats per EU).

In gap treatments, 20-m long transects marked at 10-m intervals radiate from the gap center oriented at 45° (NE), 135° (SE), 225° (SW), and 315° (NW). Sample quadrats are spaced at 1 m intervals from the center of the gap, yielding 10 quadrats per transect (9 for SE) and 39 quadrats per experimental unit. Of these, 19 fall within the 10-m radius of the gap ("gap-gap" in subsequent figures) and 20 in the adjacent forest ("gap-forest"). Because this design led to more intensive sampling toward the center the gap, for the analyses, quadrat values were differentially weighted to generate means for gap-gap and gap-forest environments, and for the experimental unit as a whole.

Plate 3. Layout of a transect and placement of a 1 x 1 m quadrat used to sample ground-surface characteristics and understory vegetation.

The following variables were sampled before (2006) and after (2007 and 2009) treatment:

- cover of ground-surface characteristics: bare ground, fine litter (<10 cm dbh), fresh wood (decay classes I-II), decayed wood (decay classes III-V) , stumps, and logging slash (sampled in 2007 only)
- counts of tree seedlings (≤1.4 m tall) by species and size class
- total cover of bryophytes
- cover of individual vascular plant species

We take a "functional group" approach to analyzing vascular plant species' responses. To that end, we

compare changes in the total abundance (summed cover) and richness of species grouped as follows:

- Growth form: herbs (including grasses, sedges, and ferns); sub-shrubs (possessing woody stolons or bases, but otherwise herbaceous), and shrubs (erect woody plants)
- Seral status: forest understory (i.e., shade-tolerant species typical of young, mature, or old-growth forests), and ruderal (i.e., early seral species including annuals, biennials, and herbaceous and woody perennials absent from the forest understory and characteristic of open sites)
- Mode of perennation: clonal (species with strong potential for clonal growth via roots, rhizomes, or stolons) and non-clonal (species with limited or no potential for clonal spread)

Table 4 lists all vascular plant species classified by growth-form, seral status, and mode of perennation (see **section 3.1.5. Vascular plant species abundance and diversity**).

This report does not include formal statistical analyses of treatment effects or within-treatment variation. Instead, our descriptions and interpretations are based on qualitative assessments of patterns.

2.2. Bryophyte Study

This study was designed within the context of the main restoration experiment to explore the dynamics of bryophyte communities and whether responses to treatments were mediated by substrate (CWD or forest floor). The study was limited to 12 of the 15 EUs (four replicates of each treatment) at the Bear site. Within each EU, we established 16-24 pairs of sample quadrats (0.2 x 0.5 m) marked with bright pin flags and referenced to fixed points in the EU (**Plate 4**). One of each quadrat pair sampled a decayed log (CWD, decay class III-V); the second sampled the adjacent forest floor. In control and thinned treatments, quadrat pairs were distributed across the entire experimental unit. In gap treatments, half of the pairs were established within the gap (gap-gap) and half in adjacent forest (gap-forest). The vast majority of quadrats survived the treatments; quadrats lost to disturbance or otherwise compromised (6% or 32 of 552 quadrats) were excluded from the analyses.

The following variables were sampled before (2006) and after (2007 and 2009) treatment:

- cover of bare ground (forest-floor quadrats only), fresh wood (≥ 5 cm dbh), fine litter (<5 cm dbh), and logging slash
- disturbance to CWD quadrats: % of quadrat missing, % smashed, % scrapped bare (but intact)
- counts of tree seedlings by species and size class
- total cover of mosses, liverworts, and vascular plants
- presence of each moss and liverwort species

Plate 4. Paired quadrat design used to sample moss and liverwort responses on decayed logs (CWD) and the forest floor.

2.3. CWD Experiment

Sites and experimental treatments.— The CWD experiment was designed to assess the consequences of retaining vs. removing down wood resulting from thinning. It used the same thinning design as in the main restoration experiment. The study was implemented at the Bear site, uphill from the main restoration experiment. Eight contiguous EUs (40 m across the slope x 60 m up/downslope) were established in 2006. One of two treatments (+CWD, -CWD) was randomly assigned to each of four EUs. Treatments were implemented during fall/early winter 2006. Felling and yarding occurred on snow (as in the main restoration experiment at Bear); trees were yarded by cable downslope along the edges of experimental units to roadside landings. Unlike the main restoration experiment, however, post-treatment sampling was limited to 2009 (year 3).

Tree measurements.— All live overstory trees (≥1.4 m tall) were identified and measured for diameter prior to treatment, but trees were not spatially mapped. Residual trees were remeasured three growing seasons after treatment (2009), coincident with remeasurements of understory vegetation.

Sampling of ground-surface characteristics and understory vegetation.— Within each EU, ground conditions and understory vegetation were sampled with a series of 1 x 1 m quadrats placed along each of three permanently marked transects. Transects are spaced 10 m apart (beginning 20 m upslope of the EU baseline) and run across the slope. Sample quadrats are spaced at 1-m intervals beginning and ending 4 m from the EU boundary (yielding 17 quadrats per transect and 51 quadrats per EU).

The following variables were sampled before (2006) and after (2009) treatment:

- cover of ground-surface characteristics: bare ground (mineral soil), fine litter (<10 cm dbh), fresh wood (decay classes I-II), decayed wood (decay classes III-V) , stumps, rock (2009 only), and logging slash (2009 only)
- counts of tree seedlings (≤1.4 m tall) by species and size class
- total cover of bryophytes
- cover of individual vascular plant species

2.4. Measures of Response

This section provides an outline (in tabular form) of the variables analyzed in the current report. For each, it notes the source of the data (field measurement), the nature of the response variable (e.g., species' frequency, species richness, community composition) and the spatial scale(s) at which it is assessed (e.g., treatment means, environments within treatments, trends across gap treatments).

Table 1. Variables assessed in the main restoration experiment, bryophyte study, and CWD experiment. Scale refers to the spatial scale at which data were analyzed: C,T,G = comparison of treatments; GF-GG = gap-forest vs. gap-gap environments; G-trans = variation across gap treatment transects. For the bryophyte study we also consider the southern (S) and northern (N) halves of the gap (GGS, GGN) and adjacent forest (GFS, GFN). +/- CWD = retention vs. removal of CWD.

Variable	Field measurement	Measure of response	Scale
Main Experiment			
Physical conditions			
Light	Modeled direct, diffuse, and total light (% of above-canopy light; PACL) using tRAYci (Brunner 2004)	Spatial maps of post-treatment light for all EUs (full tree plot) at Bear and Pine	C,T,G
		Frequency distribution of PACL	C,T,G
		Spatial distribution of PACL across gap treatments	G-trans
Ground-surface characteristics	Cover of bare ground, fine litter, fresh wood (I-II), decayed wood (III-V)	Mean cover	C,T,G and GF-GG
	Cover of logging slash	Mean cover	C,T,G; GF-GG; & G-trans
Biological responses			
Overstory structure (trees ≥1.4 m tall)	Tree sizes and spatial distributions: species, X/Y location, diameter	Stem density, basal area, and size (dbh) structure	C,T,G
Tree seedlings	Density by height class	Seedling density and richness 1. Seedling density by species 2. Species richness (per quadrat)	C,T,G & GF-GG
		Species composition (relative density of individual species)	C,T,G
		Frequency distribution of quadrat-scale density and richness	C,T,G
		Spatial distribution of density and richness across gap treatments	G-trans

Table 1. Continued.

Variable	Field measurement	Measure of response	Scale
Main Experiment			
Biological responses (continued)			
Vascular understory plants	Species cover	Mean cover of plant functional groups: 1. All vascular plants (total) 2. Growth forms (herb, sub-shrub, shrub) 3. Seral status (forest understory vs. ruderal) 4. Perennation (clonal vs. non-clonal)	C,T,G & GF-GG
		Frequency distribution of quadrat-scale cover	C,T,G
		Spatial distribution of cover across gap treatments	G-trans
		Regression of change in plant cover vs. site characteristics (% density of *Thuja plicata* by EU)	C,T,G
		Mean richness of plant functional groups: 1. All vascular plants (total) 2. Growth forms (herb, sub-shrub, shrub) 3. Seral status (forest understory vs. ruderal) 4. Perennation (clonal vs. non-clonal)	C,T,G & GF-GG
		Frequency distribution of quadrat-scale richness	C,T,G
		Spatial distribution of species richness across gap treatments	G-trans
		Regression of change in species richness vs. site characteristics (% density of *Thuja plicata* by EU)	C,T,G
		Species-area curves	C,T,G
		Dominance-diversity curves	C,T,G
		Community composition 1. NMS ordination 2. Species' frequencies of occurrence	C,T,GF,GG
Bryophytes	Bryophyte cover	Mean cover	C,T,G & GF-GG
		Spatial distribution of change in cover across gap treatments	G-trans

Table 1. Continued.

Variable	Field measurement	Measure of response	Scale
Bryophyte Study			
Biological responses			
Tree seedlings	Density by height class on CWD and forest-floor substrates	Seedling density and richness by substrate 1. Seedling density by species 2. Species richness (per quadrat)	C,T,G & GF-GG
Bryophytes	Total moss, liverwort, and vascular plant cover on CWD and forest-floor substrates	Mean cover by substrate	C,T,G & GF-GG
	Bryophyte species' presence on CWD and forest-floor substrates	Community composition (NMS ordination)	C,T,GF,GG
		Change in frequency of occurrence (% of quadrats)	C,T,GFS, GGS,GGN, GFN
Variable	Field measurement	Measure of response	Scale
CWD Experiment			
Physical conditions			
Ground-surface characteristics	Cover of bare ground, fine litter, fresh wood (I-II), decayed wood (III-V), logging slash	Mean cover	+/- CWD
Biological responses			
Overstory structure (trees $\geq$1.4 m tall)	Tree sizes: tree species, diameter	Stem density and basal area	+/- CWD
Tree seedlings	Density by height class	Seedling density and richness 1. Seedling density by species 2. Species richness (per quadrat)	+/ - CWD
Vascular understory plants	Species cover	Mean cover of vascular plants Mean richness (per quadrat)	+/- CWD
Bryophytes	Total bryophyte cover	Mean cover	

3. Results

The presentation of results is structured around a comprehensive set of figures and tables. For each measure of response, we provide a figure caption or set of captions followed by a descriptive summary. Corresponding figure(s) follow, typically on subsequent pages. Additional results and supporting information (e.g., species lists) are presented in tables interspersed among the figures. Figure and table content and location are listed below.

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3. 1. Main Restoration Experiment

3.1.1. Forest structure

Fig. 1. Treatment effects on forest structure. Effects of experimental treatments on the size (diameter) distributions of major tree species at Bear, Pine, and Pine-N. "Other species" are primarily *Abies amabilis* and *A. procera*. See **Table 3** for changes in total density and basal area of trees.

Results.— Changes in size structure were consistent with expectation and with the results of previous simulations (Sprugel et al. 2009). Size structure and species composition remained largely unchanged in control and gap treatments, which experienced declines in density proportional to initial size distributions. However, in thinned treatments, structure was significantly changed due to preferential harvest of smaller trees from the 6-m radius removal circles. As a result, post-harvest distributions were characterized by a greater proportion of larger diameter trees (notably *Pseudotsuga menziesii*).

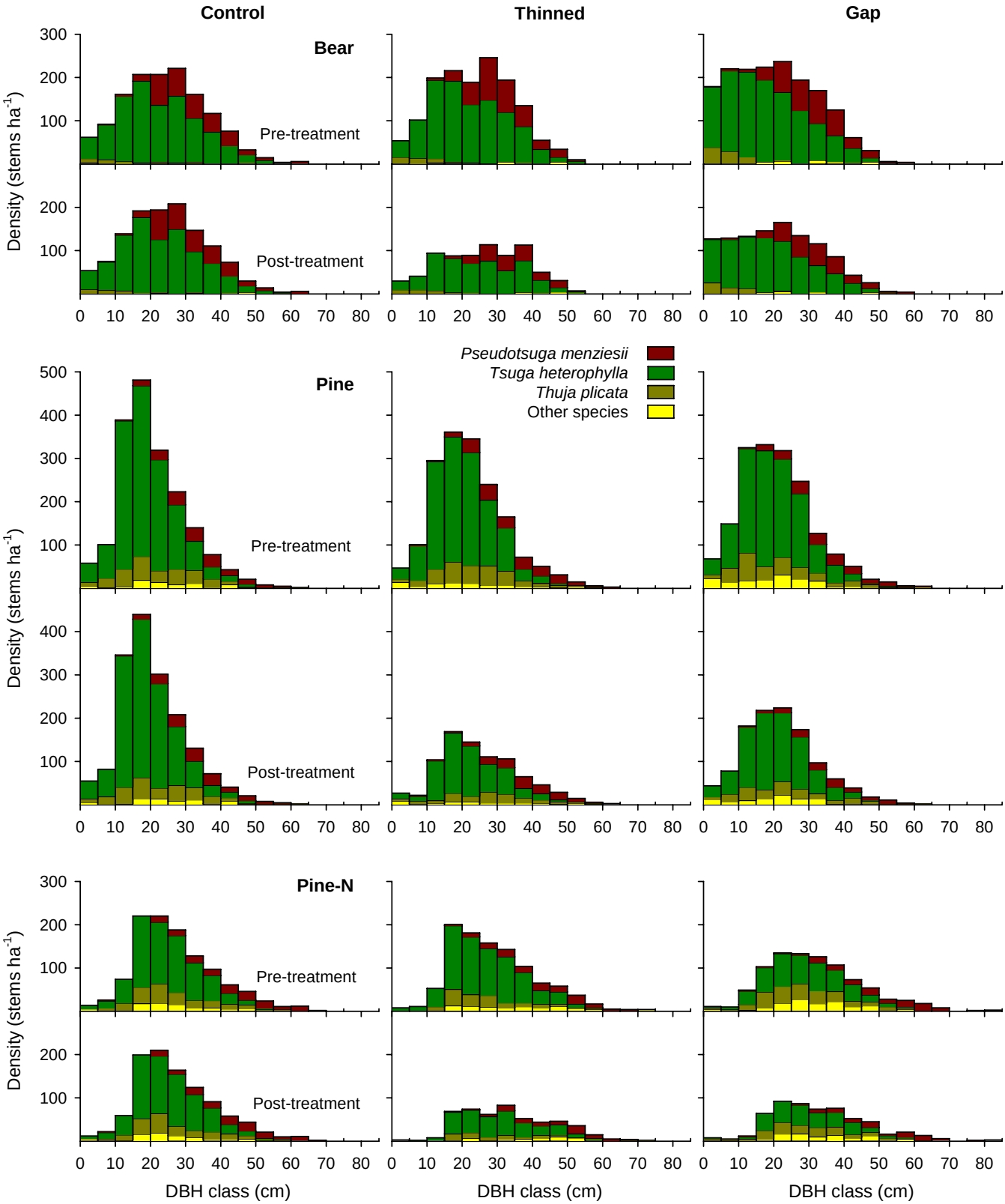

Fig. 1. Treatment effects on forest structure.

3.1.1. Forest structure (continued)

Table 3. Density and basal area of trees before and after treatment. "Row,Col" values correspond to individual EUs. The targeted basal area reduction was 30% in thinned treatments and 19.6% (area based) in gap treatments.

Results.— Greater basal area was removed than planned in nearly all experimental units (including controls). Two factors contributed to this outcome: (1) trees were removed from logging corridors along the edges of many experimental units, and (2) in gap treatments, trees were removed from "exit corridors" to facilitate removal from the gaps.

In the thinned treatment with a targeted basal area reduction of 30%, actual reduction averaged 37-39% among sites. Stem density was reduced by a greater amount (~48-52%), reflecting preferential removal of smaller-diameter trees in this treatment (see **Fig. 1**). In the gap treatment, with a targeted basal area reduction of ~20% (based on gap area), basal area was reduced by 28-34% and density by 34-35%. Reductions in the controls averaged 6-10% for basal area and 8-9 % for density.

Table 3. Density and basal area of trees before and after treatment. "Row,Col" values correspond to individual EUs; treatment averages follow. The targeted basal area reduction was 30% in thinned treatments and 19.6% (area based) in gap treatments.

			Density (stems ha^{-1})			Basal area (m^2 ha^{-1})		
Site	Treatment	Row,Col	Before	After	% Decrease	Before	After	% Decrease
Bear	Control	1,2	1,263	1,263	0	87.4	87.4	0
		1,3	1,263	1,194	5	80.9	77.8	5
		2,2	956	913	4	75.6	74.1	4
		2,7	1,356	1,169	14	70.9	59.8	14
		2,9	1,956	1,675	14	70.1	61.9	14
		Average	1,383	1,238	8	74.4	68.4	10
	Thinned	1,7	1,431	806	44	77.9	48.5	38
		1,8	1,544	725	53	71.6	40.9	43
		2,3	1,400	675	52	81.8	49.3	40
		2,5	1,288	713	45	78.2	51.8	34
		2,6	1,481	794	46	73.0	46.3	37
		Average	1,429	743	48	76.5	47.4	38
	Gap	1,5	1,344	825	39	77.4	54.0	39
		1,6	1,531	981	36	72.0	47.3	36
		1,9	1,481	1,025	31	77.6	58.4	31
		2,8	1,531	1,031	33	69.8	49.8	33
		2,10	2,444	1,700	30	72.9	50.4	30
		Average	1,747	1,184	34	73.1	51.5	34

			Density (stems ha^{-1})			Basal area (m^2 ha^{-1})		
Site	Treatment	Row,Col	Before	After	% Decrease	Before	After	% Decrease
Pine	Control	1,3	1,719	1,488	13	70.5	63.9	9
		1,5	1,744	1,613	8	79.3	75.4	5
		2,5	1,706	1,556	9	72.8	68.4	6
		1,8*	2,281	2,175	5	77.9	73.4	6
		Average	1,862	1,708	9	75.1	70.3	6
	Thinned	1,2	1,725	856	50	75.5	48.1	36
		1,4	1,744	850	51	73.3	48.4	34
		2,1	1,419	713	50	85.1	54.6	36
		2,8*	2,000	944	53	82.3	48.1	42
		Average	1,722	841	51	79.1	49.8	37
	Gap	1,1	1,919	1,250	35	75.7	56.6	25
		2,2	1,519	1,075	29	74.8	52.9	29
		2,3	1,719	1,206	30	75.4	55.4	27
		2,4	1,781	1,050	41	75.1	50.2	33
		Average	1,734	1,145	34	75.3	53.8	28

* Row and column numbers for the Pine-N site.

Table 3. Continued.

			Density (stems ha^{-1})			Basal area (m^2 ha^{-1})		
Site	Treatment	Row,Col	Before	After	% Decrease	Before	After	% Decrease
Pine-N	Control	2,4	1,031	944	8	80.7	74.9	7
		2,6	1,119	994	11	82.5	72.3	12
		2,7	1,113	1,025	8	72.9	69.1	5
		3,7	1,213	1,125	7	68.9	65.4	5
		Average	1,119	1,022	9	76.3	70.4	7
	Thinned	1,6	1,044	513	51	82.1	50.5	38
		3,5	1,038	519	50	78.3	50.2	36
		3,6	1,206	506	58	74.9	41.1	45
		4,3	875	444	49	82.9	53.9	35
		Average	1,041	496	52	79.6	48.9	39
	Gap	2,5	1,019	669	34	78.8	53.0	33
		3,3	831	506	39	81.0	58.2	28
		3,4	969	619	36	81.3	55.8	31
		4,2	700	494	29	81.6	60.4	26
		Average	880	572	35	80.7	56.9	30

3.1.2. Light distributions

Figs. 2 and 3. Post-treatment light distribution maps for tree plots at Bear and Pine. Simulated levels of direct, diffuse, and total light (percentage of above-canopy light; PACL) for the full tree plot at Bear (400 x 80 m) presented in two, 200-m sections. Individual 40 x 40 m experimental units (EUs) are outlined in white and coded by treatment (C = control, T = thinned, G = gap, and X = untreated areas not used in the experiment). Light was modeled for the period 1 Apr through 30 Sep using stem maps and a spatially explicit light model, tRAYci (Brunner 2004), parameterized for these forests (Sprugel et al. 2009). PACL was predicted at a height of 1 m above the forest floor across a 1 x 1 m grid (yielding 32000 light estimates at Bear and 16000 at Pine).

Results.— Treatments had varying effects on light distribution within, but also among, experimental units. Distributions of direct and diffuse radiation were highly variable among thinned replicates because of the random nature of tree removal (i.e., random placement of removal circles). However, in the gap treatment, regions of elevated light also varied among replicates, reflecting variation in the distribution and size structure of trees and in the width and orientation of exit corridors. Increases in diffuse light were largely centered beneath the gap (circular in shape) with minimal extension into adjacent forest. However, increases in direct light were much greater in the northern portion of the gap and extended well into forest to the north (also see **Fig. 7**).

Fig. 4. Post-treatment frequency distributions of light among experimental treatments. Frequency distributions of direct, diffuse, and total light (PACL) at the forest floor at Bear and Pine, modeled with tRAYci (see **Figs. 2 and 3**). Each line represents the mean of four (Pine) or five (Bear) replicates. Dashed lines correspond to average site values prior to treatment. Mean post-treatment values ($\pm$1 SE) are shown for comparison (inset panels); the white line represents the pre-treatment site mean. Light distributions were not modeled for EUs at Pine-N.

Results.— Changes in the amount and variation in light (PACL) were consistent with expectation and with the results of previous simulations (Sprugel et al. 2009). Compared to pre-treatment values, thinning and gap creation increased mean light by 250-300% (3.5-4 times) at Bear and 150-200% (2.5-3 times) at Pine. The range of values of direct and indirect light was also greatly increased, especially in the gap treatments, where direct light occasionally exceeded 50% of above-canopy values. In controls, light increased by ~50-60% (1.5-1.6 times) at Bear and 20-30% (1.2-1.3 times) at Pine. These unanticipated increases corresponded with reductions in tree density associated with yarding corridors.

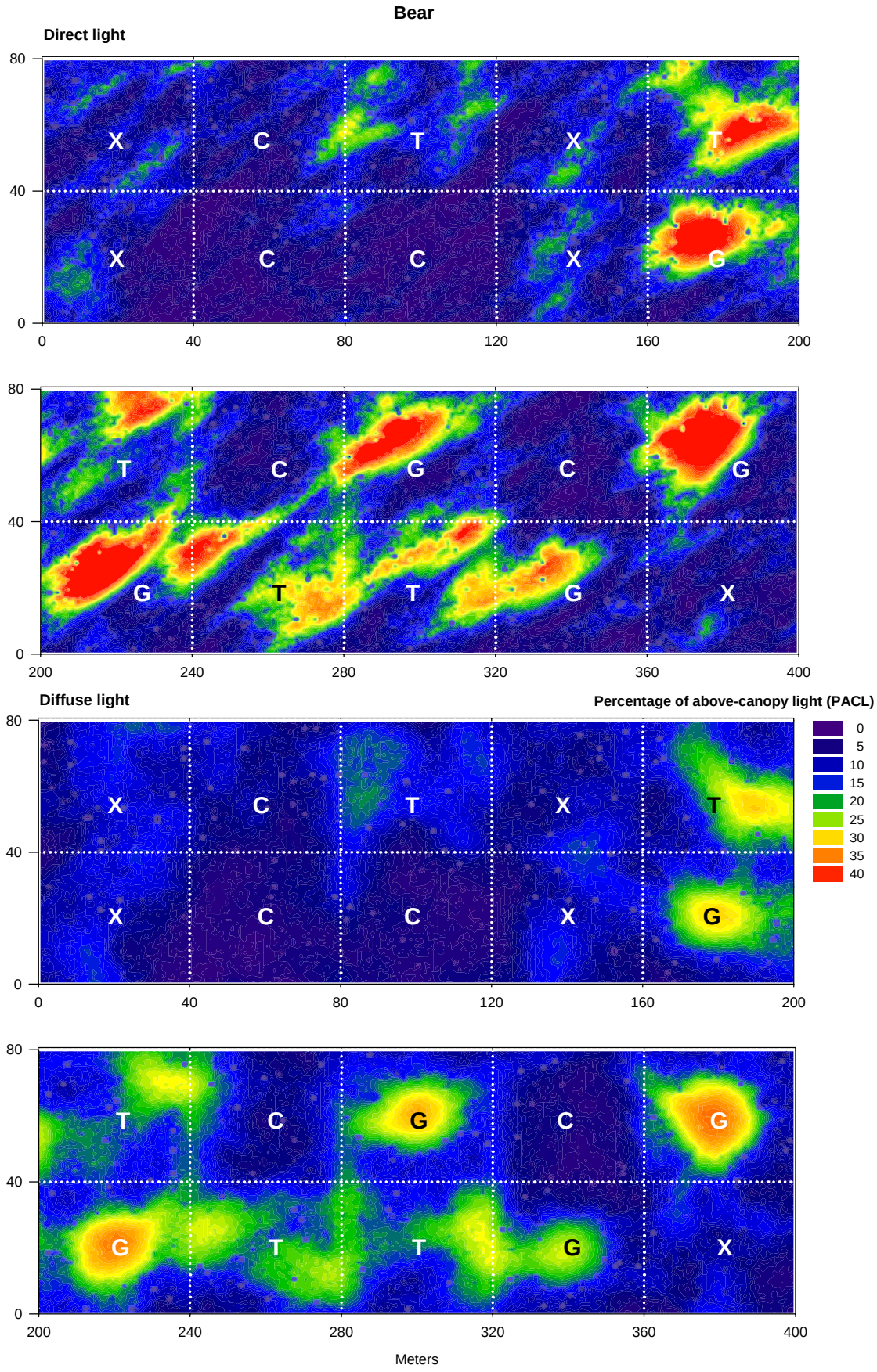

Fig. 2. Post-treatment light distribution map for the tree plot at Bear: direct and diffuse light.

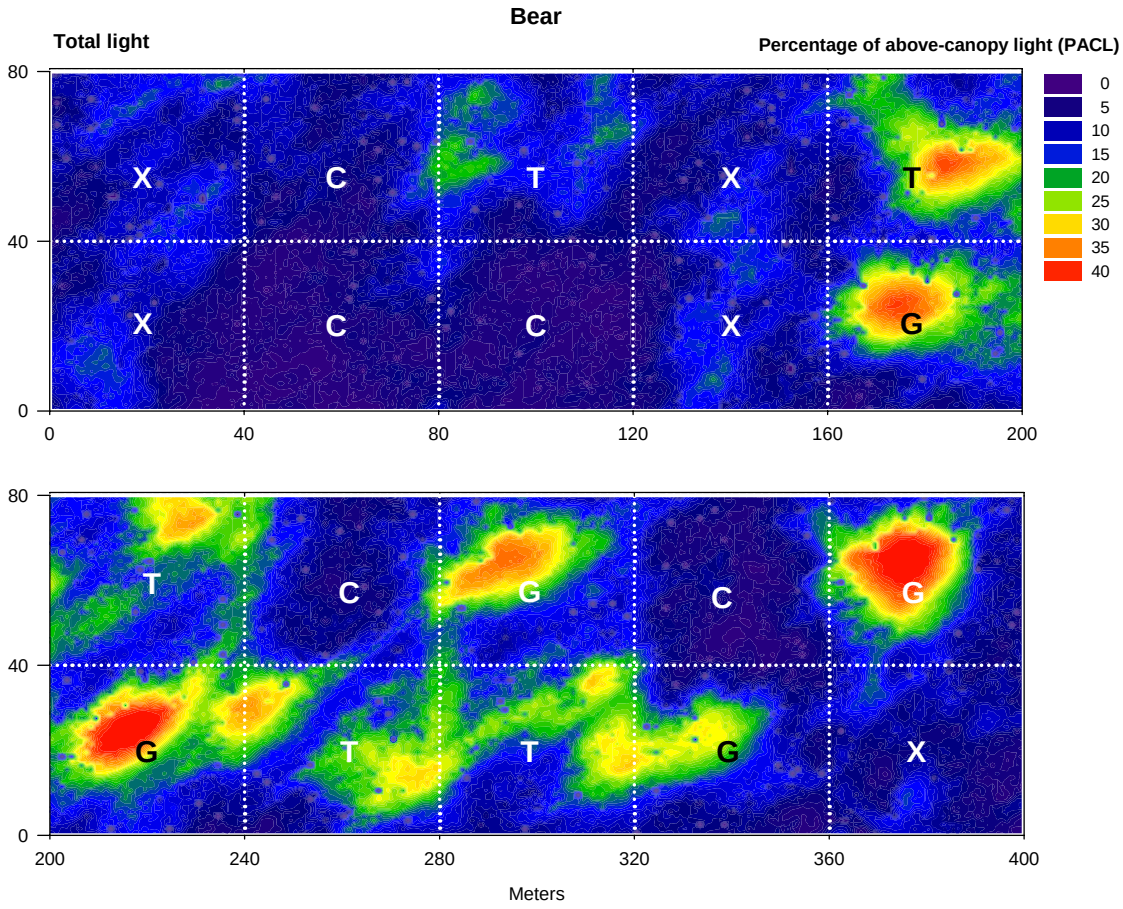

Fig. 2. Post-treatment light distribution map for the tree plot at Bear: total light.

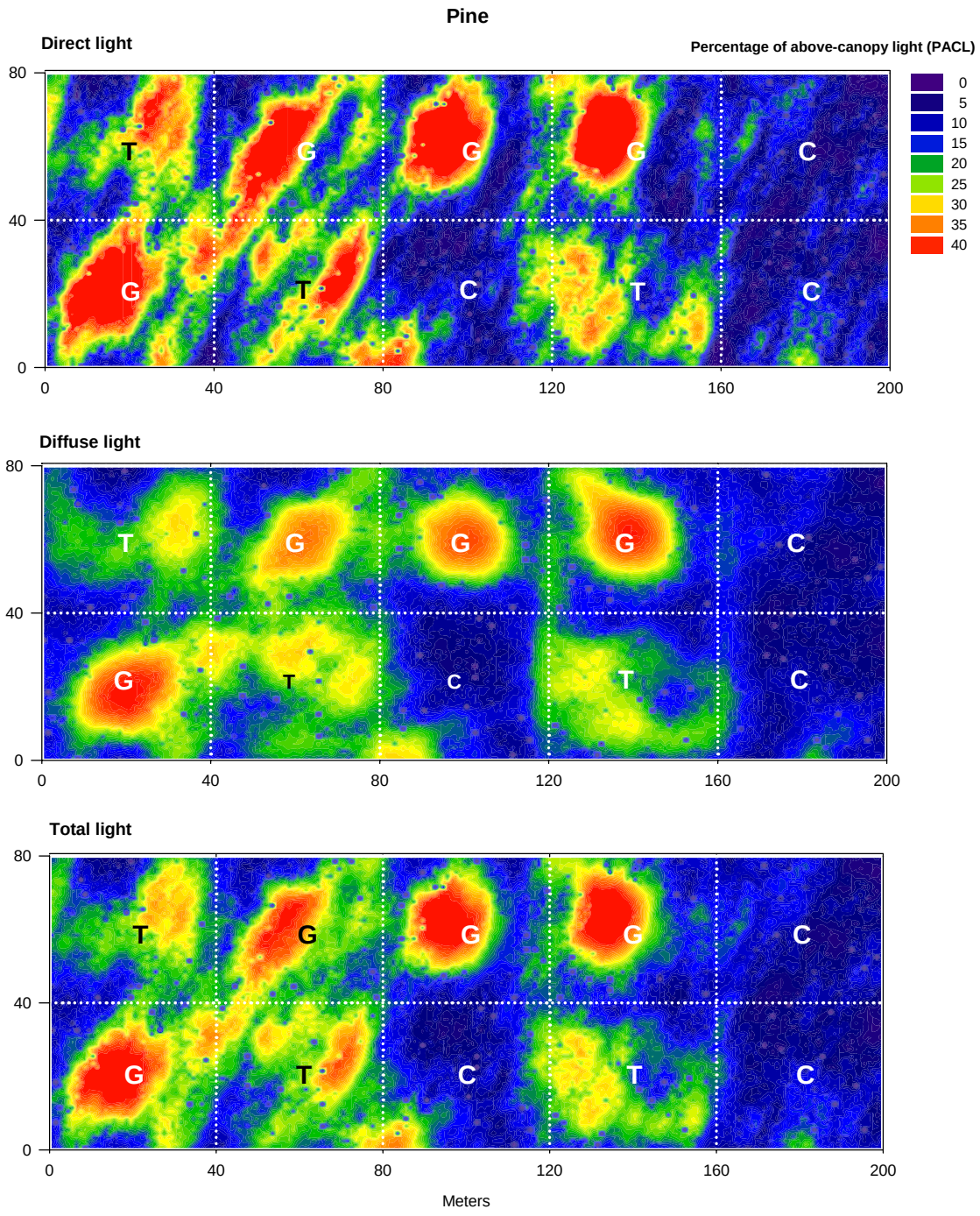

Fig. 3. Post-treatment light distribution map for the tree plot at Pine.

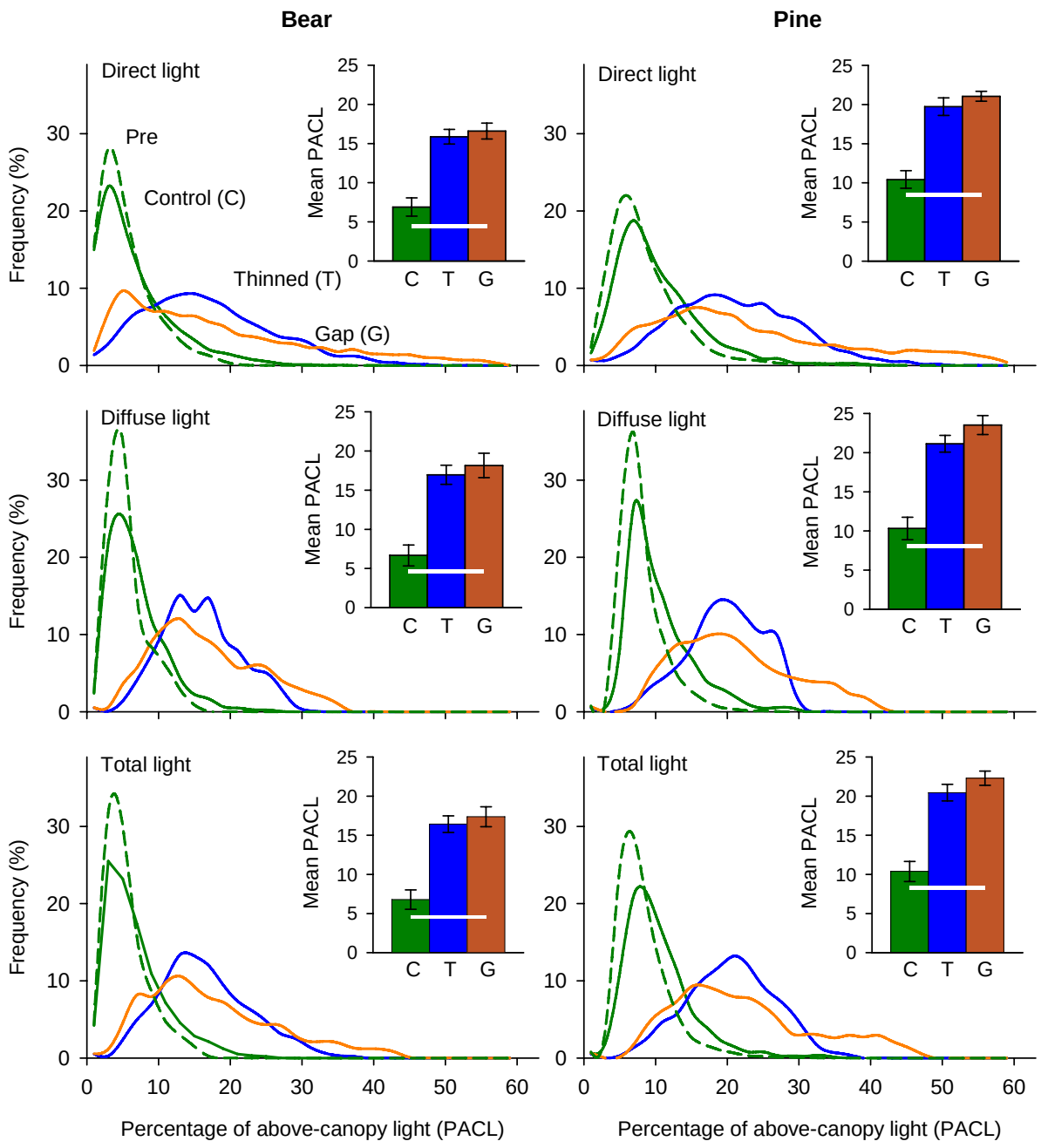

Fig. 4. Post-treatment frequency distributions of light among experimental treatments.

3.1.3. Ground-surface characteristics

Fig. 5. Changes in ground-surface characteristics and bryophyte cover among experimental treatments. Mean cover (±1 SE) of fine litter (<10 cm dbh), bare ground, fresh wood (decay classes I-II), decayed wood (decay classes III-V), logging slash, and bryophytes before (Pre) and after treatment (years 1 and 3). Logging slash was measured only in year 1. Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Each control or thinned EU was sampled with 60, 1 x 1 m quadrats. Each gap EU was sampled with 39 quadrats; quadrat values were weighted to obtain treatment means.

Results.— In general, thinning and gap creation resulted in minimal ground disturbance (<2% exposure of bare ground and no change in cover of decayed wood). Cover of bare ground tended to be greater in gap treatments at Bear and Pine, but in thinned treatments at Pine-N, although replicates showed considerable variation. Treatments resulted in small, but variable additions of fresh wood (increase in cover of <2%). Mean cover of logging slash did not exceed 30% and tended to be greater in gap than in thinned treatments (although the magnitude of this difference varied among sites).

Bryophytes showed consistent declines in cover in all treatments, including controls. Surprisingly, declines were greater in controls (44-53%) than in thinned (30-35%) or gap treatments (32-48%). The consistency of these changes within and among sites suggests an underlying temporal decline in bryophyte abundance, perhaps driven by climatic trends (warmer, drier weather at the time of sampling) that can affect bryophyte phenology or the timing of dormancy.

Fig. 6. Changes in ground-surface characteristics and bryophyte cover in gap and adjacent-forest environments. Mean cover (±1 SE) of fine litter, fresh and decayed wood, logging slash, and bryophytes before (Pre) and after treatment (years 1 and 3) in gaps (gap-gap) and adjacent forest (gap-forest). Gap-gap and gap-forest were sampled with 19 and 20 quadrats, respectively; quadrat values were weighted to obtain mean values for each environment. See **Fig. 5** for other details.

Results.— Patterns of ground disturbance within gap treatments were consistent with expectation. Although overall levels of disturbance were minimal, exposure of mineral soil was greater within the gap than in adjacent forest, except at Bear (where felling and yarding occurred on snow, resulting in virtually no soil disturbance). Cover of fresh wood was also greater within the gap than in adjacent forest. It increased over time in both environments reflecting occasional post-treatment tree fall. Cover of logging slash was similar between environments at Bear and Pine, but was twice as high in the adjacent forest than the gap at Pine-N (29 vs. 14.5%).

Bryophytes showed substantial (>50%) declines in both of the gap-treatment environments at Bear, but smaller changes at Pine and Pine-N where pre-treatment cover was lower. Similar trends were observed in the bryophyte study at Bear, both for mosses and liverworts (see section **3.3.2. Bryophyte abundance and diversity**).

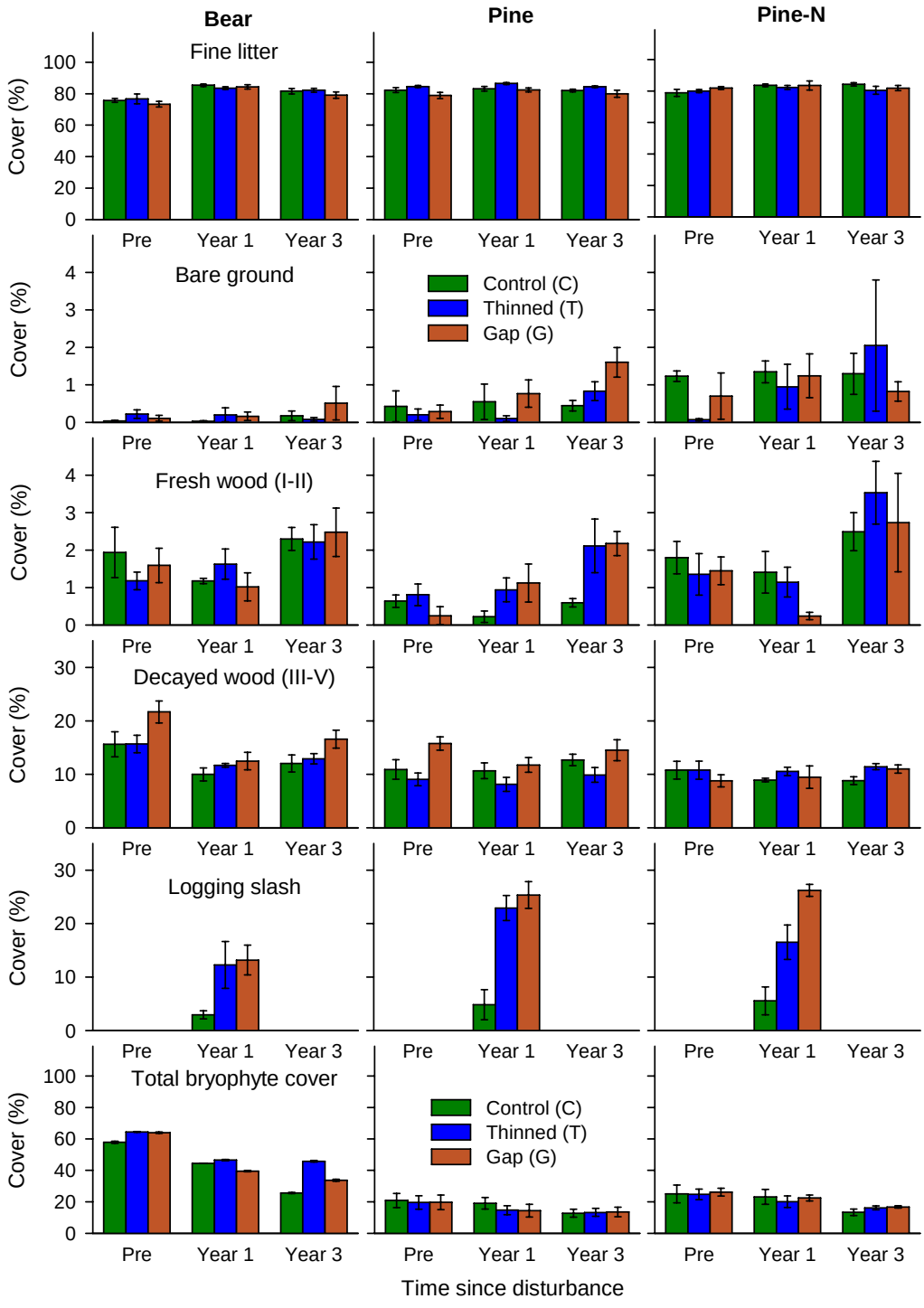

Fig. 5. Changes in ground-surface characteristics and bryophyte cover among experimental treatments.

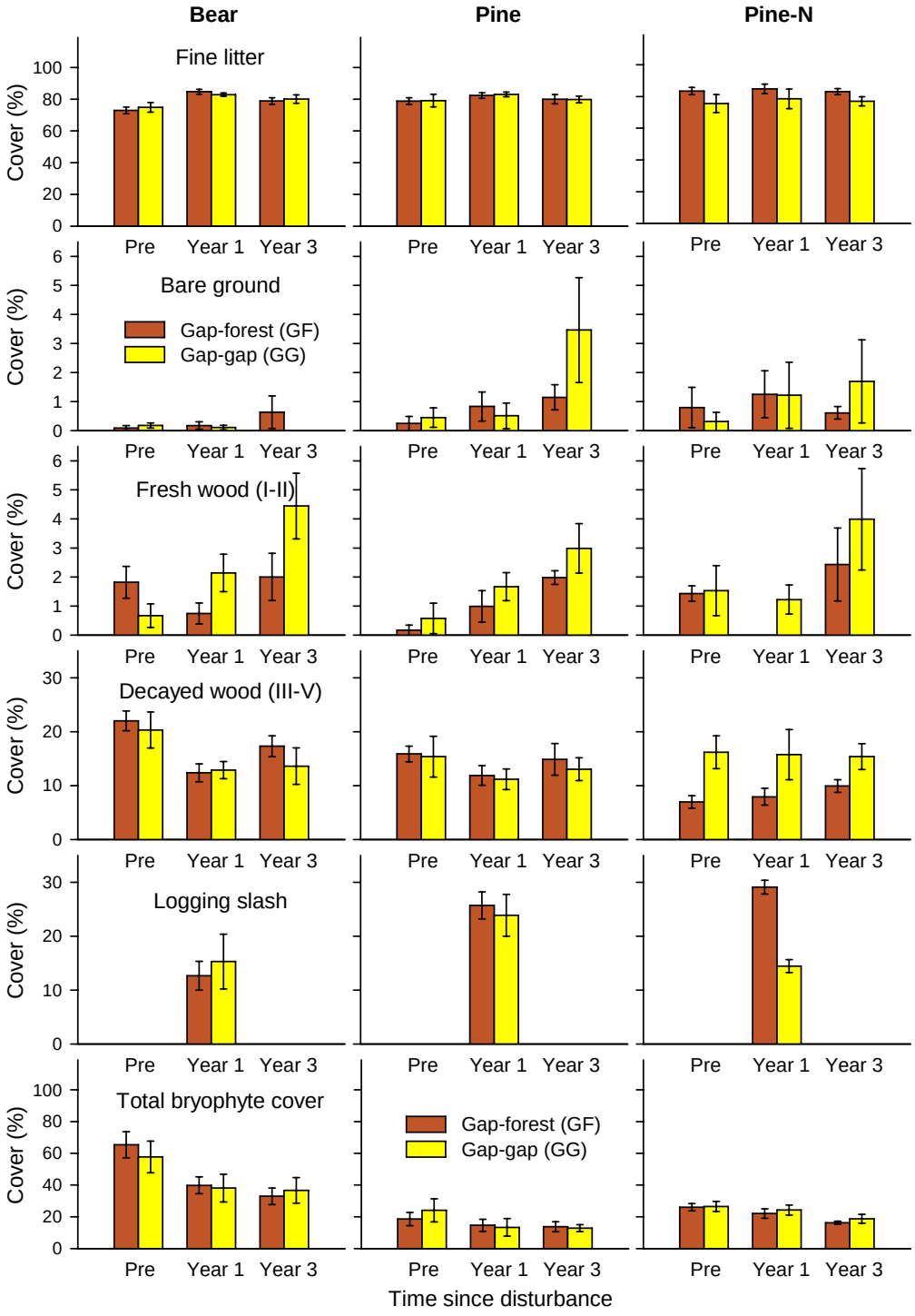

Fig. 6. Changes in ground-surface characteristics and bryophyte cover in gap and adjacent-forest environments.

3.1.3. **Ground-surface characteristics** (continued)

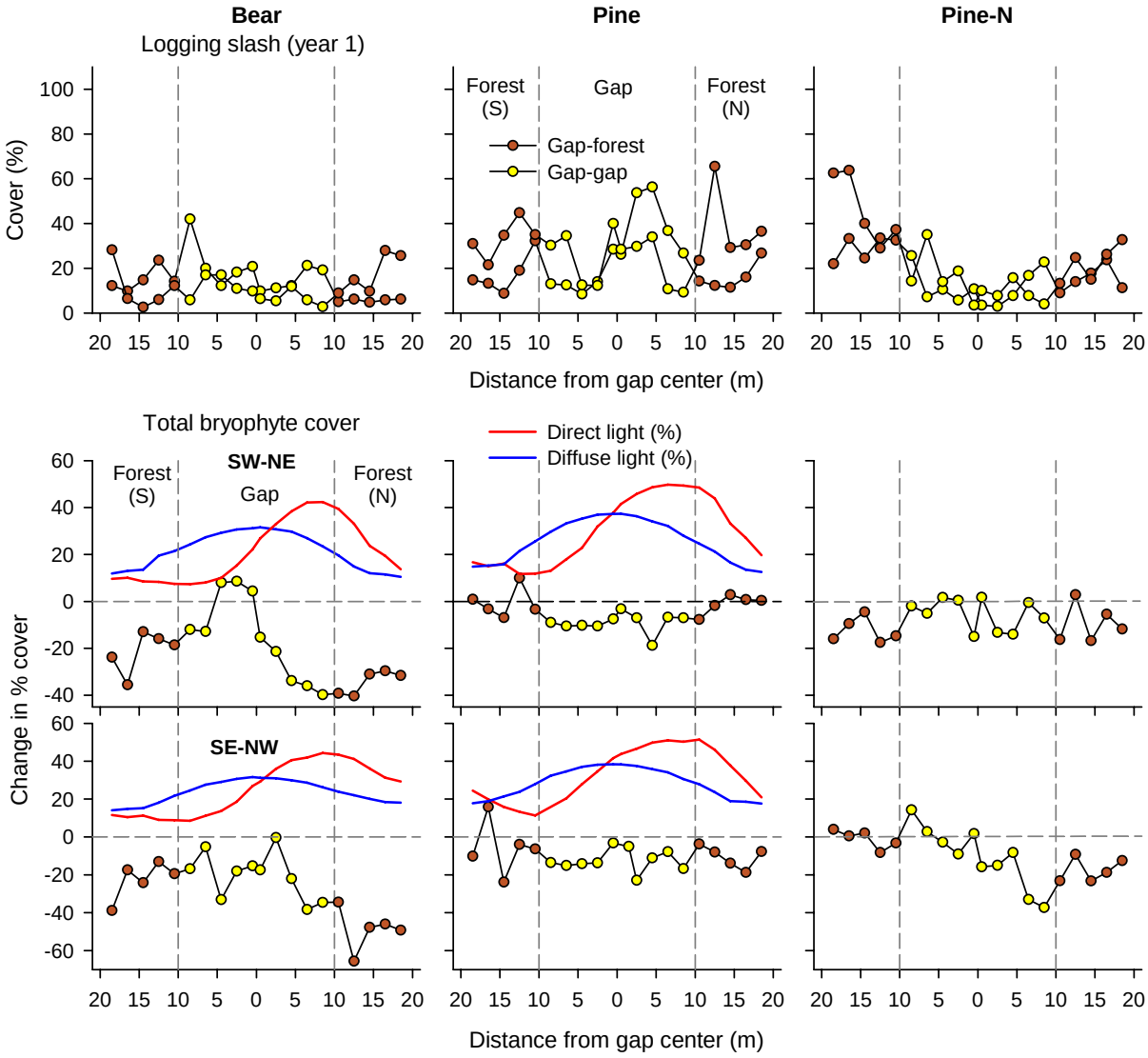

Fig. 7. Distribution of logging slash, light, and bryophyte cover across gap treatments. Transects run SW-NE and SE-NW through the center of each gap; gaps are 10 m in radius. Values represent the means of four (Pine, Pine-N) or five (Bear) transects per site. For cover of slash (measured in year 1), yellow symbols represent quadrats in the gap (gap-gap) and brown symbols represent quadrats in adjacent forest (gap-forest). Transects are plotted separately, but not labeled. For bryophytes, SW-NE and SE-NW transects are plotted in separate panels. Yellow and brown symbols represent the change in % cover (year 3 minus pre-treatment) in gap-gap and gap-forest, respectively. Direct and diffuse light (PACL, similar scaling as the cover axis) were modeled using tRAYci (see **Figs. 2 and 3**); curves represent the means of four (Pine) or five (Bear) transects. Light was not modeled at Pine-N.

Results.— Distributions of logging slash were highly uneven within and among replicates of the gap treatment (see **Plate 5**, next page). Slash cover was generally low at Bear, highly variable at Pine, and elevated in adjacent-forest at Pine-N. Declines in bryophyte cover were distinctly greater in the northern portions of gap treatments, except at Pine, where cover was generally low. Declines correlated with elevated levels of direct light (see **Plate 6**, next page).

Plate 5. Distribution of logging slash and fresh wood in a gap treatment.

Plate 6. Northern edge of a gap illustrating the decline in bryophyte cover under elevated levels of direct light**.**

3.1.4. Tree seedling density, richness, and composition

Fig. 8. Changes in tree seedling density and richness among experimental treatments. Mean density (±1 SE) and richness (number of species per quadrat) of tree seedlings before (Pre) and after treatment (years 1 and 3). "*Abies* species" is mostly *A. amabilis* and some *A. procera*. Uncommon species are not shown. Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Each control or thinned EU was sampled with 60, 1 x 1 m quadrats. Each gap EU was sampled with 39 quadrats; quadrat values were weighted to obtain treatment means. Note the variation among species in the scale of the Y axis.

Results.— Tree seedling density and richness varied among treatments, sites, and times. At all sites seedling populations were dominated by *Tsuga heterophylla*. Temporal variation among controls at all sites suggests substantial variation in annual seed production and early survival of *Tsuga.* Responses to treatments varied with time, but in year 3 seedling densities were consistently greater in thinned than in gap treatments.

Less common species showed varying responses to treatment and considerable variation among replicates within treatments. *Abies* declined in gap treatments at Bear, but increased in gap treatments at Pine. *Pseudotsuga menziesii* showed greater establishment in thinned than in gap or control treatments at all sites. *Thuja plicata* showed greater establishment in thinned treatments at Pine and in gap treatments at Pine-N. Finally, *Alnus rubra* showed transient (but highly variable) increases in thinned and gap treatments at Pine and Pine-N, but not at Bear where seed sources may be limiting. In combination, species establishment patterns resulted in large increases in richness in thinned and gap treatments at Pine and Pine-N, but not at Bear.

Fig. 9. Post-treatment composition of tree seedlings among experimental treatments. Variation in the relative abundance (density) of species among treatments and sites in year 3. White numbers represent total densities for each site x treatment combination. See **Fig. 8** for other details.

Results.— The composition of the tree seedling community varied significantly among sites and treatments in year 3. Although *Tsuga* dominated all sites and treatments, other species comprised >25% of the seedling community in gap treatments at Pine and Pine-N. *Alnus* was common at both sites and *Thuja* at Pine-N.

Fig. 10. Changes in tree seedling density and richness in gap and adjacent-forest environments. Mean density (±1 SE) and richness (number of species per quadrat) of tree seedlings before (Pre) and after treatment (years 1 and 3) in gaps (gap-gap) and adjacent forest (gap-forest). Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Gap-gap and gap-forest were sampled with 19 and 20 quadrats, respectively; quadrat values were weighted to obtain mean values for each environment. Note the variation among species in the scale of the Y axis. See **Fig. 8** for other details.

Results.— Total seedling densities were consistently greater in gap than in adjacent-forest environments. Trends were driven, in large part, by those of *Tsuga*. However, other species showed varying patterns within and among sites, and over time. *Abies* declined in both environments at Bear, but showed minimal change at Pine-N. *Pseudotsuga* showed comparable establishment in both environments at all sites, but establishment was limited to year 3. *Thuja* and *Alnus* showed greater establishment in gaps than in adjacent forest, although a large percentage of *Alnus* did not survive to year 3. In contrast, *Thuja* did not establish until year 3.

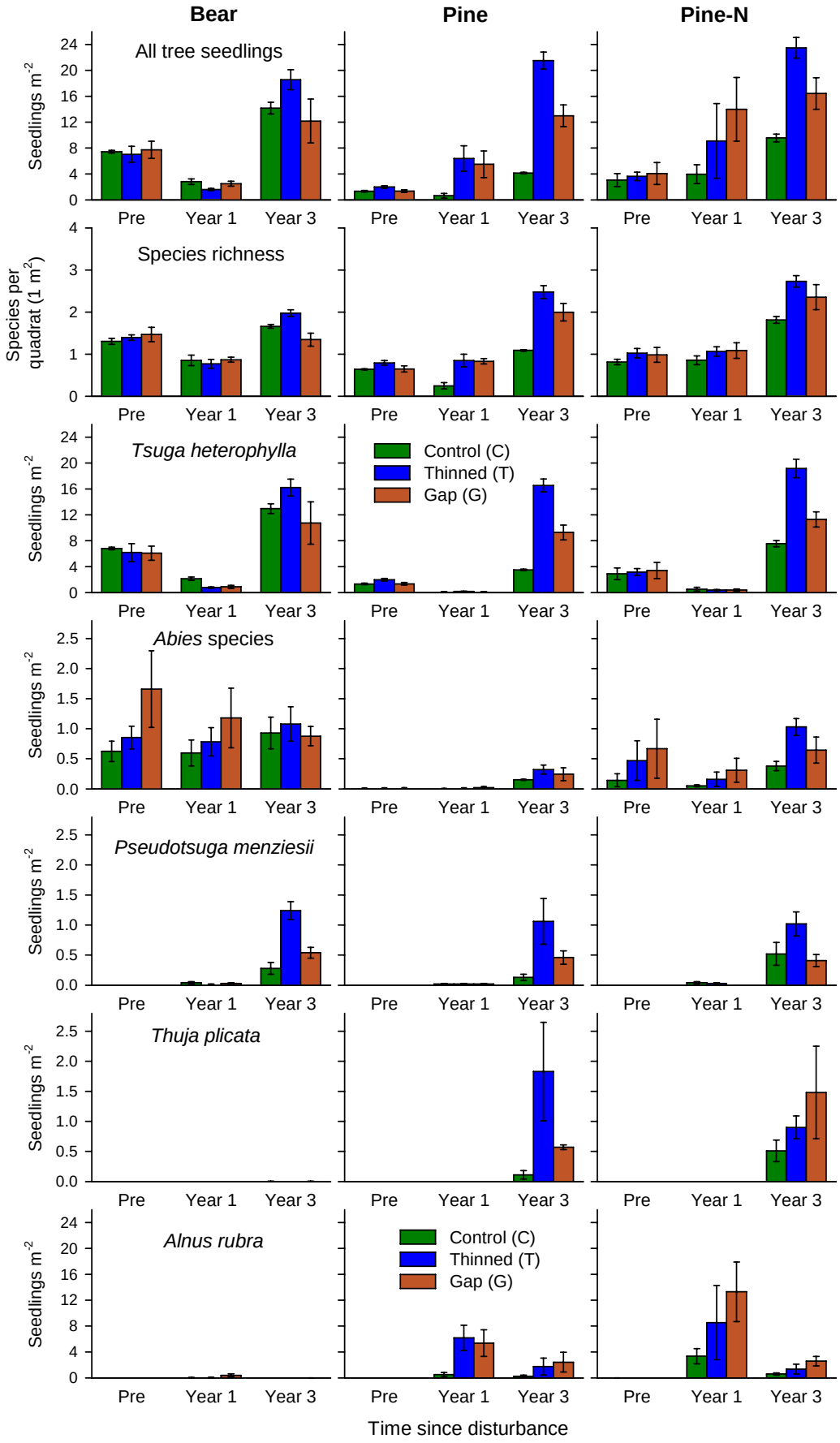

Fig. 8. Changes in tree seedling density and richness among experimental treatments.

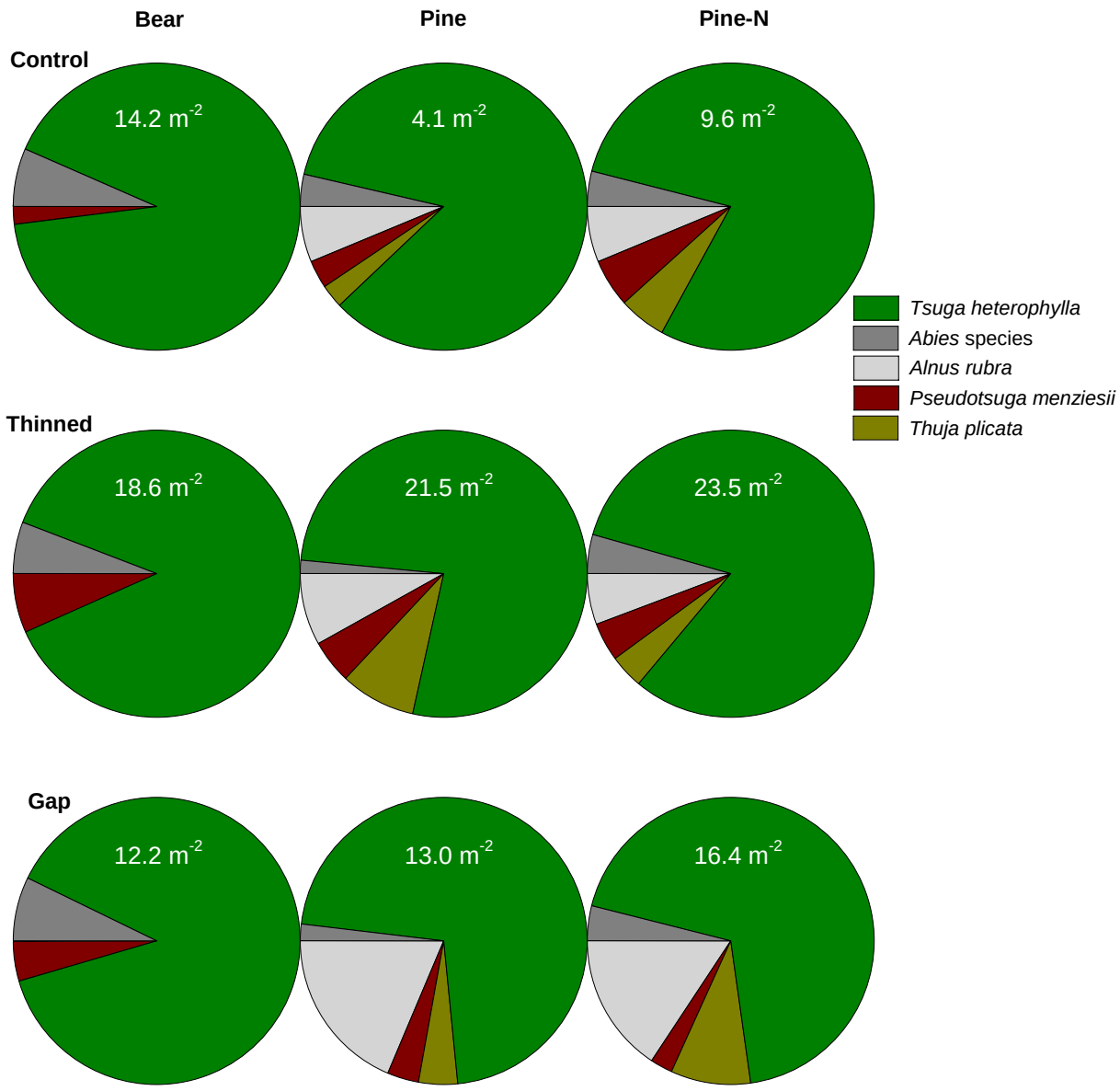

Fig. 9. Post-treatment composition of tree seedlings among experimental treatments.

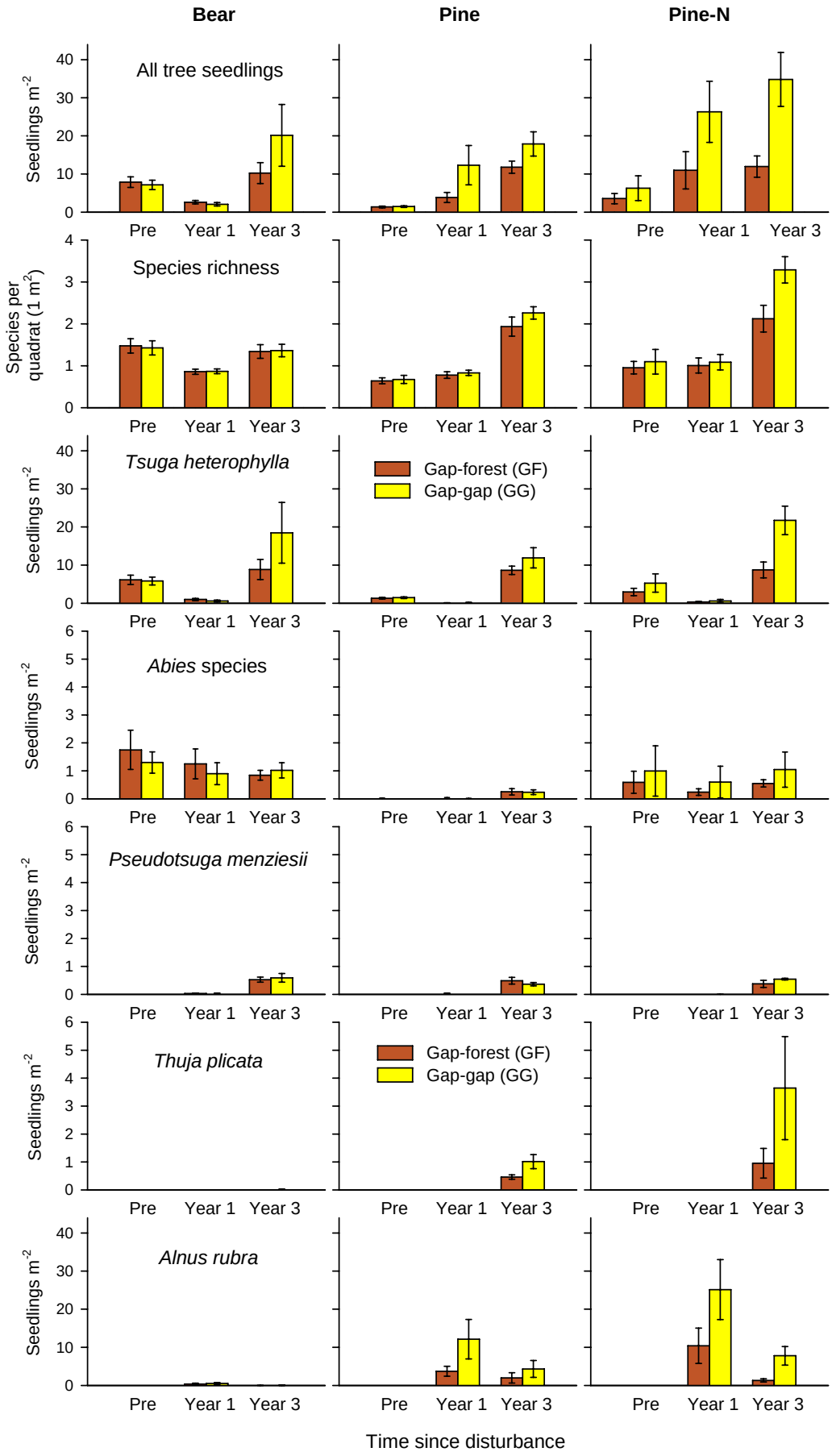

Fig. 10. Changes in tree seedling density and richness in gap and adjacent-forest environments.

3.1.4. Tree seedling density, richness, and composition (continued)

Fig. 11. Post-treatment distributions of tree seedling density and richness across gap treatments. Transects run SW-NE and SE-NW through the center of each gap; gaps are 10 m in radius. Values represent the means of four (Pine, Pine-N) or five (Bear) transects per site in year 3. Yellow symbols represent quadrats within the gap (gap-gap) and brown symbols represent quadrats in adjacent forest (gap-forest). Transects are plotted separately, but not labeled. Direct and diffuse light (PACL, similar scaling as the density axis) were modeled using tRAYci (see **Figs. 2 and 3**); curves represent the means of both transects from four (Pine) or five (Bear) replicates per site. Light was not modeled at Pine-N. See **Fig. 8** for other details.

Results.— Seedling distributions across gap treatments showed distinct patterns, but these differed among sites. At Bear and Pine, seedling density (>50 m^{-2}) and richness peaked at the southern edges of gaps and declined to the north. Trends were consistent among species at Bear, but less so at Pine. Regions of minimal seedling establishment near the northern edges of gaps coincided with elevated levels of direct light. In contrast, at Pine-N, seedling density and richness increased from forest edges to the centers of gaps, where peak densities exceeded >60 seedlings m^{-2}. This trend was displayed by shade-intolerant *Alnus*, as well as shade-tolerant *Thuja* and *Tsuga*.

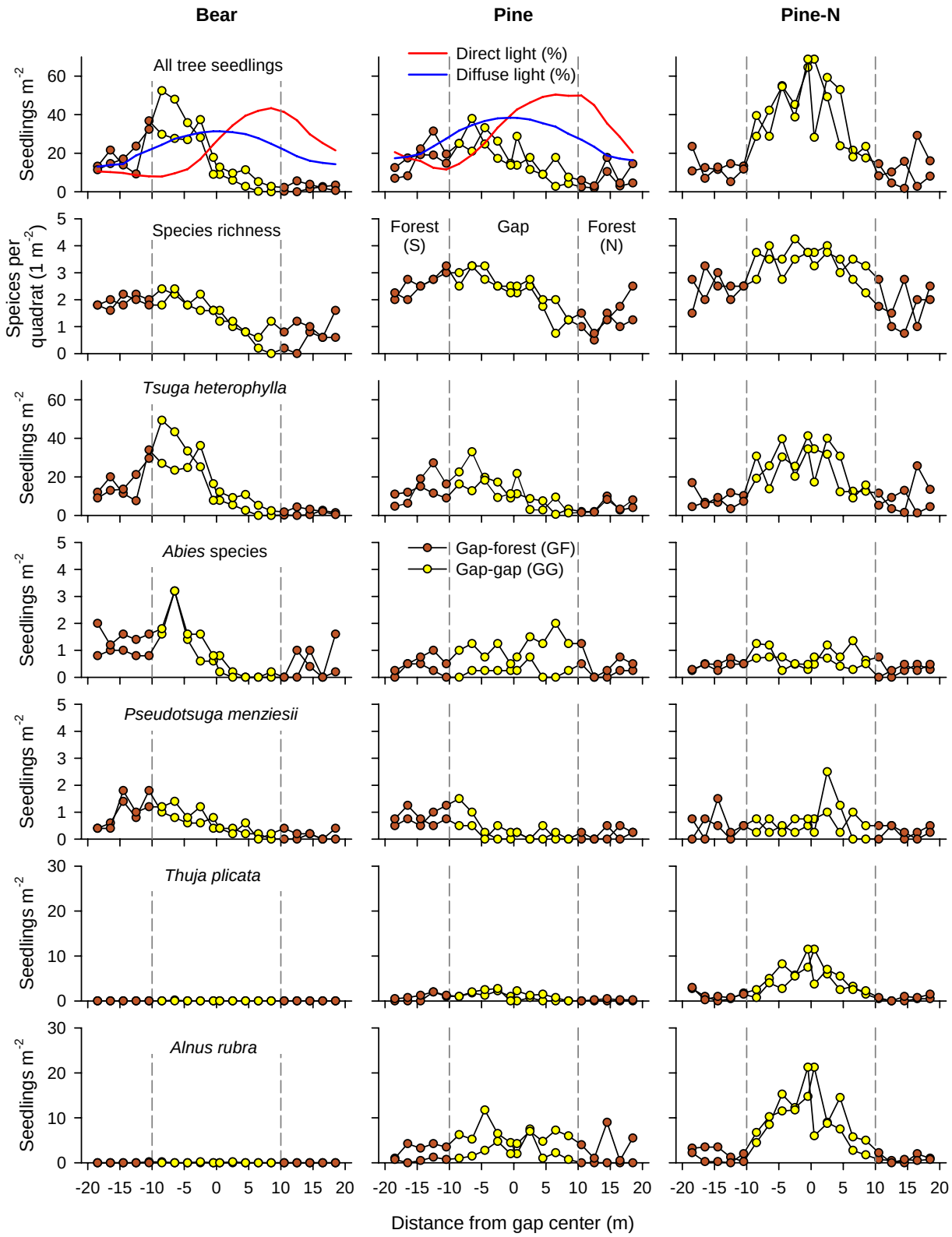

Fig. 11. Post-treatment distributions of tree seedling density and richness across gap treatments.

3.1.4. Tree seedling density, richness, and composition (continued)

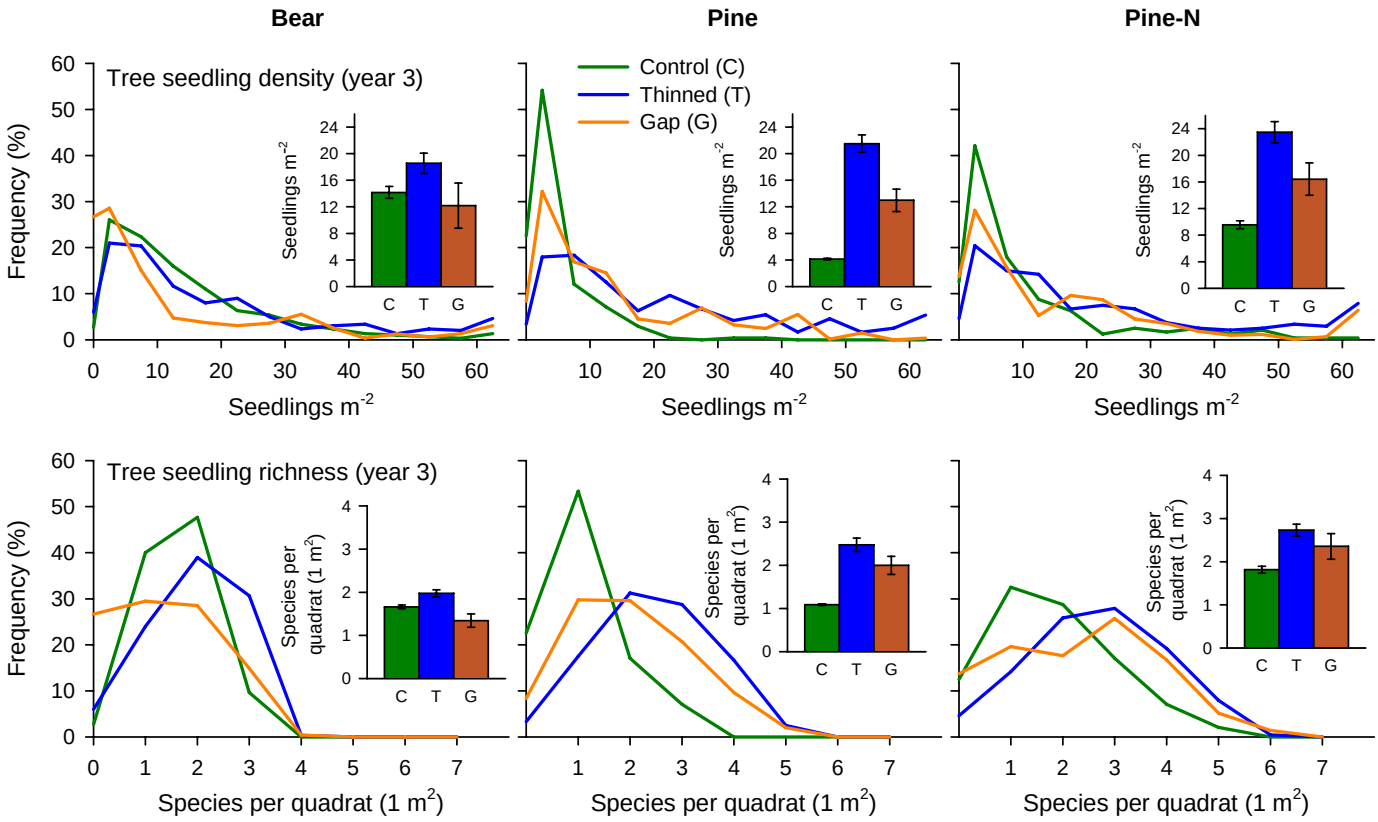

Fig. 12. Post-treatment frequency distributions of tree seedling density and richness among experimental treatments. Frequency distributions of tree seedling density and richness (number of species per quadrat) in year 3 at each site. Each line represents the mean of four (Pine, Pine-N) or five (Bear) replicates, each sampled with 60 (control and thinned) or 39 (gap treatment) quadrats. Values for gaps are weighted means of quadrats. Mean density and richness (±1 SE) for each treatment are shown for comparison (inset panels).

Results.— Changes in the frequency distributions of seedling density and richness were consistent with expectation, but not at all sites. At Pine and Pine-N, thinning and gap creation increased the proportion of quadrats with moderate or relatively high levels of seedling density or richness. Frequency distributions were similar between the thinned and gap treatments. At Bear, however, seedling establishment was not enhanced by gap creation and only minimally by thinning.

3.1.5. Vascular plant species abundance and diversity

Table 4. Classification of vascular plant species. All species (but not understory trees) were classified by growth form (H= herb, SS= sub-shrub, S= shrub), seral status (F= forest understory, R = ruderal), and degree of clonality (C = strong potential for clonal growth, L/NC = limited potential for clonal growth or non-clonal). U = unclassified. Asterisks denote exotic species.

Species	Database code	Growth form	Seral status	Degree of clonality
Herbs (includes grasses, sedges, and ferns)				
Achlys triphylla	ACTR	H	F	C
Actaea rubra	ACRU	H	F	L/NC
Adenocaulon bicolor	ADBI	H	F	L/NC
Agrostis scabra	AGSC	H	R	C
Anaphalis margaritacea	ANMA	H	R	L/NC
Aruncus sylvester	ARSY	H	F	L/NC
Asarum caudatum	ASCA3	H	F	C
Athyrium filix-femina	ATFI	H	F	L/NC
Blechnum spicant	BLSP	H	F	L/NC
Carex deweyana	CADE	H	U	L/NC
Carex mertensii	CAME2	H	U	L/NC
Carex species	CAREX	H	U	L/NC
*Chrysanthemum leucanthemum**	CHLE2	H	R	L/NC
Circaea alpina	CIAL	H	F	C
Cirsium brevistylum	CIBR2	H	R	L/NC
Clintonia uniflora	CLUN	H	F	C
Corallorhiza mertensiana	COME	H	F	L/NC
Deschampsia elongata	DEEL	H	R	L/NC
Dicentra formosa	DIFO	H	F	L/NC
Digitalis purpurea	DIPU	H	R	L/NC
Disporum species	DISPO	H	F	L/NC
Dryopteris austriaca	DRAU2	H	F	L/NC
Epilobium angustifolium	EPAN	H	R	C
Epilobium species	EPILO	H	R	L/NC
Epilobium watsonii	EPWA	H	R	L/NC
Equisetum species	EQUIS	H	R	C
Galium triflorum	GATR	H	F	C
Goodyera oblongifolia	GOOB	H	F	L/NC
Gramineae (unknown taxon)	GRAMIN	H	U	U
Gymnocarpium dryopteris	GYDR	H	F	C
Habenaria orbiculata	HAOR	H	F	L/NC
Hieracium albiflorum	HIAL	H	F	L/NC
Hypopitys monotropa	HYMO	H	F	L/NC
*Lactuca muralis**	LAMU	H	R	L/NC
Liliaceae (unknown taxon)	LILIAC	H	F	U
Listera caurina	LICA3	H	F	L/NC

Table 4. Continued.

Species	Database code	Growth form	Seral status	Degree of clonality
Listera cordata	LICO3	H	F	L/NC
Luzula campestris	LUCA2	H	R	L/NC
Luzula parviflora	LUPA	H	F	L/NC
Luzula species	LUZUL	H	U	L/NC
Lycopodium clavatum	LYCL	H	F	C
Maianthemum dilatatum	MADI2	H	F	C
Osmorhiza chilensis	OSCH	H	F	L/NC
*Plantago major**	PLMA	H	R	L/NC
Polypodiaceae (unknown fern)	POLYPO	H	F	U
Polypodium glycyrrhiza	POGL4	H	F	L/NC
Polystichum munitum	POMU	H	F	L/NC
*Prunella vulgaris**	PRVU	H	R	L/NC
Pteridium aquilinum	PTAQ	H	U	C
Pyrola chlorantha	PYCH	H	F	L/NC
Pyrola secunda	PYSE	H	F	C
Pyrola species	PYROL	H	F	U
Pyrola uniflora	PYUN	H	F	L/NC
Satureja douglasii	SADO	H	F	C
*Senecio sylvaticus**	SESY	H	R	L/NC
Smilacina stellata	SMST	H	F	C
Stellaria crispa	STCR	H	R	L/NC
Streptopus amplexifolius	STAM	H	F	L/NC
Streptopus species	STREP	H	F	L/NC
*Taraxacum officinale**	TAOF	H	R	L/NC
Tiarella trifoliata	TITR	H	F	L/NC
Trautvetteria caroliniensis	TRCA3	H	F	L/NC
Trientalis latifolia	TRLA2	H	F	C
Trillium ovatum	TROV	H	F	L/NC
*Veronica officinalis**	VEOF	H	R	L/NC
Viola glabella	VIGL	H	F	L/NC
Viola sempervirens	VISE	H	F	L/NC
Sub-shrubs				
Chimaphlia menziesii	CHME	SS	F	L/NC
Cornus canadensis	COCA	SS	F	C
Linnaea borealis	LIBO2	SS	F	C
Rubus lasiococcus	RULA	SS	F	C
Rubus pedatus	RUPE	SS	F	C
Rubus ursinus	RUUR	SS	F	C
Shrubs				
Acer circinatum	ACCI	S	F	L/NC
Berberis nervosa	BENE	S	F	C
Gaultheria shallon	GASH	S	F	C

Table 4. Continued.

Species	Database code	Growth form	Seral status	Degree of clonality
Holodiscus discolor	HODI	S	F	L/NC
Menziesia ferruginea	MEFE	S	F	L/NC
Oplopanax horridum	OPHO	S	F	C
Ribes species	RIBES	S	R	NC
Rosa gymnocarpa	ROGY	S	F	C
Rubus leucodermis	RULE	S	R	L/NC
Rubus parviflorus	RUPA	S	U	C
Rubus spectabilis	RUSP	S	U	C
Sambucus racemosa	SARA	S	R	L/NC
Vaccinium parvifolium	VAPA	S	F	L/NC

3.1.5. Vascular plant species abundance and diversity (continued)

Fig. 13. Changes in cover of vascular plant species among experimental treatments. Mean total cover (±1 SE) before (Pre) and after treatment (years 1 and 3) and cover of plant species grouped by growth form (herb, shrub, or sub-shrub), seral status (forest understory vs. ruderal), and degree of clonality (clonal = strong potential for clonal growth vs. non-clonal = limited or no potential for clonal growth). Some species remained unclassified for particular traits (see **Table 4** for species classification). Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Each control or thinned EU was sampled with 60 quadrats. Each gap EU was sampled with 39 quadrats; quadrat values were weighted to obtain treatment means. *Pteridium aquilinum* (bracken) was common, but not classified as a forest understory or ruderal species.

Results.— Increases in plant cover in response to treatments varied among sites, but were not evident until year 3. Increases were small at Bear, but considerably larger at Pine and Pine-N (despite lower initial cover). The mean increase appeared greater in gap than in thinned treatments, but only at Pine and Pine-N. However, variation among gap replicates was also large (particularly at Pine-N). We explore a strong correlate of this variation in **Fig. 14**.

Trends in total plant cover were driven by herbaceous forest understory species. Ruderal species showed limited development (except in gaps at Pine-N, see **Fig. 15**). Ruderals were primarily perennial, native species (data not shown). A total of 8 exotic species was observed (Table 4), but other than *Digitalis purpurea* and *Lactuca muralis*, which were abundant in gaps at Pine-N, frequencies of exotics remained low. Contrary to expectation, clonal species did not show greater increases in cover than non-clonal species.

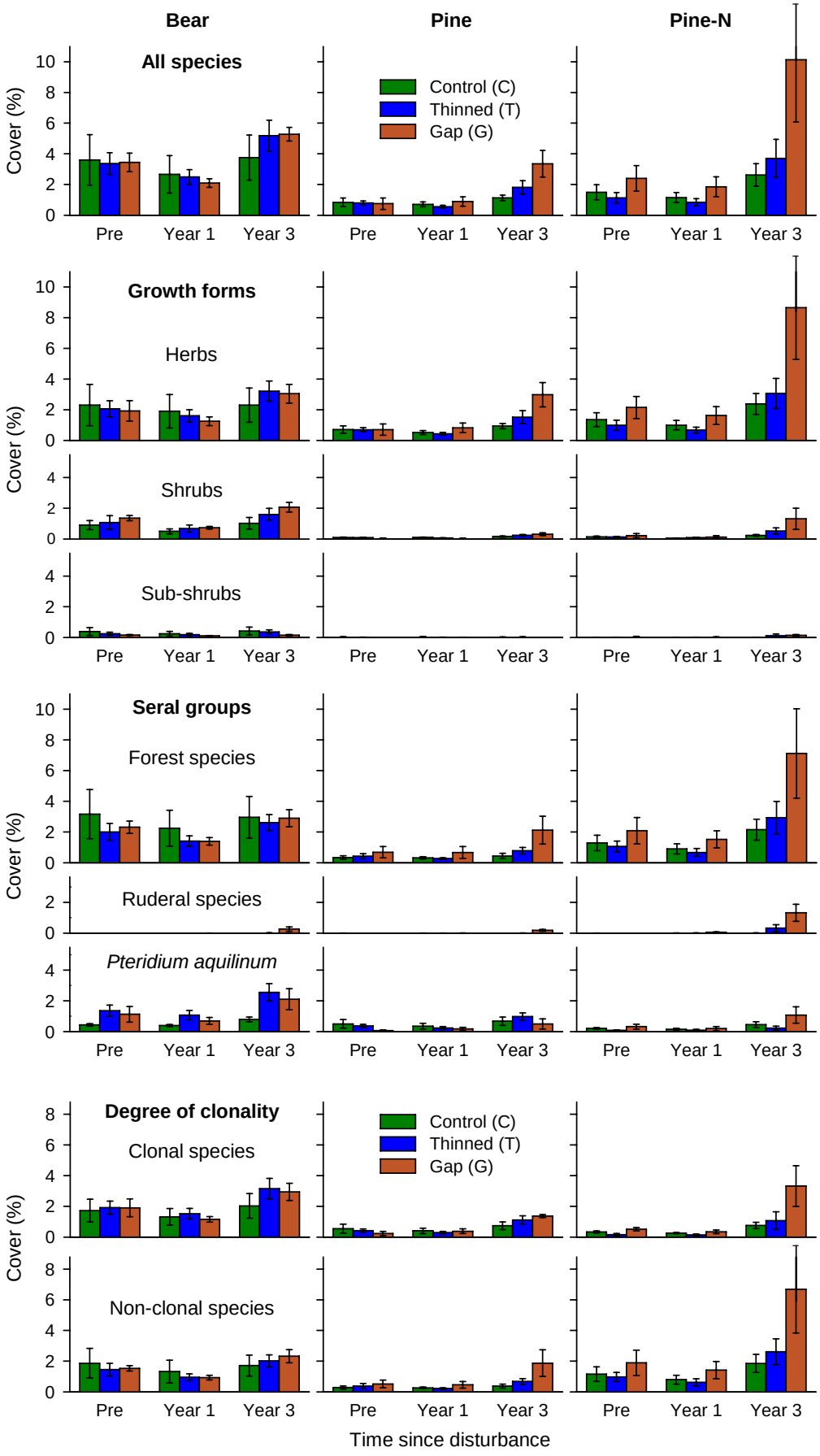

Fig. 13. Changes in cover of vascular plant species among experimental treatments.

3.1.5. Vascular plant species abundance and diversity (continued)

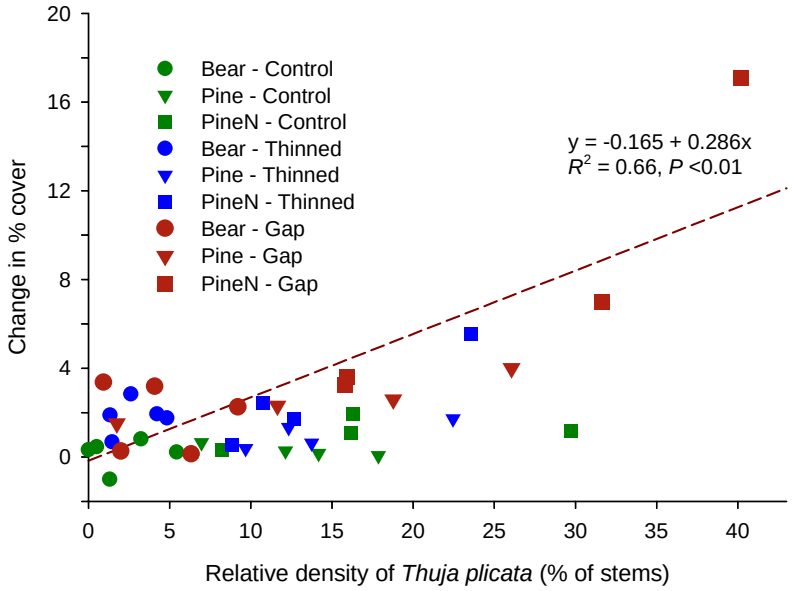

Fig. 14. Relationship between change in vascular plant cover and relative density of *Thuja plicata*. Points represent the differences between year 3 and pre-treatment values of individual EUs. EU values are the means of 60 quadrats for control and thinned treatments and 39 quadrats (weighted) for gap treatments. Relative density of *Thuja* is based on the total of number of trees (≥1.4 m tall) before treatment. The relationship was tested for all treatments, but significant only for the gap treatment (dashed line). Note the low densities of *Thuja* at Bear.

Results.— In the gap treatment, increases in total vascular plant cover were positively correlated with the relative density of *Thuja plicata* (an indicator of moister, more productive sites). However, a similar relationship was not observed in the thinned treatment. This suggests that at higher *Thuja* density, responses to gap creation were stronger than in thinned treatments. Unfortunately, thinned treatments did not have as broad a range of *Thuja* densities as did gap treatments, limiting our ability to generalize from this result.

3.1.5. Vascular plant species abundance and diversity (continued)

Fig. 15. Changes in cover of vascular plant species in gap and adjacent-forest environments. Mean total cover (±1 SE) before (Pre) and after treatment (years 1 and 3) in gaps (gap-gap) and adjacent forest (gap-forest), and cover of plant species grouped by growth form, seral status, and degree of clonality (see **Fig. 13** for details). Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Gap-gap and gap-forest were sampled with 19 and 20 quadrats, respectively; quadrat values were weighted to obtain mean values for each environment.

Results.— As expected, increases in cover in gap treatments were driven by establishment and growth within the gaps (**Plate 7**). However, gap creation also resulted in enhanced cover in the adjacent forest. Increases in both environments were primarily due to herbaceous forest understory species. Ruderal species contributed significantly to cover within the gaps at all sites, but particularly at Pine-N. Counter to expectation, *Pteridium aquilinum* did not respond more strongly in gap than in adjacent-forest environments.

Plate 7. Understory response within a gap (year 3). The dominant species is the ruderal clonal herb, *Epilobium angustifolium*. *Sambucus racemosa* is also present (small erect shrub in the lower right).

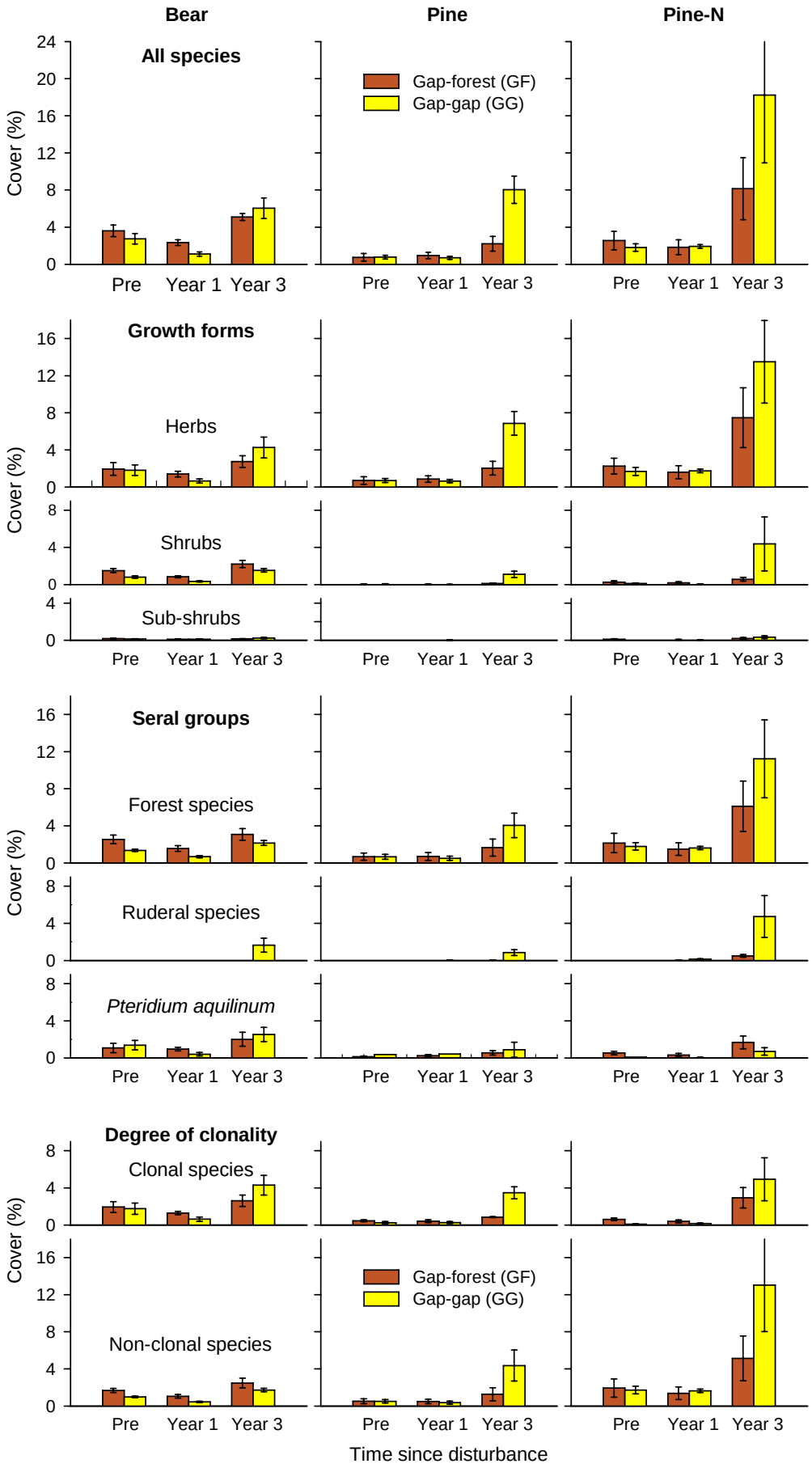

Fig. 15. Changes in cover of vascular plant species in gap and adjacent-forest environments.

3.1.5. Vascular plant species abundance and diversity (continued)

Fig. 16. Distribution of cover of vascular plant species across gap treatments. Transects run SW-NE and SE-NW through the center of each gap; gaps are 10 m in radius. Values for each plant group represent the means of four (Pine, Pine-N) or five (Bear) transects per site. Yellow symbols represent quadrats within the gap (gap-gap) and brown symbols represent quadrats in adjacent forest (gap-forest). Green lines represent pre-treatment values. Transects are plotted separately, but not labeled. Direct and diffuse light (PACL, similar scaling as the cover axis) were modeled using tRAYci (see **Figs. 2 and 3**); curves represent the means of both transects from four (Pine) or five (Bear) replicates per site. Light was not modeled at Pine-N.

Results.— Patterns of increase in plant cover across gap treatments were highly variable within and among sites. Increases were more common within gaps, but were uneven from quadrat to quadrat. Areas of greatest increase generally correlated with increases in diffuse light. Ruderal species, which were largely restricted to gap openings, showed greatest development toward the centers of gaps. Both clonal and non-clonal species showed potential for increase both within gaps and in adjacent forest, particularly where they were present prior to treatment, suggesting growth of surviving plants.

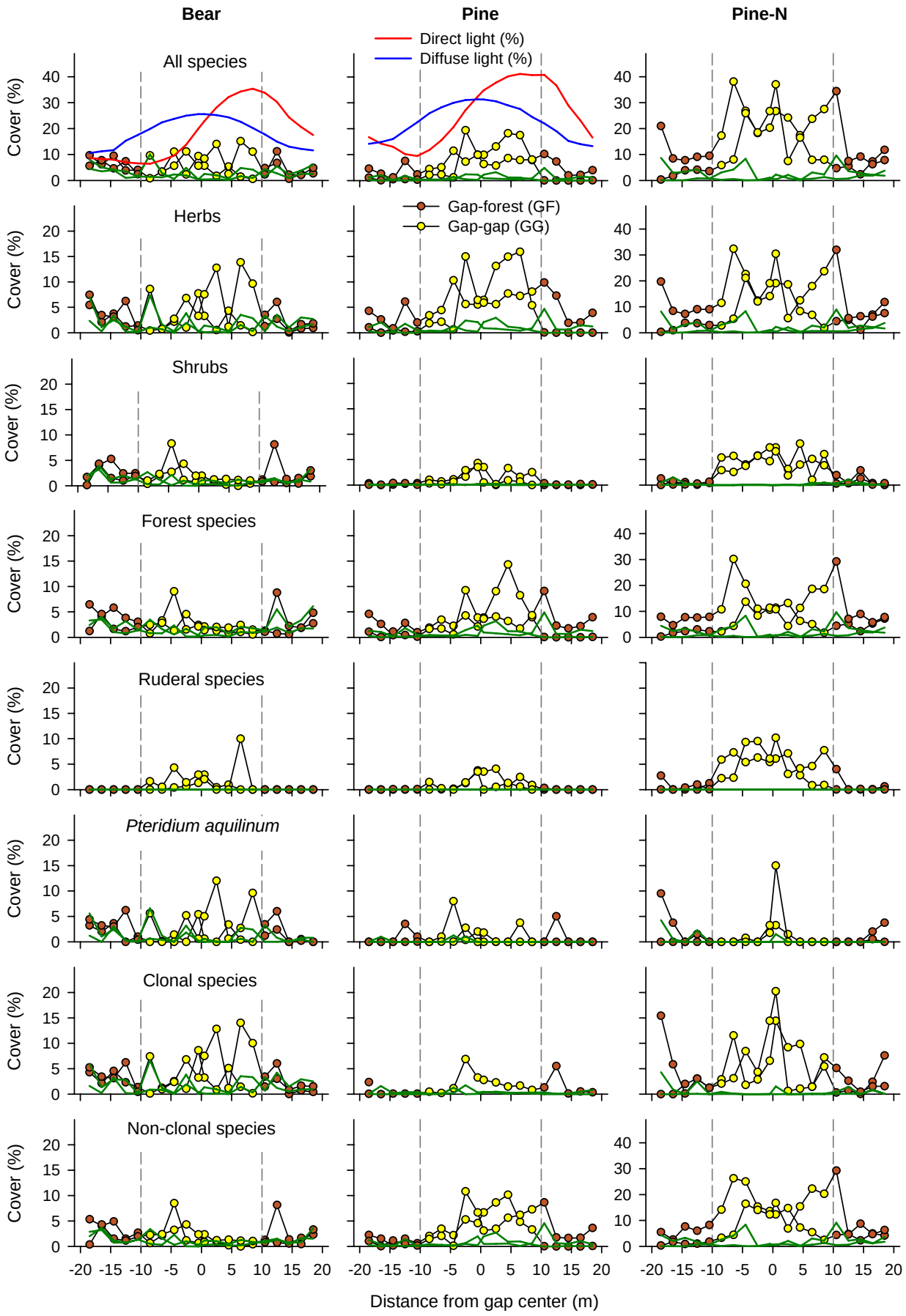

Fig. 16. Distribution of cover of vascular plant species across gap treatments.

3.1.5. Vascular plant species abundance and diversity (continued)

Fig. 17. Changes in richness of vascular plant species among experimental treatments. Mean total richness (±1 SE) before (Pre) and after treatment (years 1 and 3) and richness of plant species grouped by growth form (herb, shrub, or sub-shrub), seral status (forest understory vs. ruderal), and degree of clonality (clonal = strong potential for clonal growth vs. non-clonal = limited or no potential for clonal growth). Some species remained unclassified for particular traits (see **Table 4** for species classification). Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Each control or thinned EU was sampled with 60 quadrats. Each gap EU was sampled with 39 quadrats; quadrat values were weighted to obtain treatment means.

Results.— Vascular plant richness increased in response to treatments at Pine and Pine-N, but not at Bear. Effects appeared larger in gap than in thinned treatments, particularly at Pine-N. However, regression analyses (see **Fig. 18**) indicate that these differences may reflect confounding by other sources of variation within sites.

Increases in richness were dominated by herbaceous species (although shrub richness also increased at Pine-N). These included additions of both forest-understory and ruderal taxa, as well as species with clonal and non-clonal growth habits.

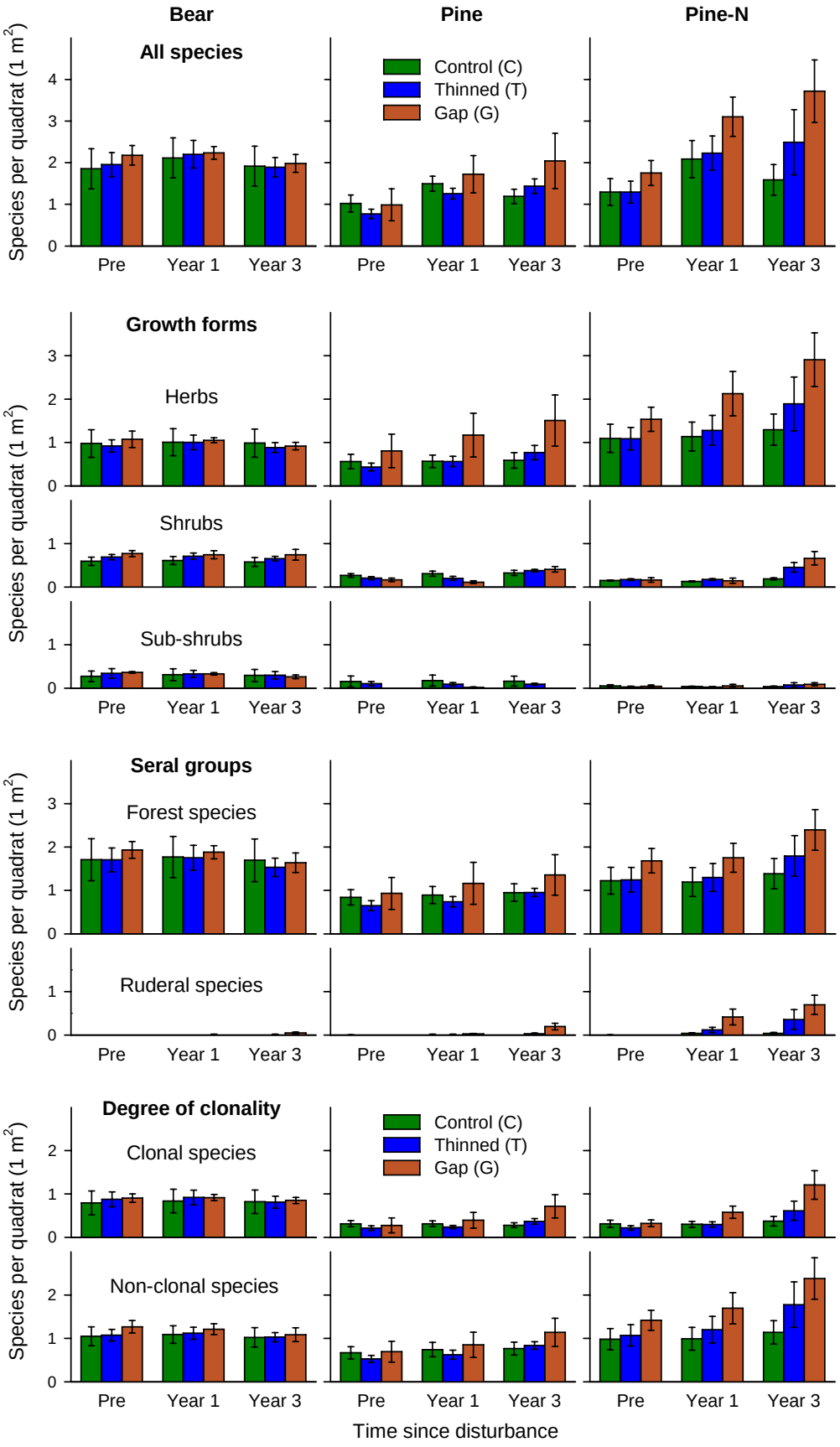

Fig. 17. Changes in richness of vascular plant species among experimental treatments.

3.1.5. **Vascular plant species abundance and diversity** (continued)

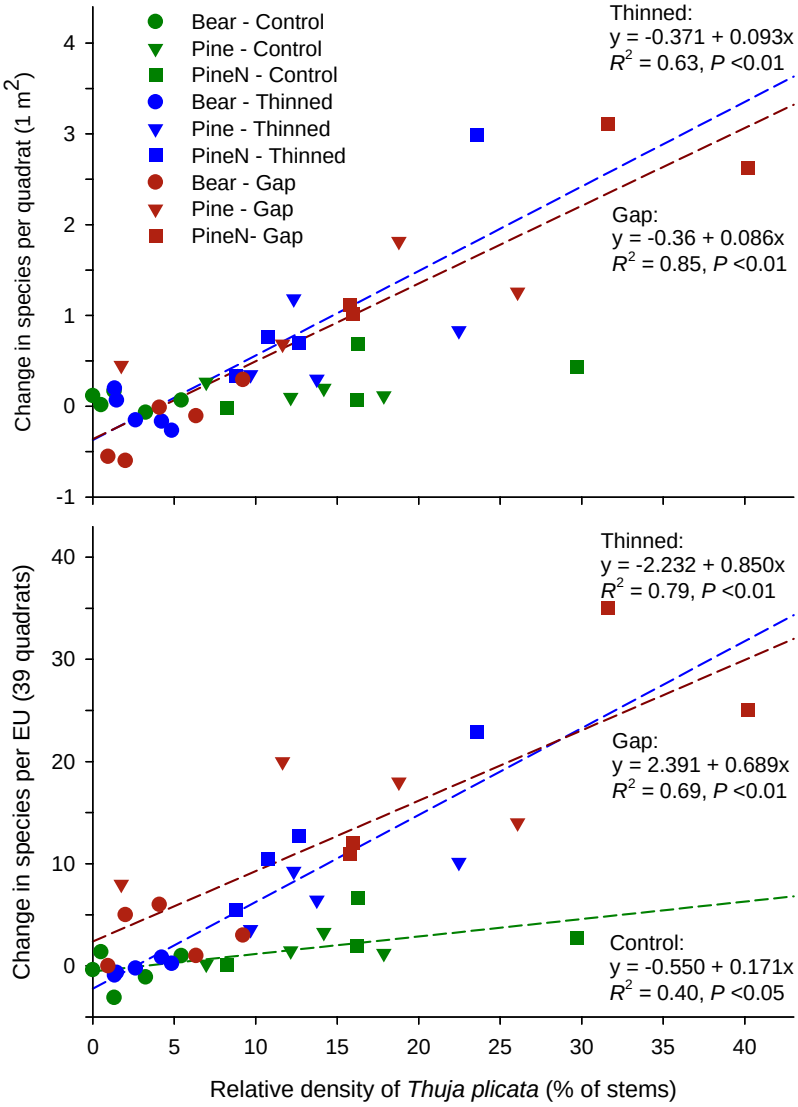

Fig. 18. Relationships between changes in vascular plant species richness and relative density of *Thuja plicata*. Points represent the differences between year 3 and pre-treatment values of individual EUs. Quadrat-scale richness values (top panel) represent the means of 60 quadrats for control and thinned treatments and 39 quadrats (weighted) for gap treatments. Richness values for experimental units (bottom panel) represent the cumulative number of species found in 39 quadrats (maximum number of quadrats sampled in gap treatments). Corresponding values for control and thinned treatments (sampled with 60 quadrats) derive from species-area estimates (see **Fig. 22**). Relative density of *Thuja* is based on the total of number of trees (≥1.4 m tall) before treatment. Regression lines are shown for treatments in which the relationship was significant. Note the low densities of *Thuja* at Bear.

Results.— In both thinned and gap treatments, increases in richness at both local (quadrat) and larger (EU) spatial scales were highly correlated with relative density of *Thuja plicata* (an indicator of moister, more productive sites). However, the slopes of the relationships did not differ between treatments. At a given density of *Thuja*, richness responses to thinning and gap creation were similar; contrast this with mean values in **Fig. 17**, in which increases in cover appear greater for gap treatments.

3.1.5. Vascular plant species abundance and diversity (continued)

Fig. 19. Changes in richness of vascular plant species in gap and adjacent-forest environments. Mean total richness (±1 SE) before (Pre) and after treatment (years 1 and 3) in gaps (gap-gap) and adjacent forest (gap-forest), and richness of plant species grouped by growth form, seral status, and degree of clonality (see **Fig. 13** for details). Each bar represents the mean of four (Pine, Pine-N) or five (Bear) replicates. Gap-gap and gap-forest were sampled with 19 and 20 quadrats, respectively; quadrat values were weighted to obtain mean values for each environment. See **Fig. 17** for other details.

Results.— As expected, increases in species richness in gap treatments were driven by establishment within the gaps. Richness either did not increase in adjacent forest (Bear) or only minimally (Pine and Pine-N). Increases within gaps were attributed primarily to herbaceous species (both forest understory and ruderal) and secondarily to shrubs. At Pine-N, the emergence of ruderal species in gaps contributed more to increases in richness than did establishment or spread of forest understory species. Increases were greater among non-clonal than clonal species, suggesting a process driven by plant establishment rather than vegetative spread.

Fig. 20. Distribution of vascular plant species richness across gap treatments. Transects run SW-NE and SE to NW through the center of each gap; gaps are 10 m in radius. Values for each plant group represent the means of four (Pine, Pine-N) or five (Bear) transects. Yellow symbols represent quadrats within the gap (gap-gap) and brown symbols represent quadrats in adjacent forest (gap-forest). Green lines represent pre-treatment values. Transects are plotted separately, but not labeled. Direct and diffuse light (PACL) were modeled using tRAYci (see **Figs. 2 and 3**); curves represent the means of both transects from four (Pine) or five (Bear) replicates. For scale, the maximum for direct light is ~51%. Light was not modeled at Pine-N.

Results.— Changes in species richness across gap treatments were similar among sites, although increases were muted at Bear. Richness peaked toward the centers of gaps, although some plant groups showed comparable richness at the northern edges of gaps (shrubs, forest species, and non-clonal species at Pine-N). Increases in richness were minimal in adjacent forest suggesting limited establishment of new species in these environments.

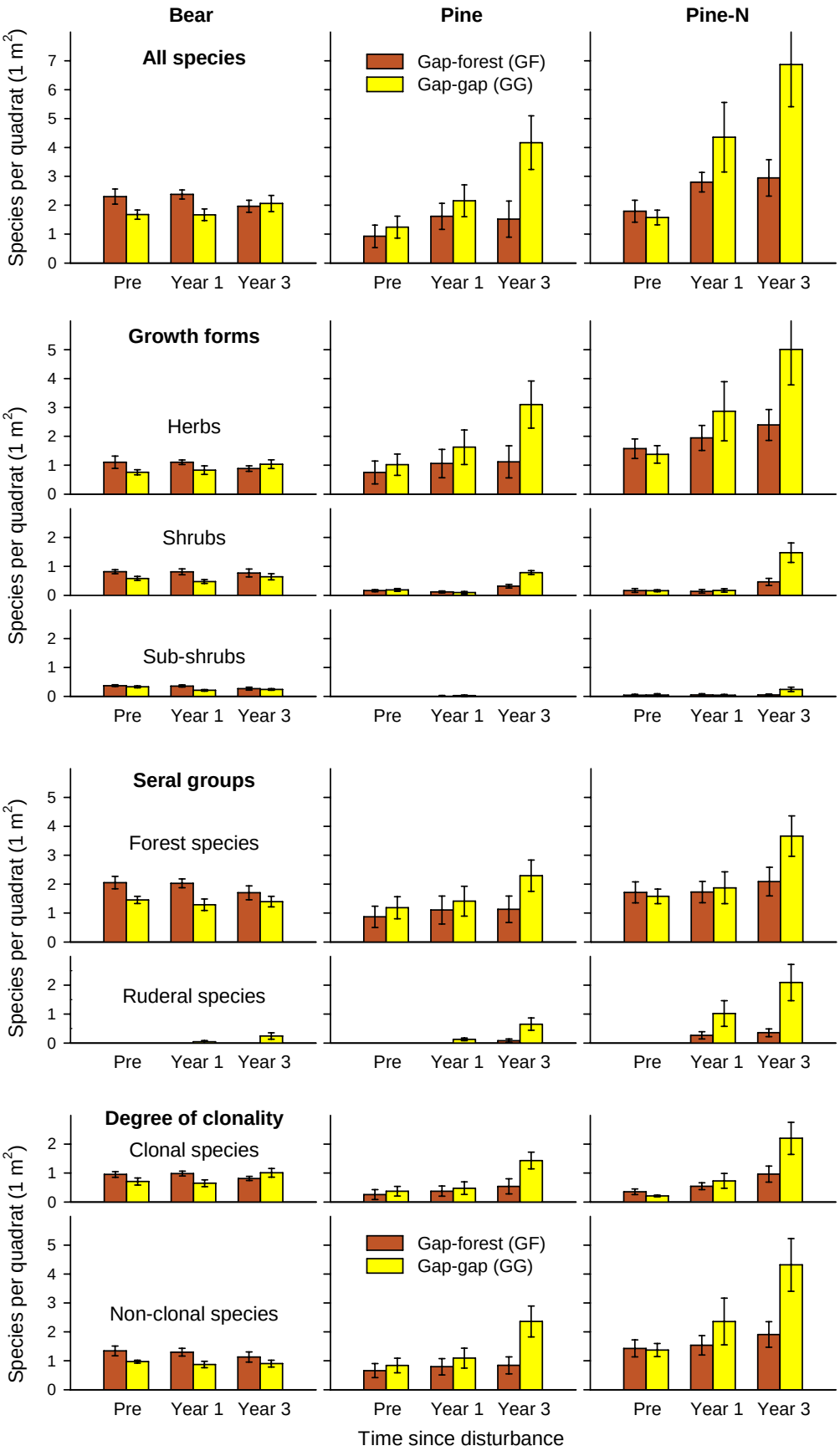

Fig. 19. Changes in richness of vascular plant species in gap and adjacent-forest environments.

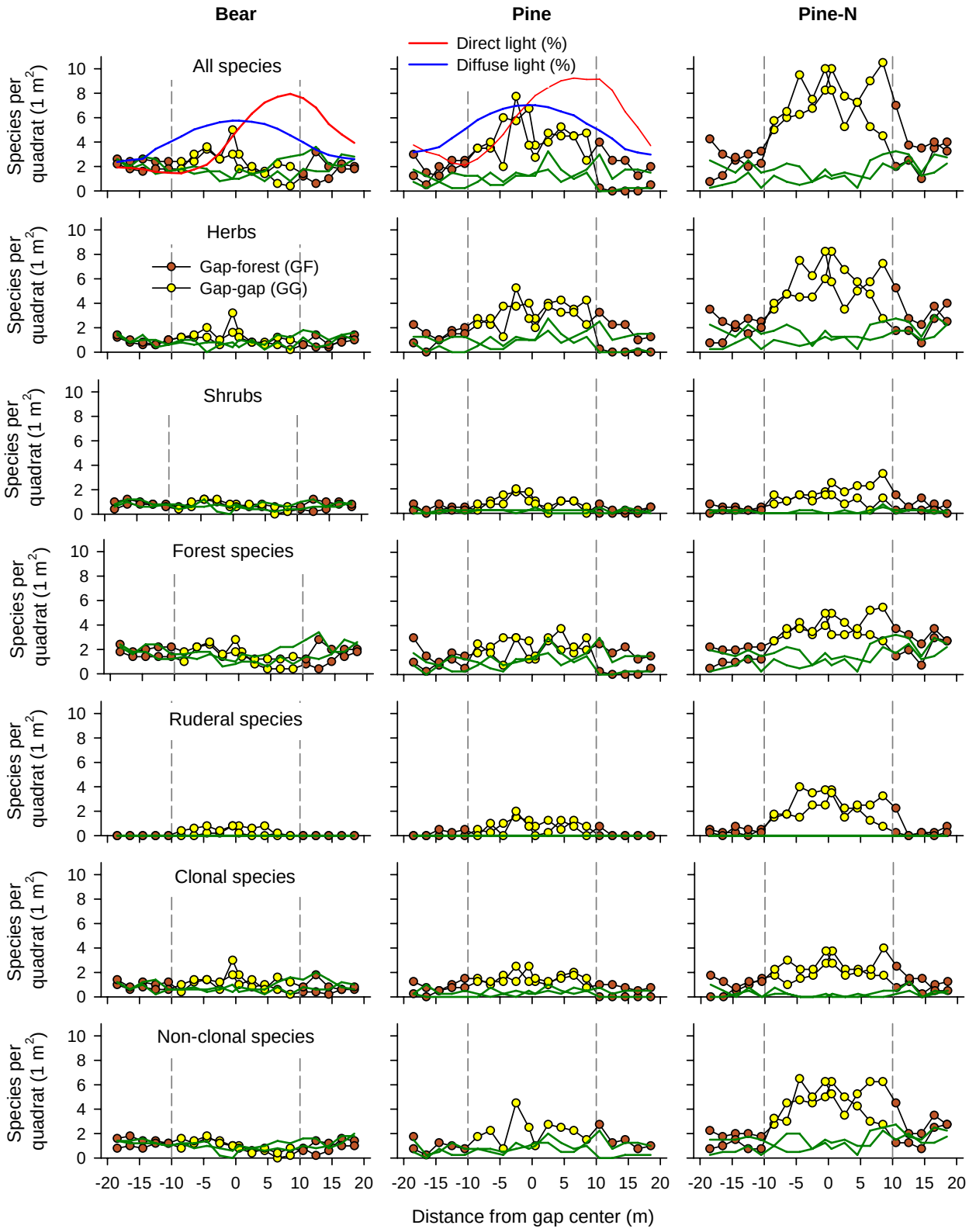

Fig. 20. Distribution of vascular plant species richness across gap treatments.

3.1.5. **Vascular plant species abundance and diversity** (continued)

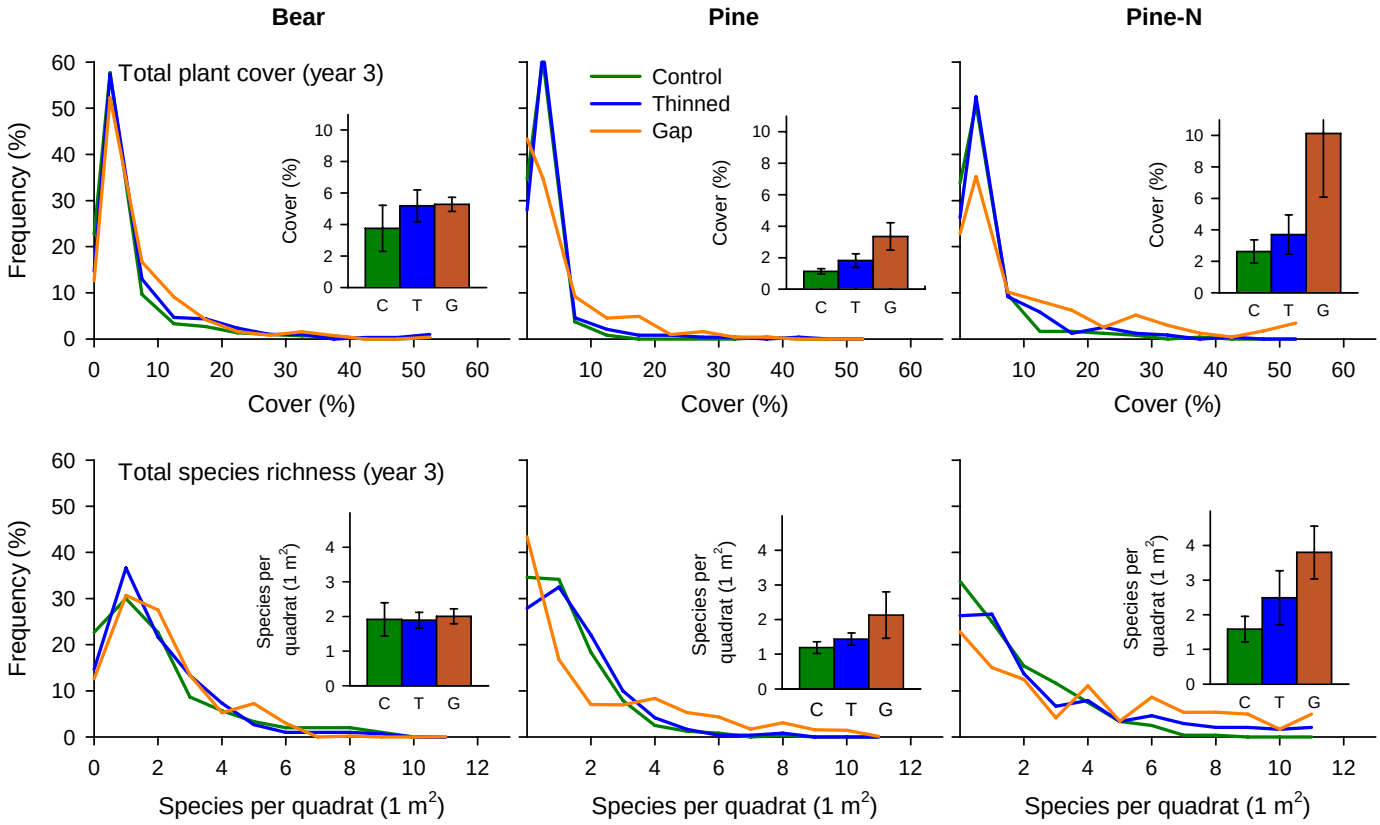

Fig. 21. Post-treatment frequency distributions of vascular plant cover and richness among experimental treatments. Frequency distributions of total cover and richness (number of species per quadrat) in year 3 at each site. Each line represents the mean of four (Pine, Pine-N) or five (Bear) replicates, each sampled with 60 (control and thinned) or 39 (gap treatment) quadrats. Values for gaps are weighted means of quadrats. Mean cover and richness (±1 SE) for each treatment are shown for comparison (inset panels).

Results.— Changes in the frequency distributions of plant cover and richness were consistent with expectation at Pine and Pine-N (but less so at Bear). In the former, thinning and gap creation increased the proportion of quadrats with moderate or relatively high levels of total plant cover and richness. This shift in distribution was particularly evident in gap treatments. At Bear, however, distributions of cover and richness remained similar among treatments.

3.1.5. **Vascular plant species abundance and diversity** (continued)

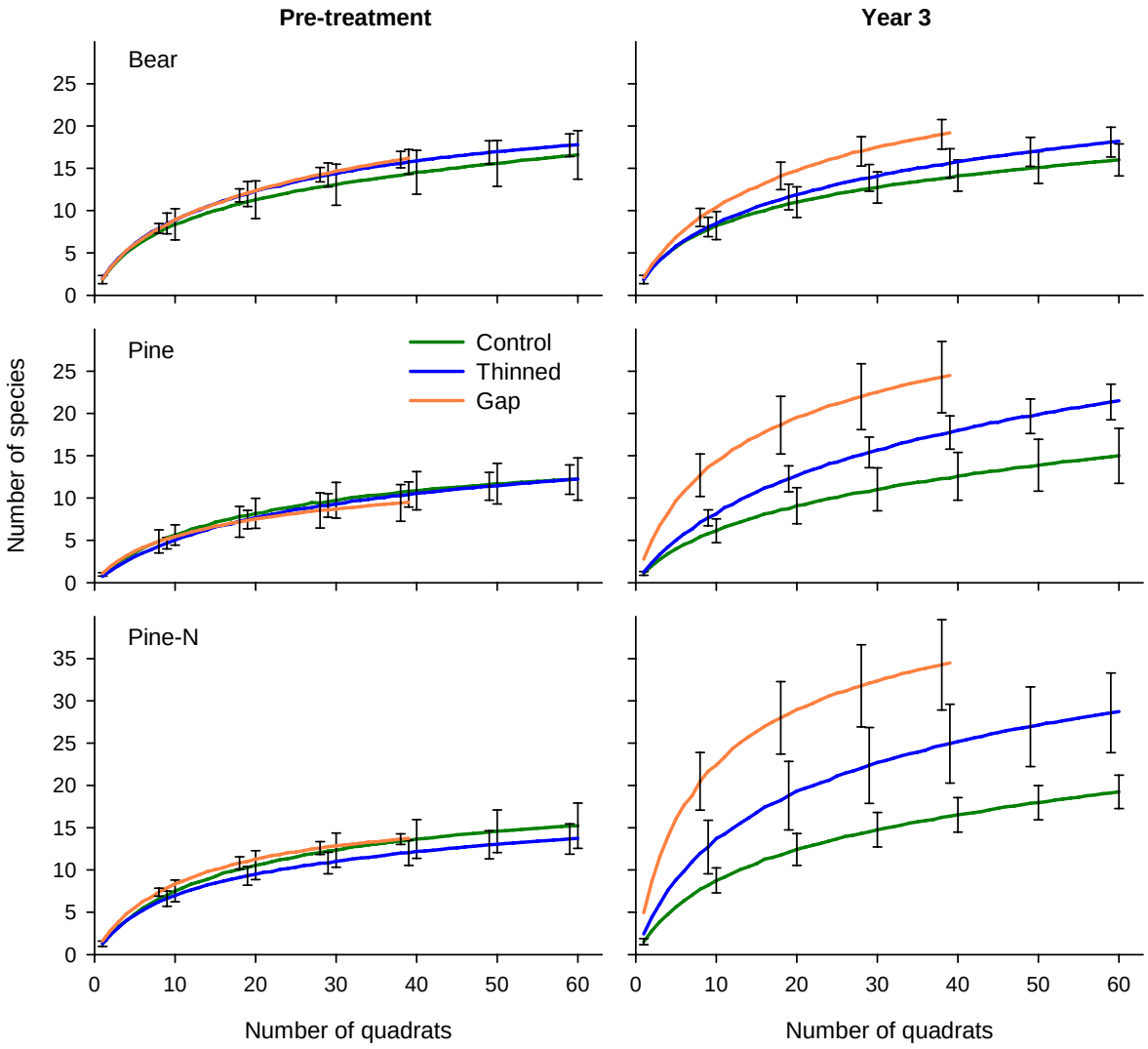

Fig. 22. Species-area (species-accumulation) curves among experimental treatments. Values represent the means (±1 SE) of curves generated for each of four (Pine, Pine-N) or five (Bear) replicates, before and after treatment (year 3). Control and thinned EUs were sampled with a total of 60 quadrats and gap EUs with a total of 39 quadrats.

Results.— Changes in the forms of species-area curves illustrate the dramatic effects of treatments on species richness at larger spatial scales. At all sites (but most notably at Pine and Pine-N), thinning and especially gap creation resulted in significant increases in the number of species present within experimental units. At Pine-N, for example, sampling of 39 quadrats (the full set of quadrats for gap treatments) produced an average of 34 species vs. 25 for thinned treatments and 16 for controls. Similar patterns of smaller magnitude were observed at Pine.

3.1.5. Vascular plant species abundance and diversity (continued)

Fig. 23. Dominance-diversity curves illustrating effects of experimental treatments on the richness and distribution of abundance of species. Circles are used for pre-treatment distributions and triangles for post-treatment (year 3) distributions. Curves illustrate the total number of species (distance along the horizontal axis) and the distribution of abundance (log-transformed) in descending order. Steeper curves indicate stronger dominance by fewer species. Species are color coded by seral status (forest understory, ruderal, and unclassified). *Pteridium aquilinum* (which was not unclassified) is coded separately. Cover values represent the means of four (Pine, Pine-N) or five (Bear) replicates; values for gap EUs are weighed means of quadrat values. See **Table 4** for a complete list of species and their classification by seral status.

Results.— Dominance-diversity curves illustrate significant effects of thinning and gap creation on the diversity and distribution of abundance of vascular plant species. However, these effects differed markedly among sites. At Bear, pre- and post-treatment curves were nearly identical in thinned treatments and only marginally different in gap treatments. In contrast, at Pine and especially Pine-N, thinning and gap creation resulted in the addition of many new species (mainly ruderals and some unclassified species) and a more equitable distribution of abundance (i.e., a shallower, longer slope). Although *Pteridium aquilinum* increased in abundance in all treatments at all sites, it did not always increase in rank abundance.

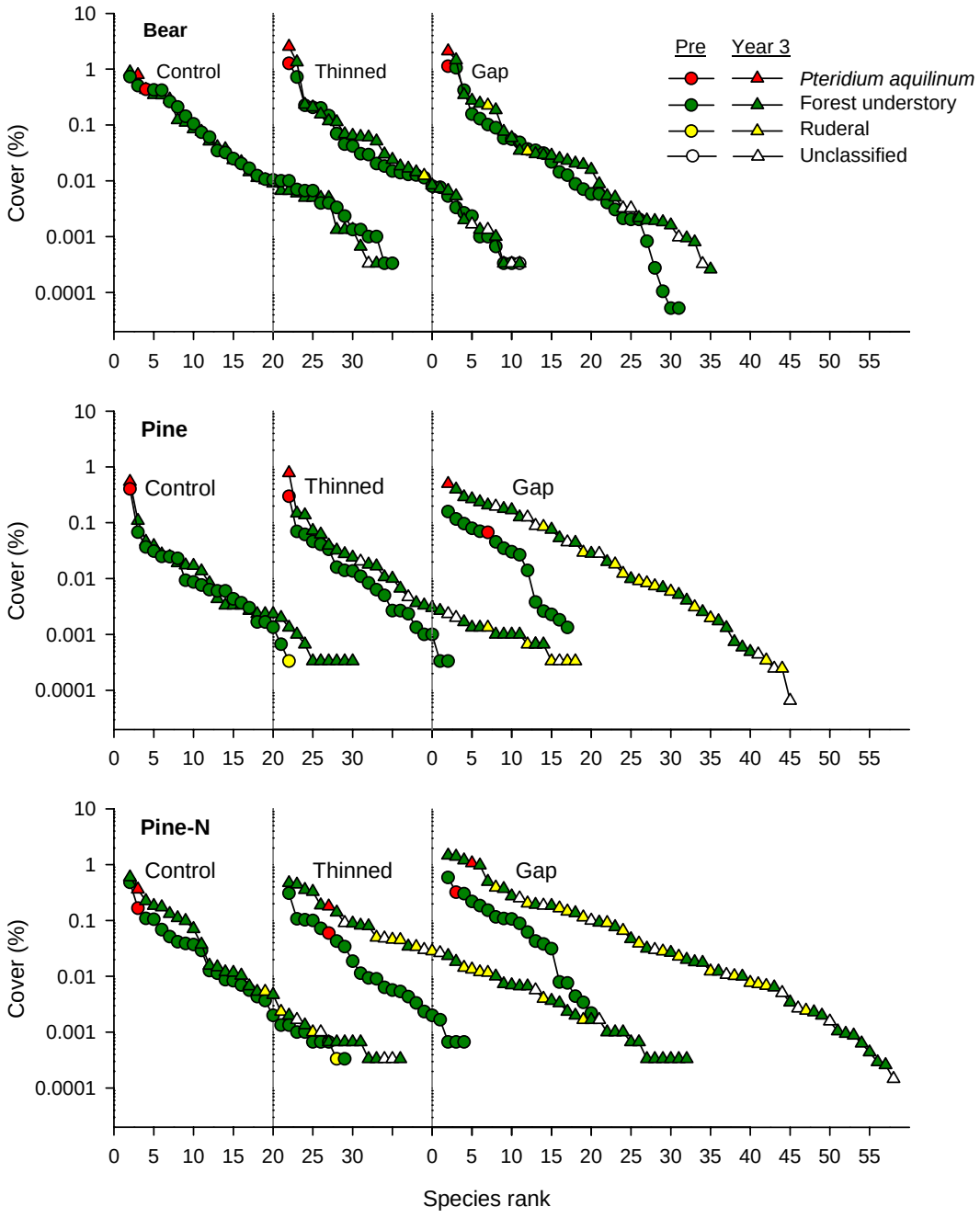

Fig. 23. Dominance-diversity curves illustrating effects of experimental treatments on the richness and distribution of abundance of species.

3.1.6. Vascular plant species composition

Fig. 24. Nonmetric multi-dimensional scaling (NMS) ordination, illustrating changes in the composition of vascular plant species among experimental treatments and sites over time. Points (samples) represent the centroids (means) of each site x treatment x time combination. Samples represent the average species composition of experimental units at three points in time; gap (gap-gap) and adjacent-forest (gap-forest) environments were treated as separate samples. Treatments are coded by color and sites by symbol. Treatment centroids are connected with lines; arrows illustrate the directions of compositional trends (arrowheads point to year 3 values). Species scores are plotted in the upper right panel (NMS1 vs. NMS2); only species present in ≥10% of samples are shown. Species are coded by seral status (forest understory, ruderal, and unknown). The analysis was based on 156 samples and 61 species. Species cover was arcsine square root transformed; only taxa present in ≥5% of samples were included. NMS was implemented in PC-ORD (v. 4.41) using the "slow and thorough" autopilot setting, Bray-Curtis as the distance measure, maximum number of iterations of 400 (200 runs with real and randomized data), with a random start, and an instability criterion of 0.00001 (McCune and Grace 2002). A three-dimensional solution was chosen with a final stress value of 11.27.

Results.— Thinning and gap creation resulted in significant changes in species composition, consistent with effects on cover and richness. However, NMS also highlights the differences in initial species composition among sites. Bear, Pine, and Pine-N occupy fairly distinct regions in ordination space (distributed along NMS3; lower left panel). The frequencies of species contributing to these differences are shown in **Figs. 25-27** (below).

Thinning, and to a greater extent gap creation, resulted in significant movement along NMS1 (upper left panel). This reflects the establishment of ruderal herbs (e.g., *Digitalis purpurea*, *Epilobium angustifolium,* and *E. watsonii*) and shrubs (*Sambucus racemosa*) (upper right panel), but also the release of clonal forest herbs that can respond positively to increases in light (e.g., *Trientalis latifolia* and *Galium triflorum*). Changes in the frequencies of principal species are illustrated in **Figs. 25-27** (below).

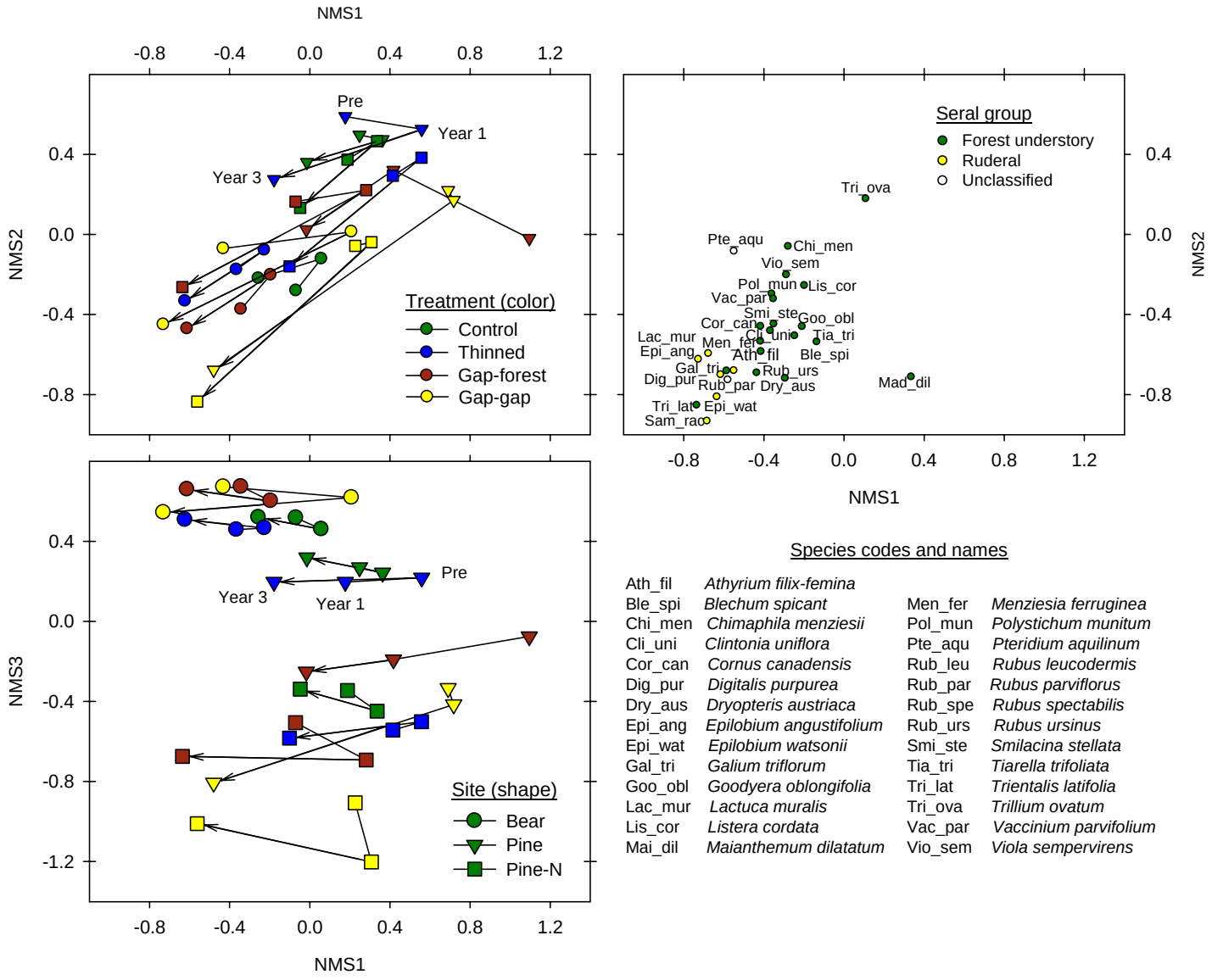

Fig. 24. Nonmetric multi-dimensional scaling (NMS) ordination, illustrating changes in the composition of vascular plant species among experimental treatments and sites over time.

3.1.6. Vascular plant species composition (continued)

Figs. 25, 26, and 27. Changes in frequency of occurrence of selected species among experimental treatments. Frequency is the mean percentage of quadrats in which a species was observed among four (Pine, Pine-N) or five (Bear) replicates. Species frequencies in gap (gap-gap) and adjacent forest (gap-forest) environments are presented separately and are based on weighted frequencies of quadrats. Forest understory species are illustrated in **Figs. 25 and 26** and ruderal/unclassified species in **Fig. 27**. Only species with a mean frequency of ≥10% in at least one treatment x time combination are shown. Seral status and potential for clonal growth are noted in parentheses. See **Table 4** for a complete list of species.

Results.— Individual herb and shrub species showed a diversity of abundance (frequency) patterns in space and time. Pre-treatment distributions varied markedly among sites: *Pteridium aquilinum* and the shrubs, *Menziesia ferruginea* and *Vaccinium parvifolium*, were most frequent at Bear. Other herbaceous species (e.g., *Galium triflorum*, *Viola sempervirens*, and *Polystichum munitum*) were uncommon at Bear, but frequent at Pine or Pine-N.

Several species showed negative responses to thinning or gap creation. These included *Chimaphila menziesii*, *Trillium ovatum*, and *Vaccinium parvifolium* at Bear and Pine-N and *Clintonia uniflora* at Pine (**Figs. 25 and 26**). All are associated with late-seral forests in this region (Halpern and Spies 1995). More often, however, forest understory species showed positive responses to thinning and gap creation (both within the gap and in adjacent forest). Among the most responsive species were the clonal herb, *Galium triflorum*, the non-clonal herb, *Tiarella trifoliata*, and the non-clonal ferns, *Athyrium filix-femina* and *Blechnum spicant*, all at Pine and Pine-N (**Figs. 25 and 26**). The ferns showed particularly large increases within gap openings (**Fig. 26**).

Consistent with trends in cover and richness, ruderal species showed localized establishment within gap openings, with occasional establishment in adjacent forest or thinned treatments (**Fig. 27**). The most common ruderals included the herbs, *Anaphalis margaritacea* (Pine and Pine-N) and *Epilobium angustifolium* (all sites), and the shrubs, *Rubus leucodermis* and *Sambucus racemosa* (Pine-N). *Rubus parviflorus* and *R. spectabilis*, which were not assigned a seral status *a priori*, showed similar patterns (Pine and Pine-N). The apparent absence of these *Rubus* species in year 1 reflects our inability to identify *Rubus* seedlings to species; these were abundant, but recorded at the genus level and are not reflected in these species-level summaries.

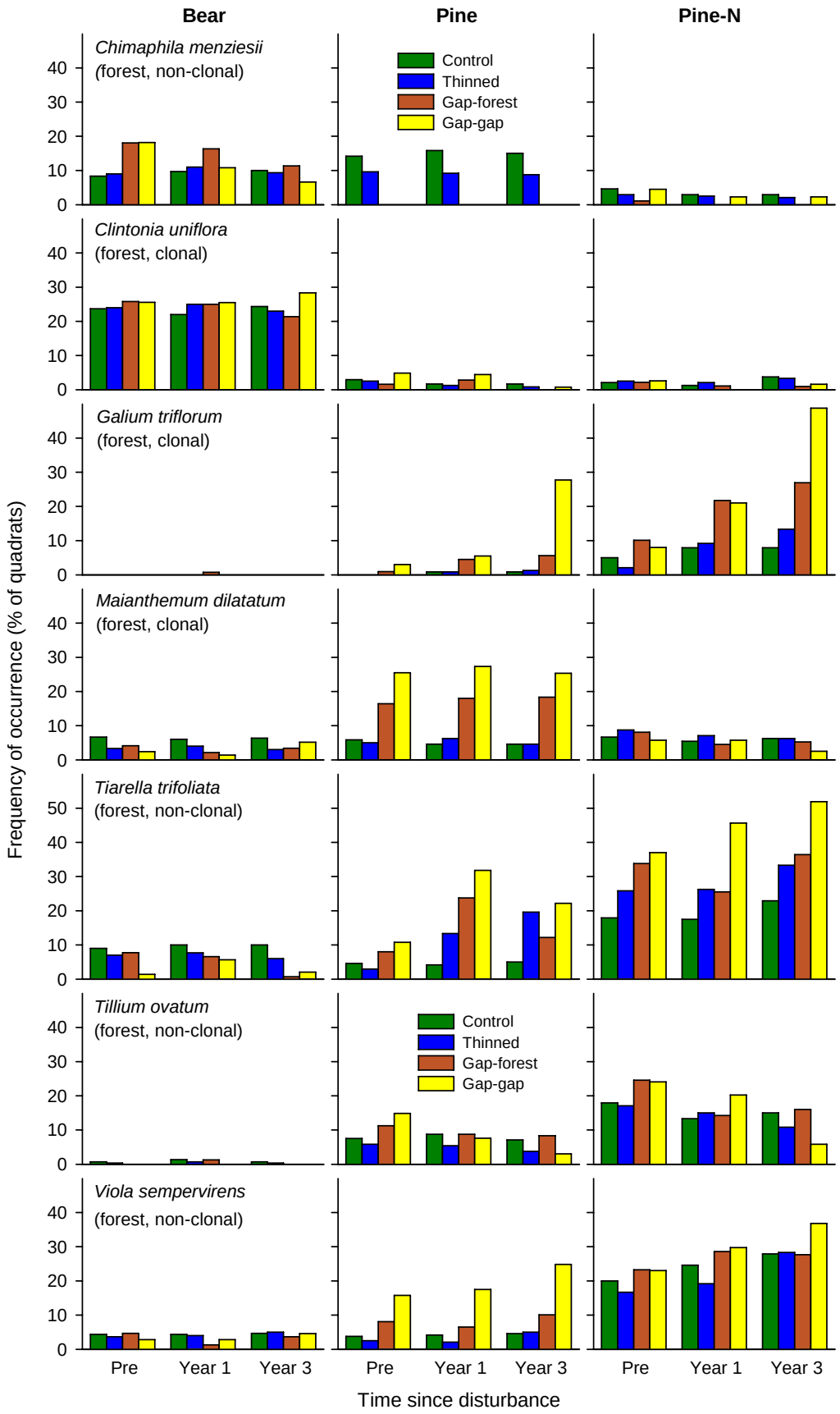

Fig. 25. Changes in frequency of occurrence of selected forest understory species among experimental treatments.

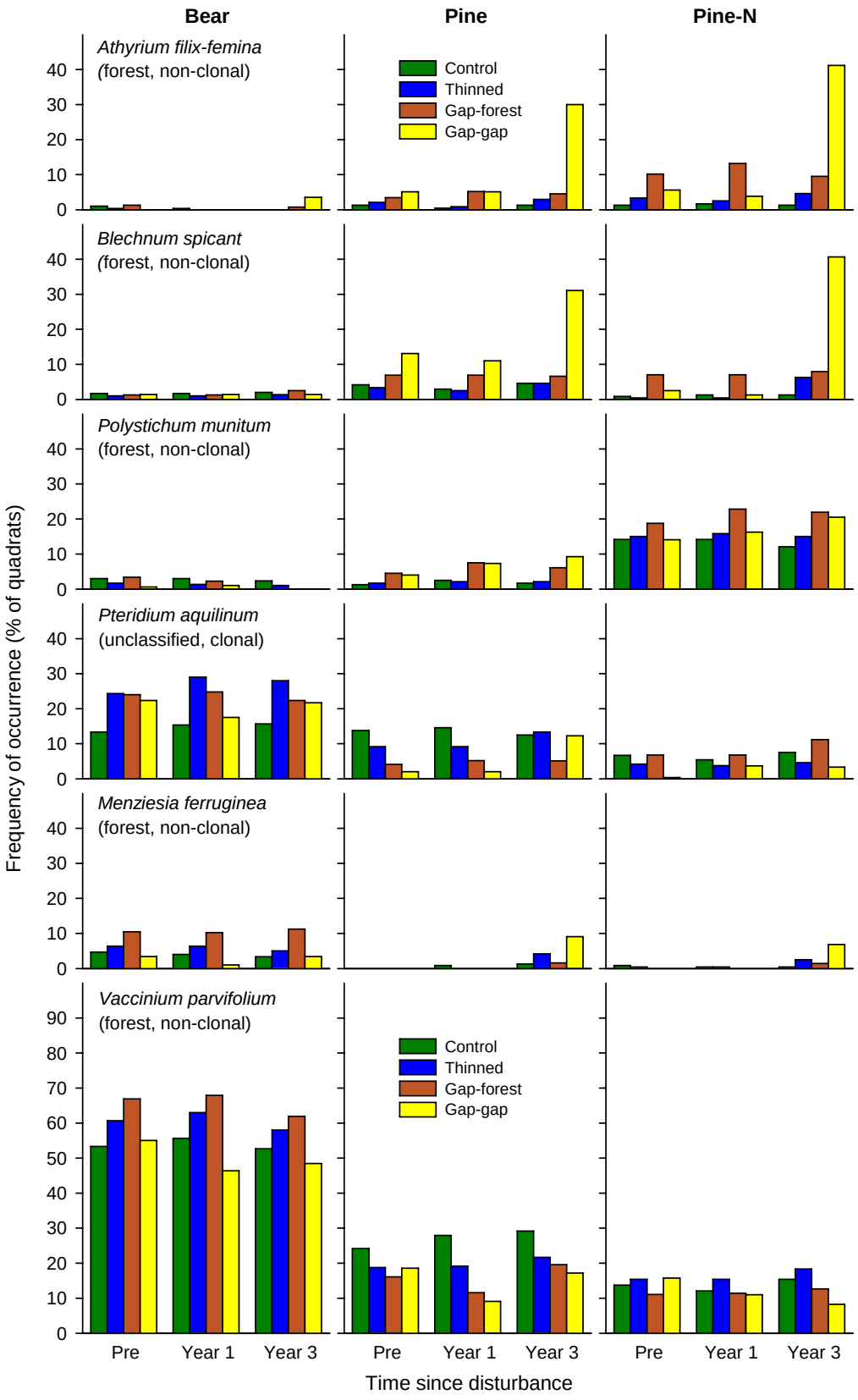

Fig. 26. Changes in frequency of occurrence of selected forest understory species among experimental treatments.

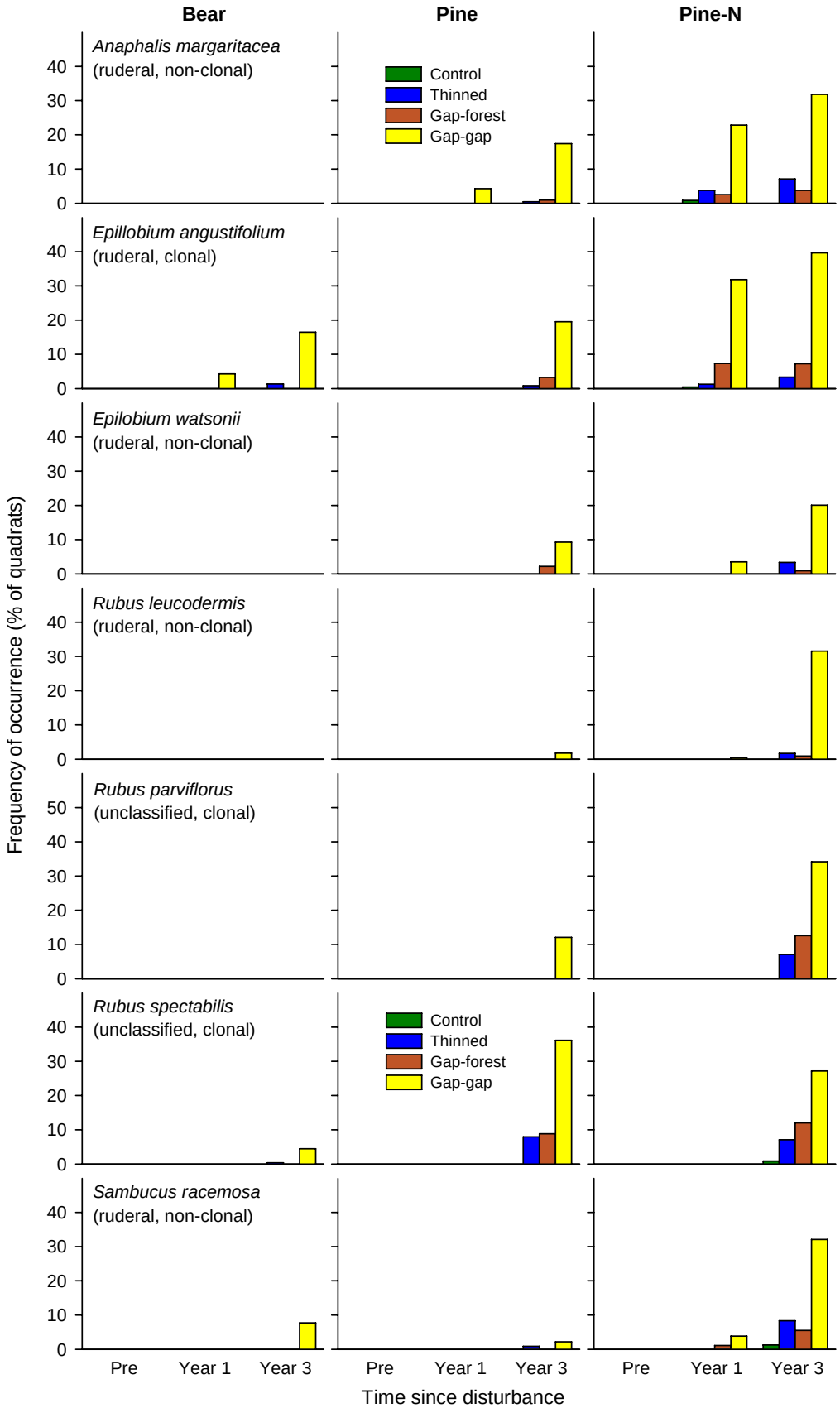

Fig. 27. Changes in frequency of occurrence of selected ruderal species among experimental treatments.

3.2. Bryophyte Study

3.2.1. Tree seedling density, richness, and composition

Fig. 28. Changes in density and richness of tree seedlings on CWD and forest-floor substrates among experimental treatments at Bear. Mean density (±1 SE) and richness (number of species per quadrat) of tree seedlings before (Pre) and after treatment (years 1 and 3) in quadrats representing CWD or forest-floor substrates. "*Abies* species" is mostly *A. amabilis* and some *A. procera*. Each bar represents the mean of four replicates, each sampled with 16 to 24, 0.1 m^2 quadrats.

Results.— Although the emphasis of this study is on bryophytes, it also allows us to examine how substrates mediate the distribution and dynamics of tree seedlings. Seedling densities before and after treatment were an order of magnitude greater on CWD than on the forest floor, reflecting the preference for decayed logs of *Tsuga heterophylla*, the dominant species. In contrast, *Abies* (mostly *A. amabilis*) was more common on the forest floor. Similar to trends in the main experiment, *Tsuga* showed considerable variation over time in the control, highlighting the importance of annual variation in seed production. As such, there was no apparent affect of thinning or gap creation. *Pseudotsuga menziesii* showed limited establishment on either substrate, but responded positively to thinning and gap creation on the forest floor. Seedling richness was greater on CWD than on the forest floor, but it was not affected by thinning or gap creation.

Fig. 29. Changes in tree seedling density and richness in gap and adjacent-forest environments. Mean density (±1 SE) and richness (number of species per quadrat) of tree seedlings before (Pre) and after treatment (years 1 and 3) in gaps (gap-gap) and adjacent forest (gap-forest) environments in quadrats representing CWD or forest-floor substrates. Each bar represents the mean of four replicates, each sampled with 16 to 24, 0.1 m^2 quadrats.

Results.— Within the gap treatments, regeneration densities were greater within gaps than in adjacent forest. Differences in total density were driven by regeneration patterns of *Tsuga*, which showed substantial increases on the forest floor in gaps, as well as on CWD. *Pseudotsuga* also showed preferential establishment within the gaps on both CWD and the forest floor. For *Abies*, patterns were dependent on substrate: seedlings on CWD showed complete mortality in gaps, but densities were stable in adjacent forest. Seedlings on the forest floor initially declined, then increased in both environments. Patterns of richness in gaps and adjacent forest varied with time and substrate reflecting underlying variation in seed production, substrate preferences, and positional effects.

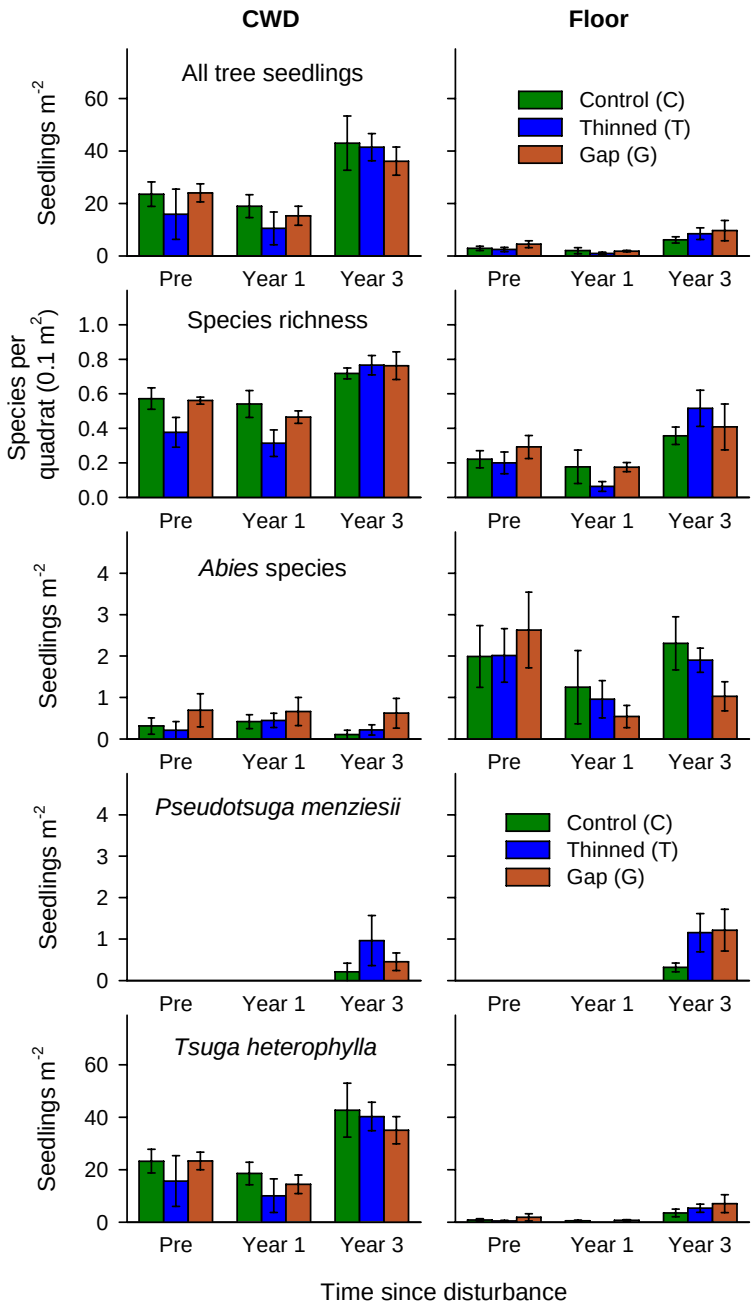

Fig. 28. Changes in tree seedling density and richness on CWD and forest-floor substrates among experimental treatments at Bear.

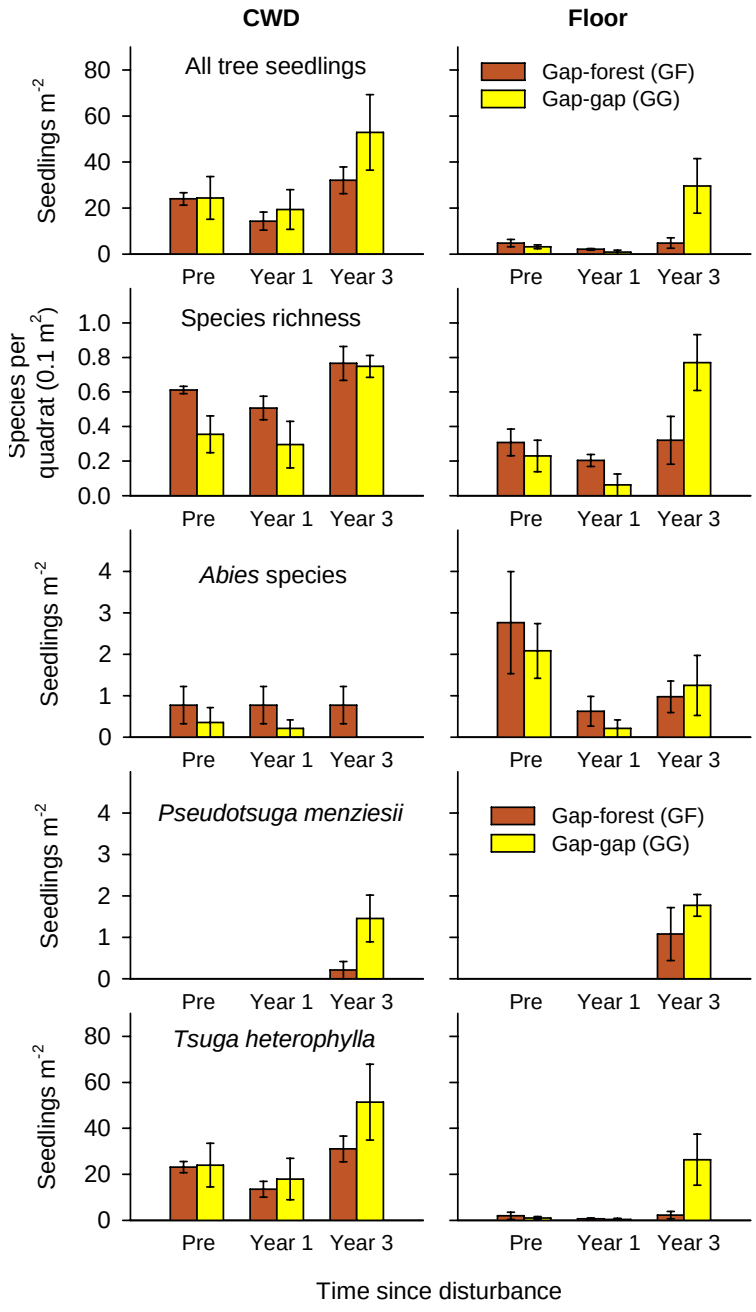

Fig. 29. Changes in tree seedling density and richness in gap and adjacent-forest environments.

3.2.2. Bryophyte abundance and diversity

Table 5. Moss and liverwort species observed in the bryophyte study. Nomenclature follows Lawton (1971), Schofield (2002), and Norris and Shevock (2004).

Species	Database code
Mosses	
Brachythecium asperrimum	BRAASP
Brachythecium hylotapetum	BRAHYL
Brachythecium oedipodium	BRAOED
Buxbaumia viridis	BUXVIR
Dicranum fuscescens	DICFUS
Dicranum scoparium	DICSCO
Eurhynchium oreganum	EURORE
Homalothecium megaptilum	HOMMEG
Hylocomium splendens	HYLSPL
Hypnum circinale	HYPCIR
Isothecium stoloniferum	ISOSTO
Neckera douglasii	NECDOU
Orthotrichium lyellii	ORTLYE
Plagiothecium undulatum	PLAUND
Pleurozium schreberi	PLESCH
Pseudotaxiphyllum elegans	PSEELE
Rhizomnium glabrescens	RHIGLA
Rhytidiadelphus loreus	RHYLOR
Rhytidiopsis robusta	RHYROB
Liverworts	
Bazzania ambigua	BAZAMB
Blepharostoma trichophyllum	BLETRI
Calypogeia species[†]	CALYP
Cephalozia species*	CEPHA
Diplophyllum albicans	DIPALB
Lepidozia reptans	LEPREP
Lophocolea heterophylla	LOPHET
Ptilidium californicum	PTICAL
Riccardia species	RICCA
Scapania bolanderi	SCABOL

[†] Includes *Calypogeia muelleriana* and *C. suecica*
* Includes *Cephalozia lunulifolia* and *C. bicuspidata*

3.2.2. Bryophyte abundance and diversity (continued)

Fig. 30. Changes in cover and richness of bryophytes among experimental treatments. Mean cover and richness (±1 SE) of moss and liverwort species before (Pre) and after treatment (years 1 and 3) in quadrats representing CWD or forest-floor substrates. Each bar represents the mean of four replicates, each sampled with 16 to 24, 0.1 m^2 quadrats. Total cover of vascular plants is shown for comparison. Note the variation for moss and liverwort cover in the scale of the Y axis.

Results.— Typical of these forests, moss and liverwort communities showed greater development on CWD than on the forest-floor and liverworts were largely restricted to CWD. In contrast to vascular plants, which increased in thinned and gap treatments, bryophytes showed consistent declines in all treatments (including controls). Declines were greater for CWD than for forest-floor samples. However, local richness of moss and liverwort species increased in all treatments on both substrates. Declines in cover may have allowed for recruitment of new species or for detection of cryptic or infrequent species present prior to treatment.

Fig. 31. Changes in cover and richness of bryophytes in gap and adjacent-forest environments. Mean cover and richness (±1 SE) of moss and liverwort species before (Pre) and after treatment (years 1 and 3) in gap (gap-gap) and adjacent forest (gap-forest) environments in quadrats representing CWD or forest-floor substrates. Each bar represents the mean of four replicates, each sampled with 16 to 24, 0.1 m^2 quadrats. Total cover of vascular plants is shown for comparison.

Results.— Trends within the gap treatment suggest differing responses on CWD and forest-floor substrates. Cover declined on CWD in both gap and adjacent-forest environments, but did not show directional trends on the forest floor. Richness increased on both substrates in both environments.

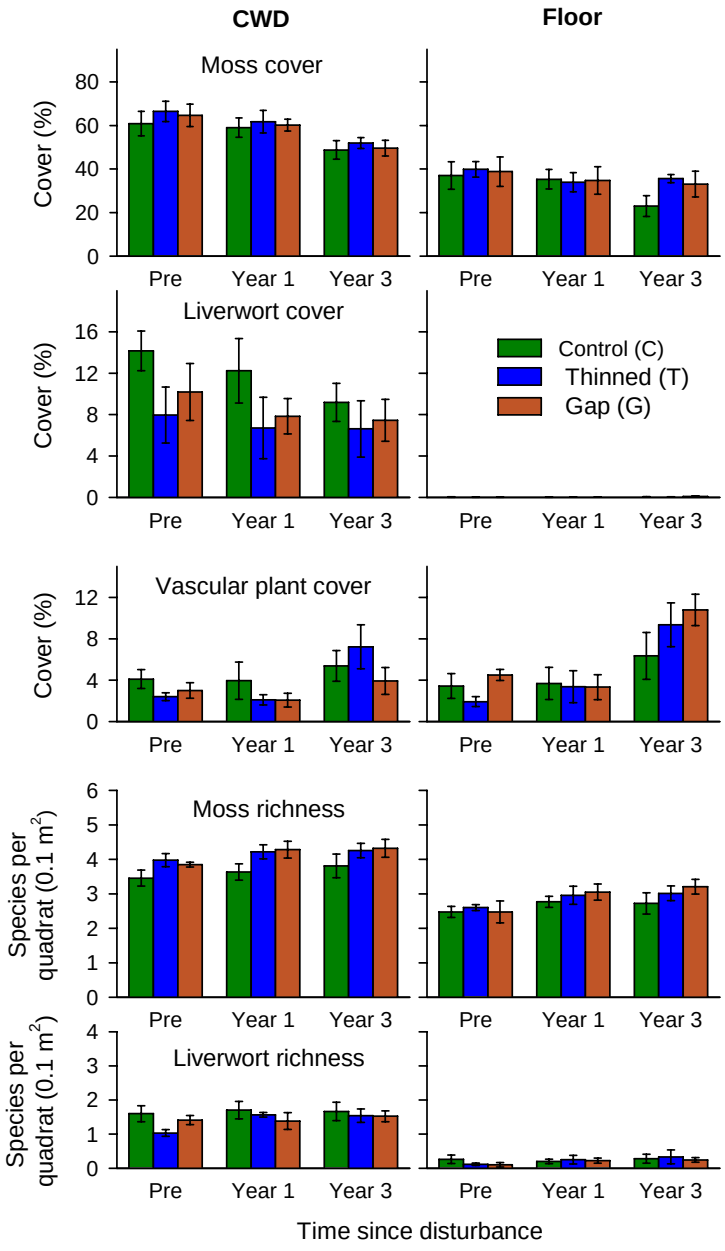

Fig. 30. Changes in cover and richness of bryophytes among experimental treatments.

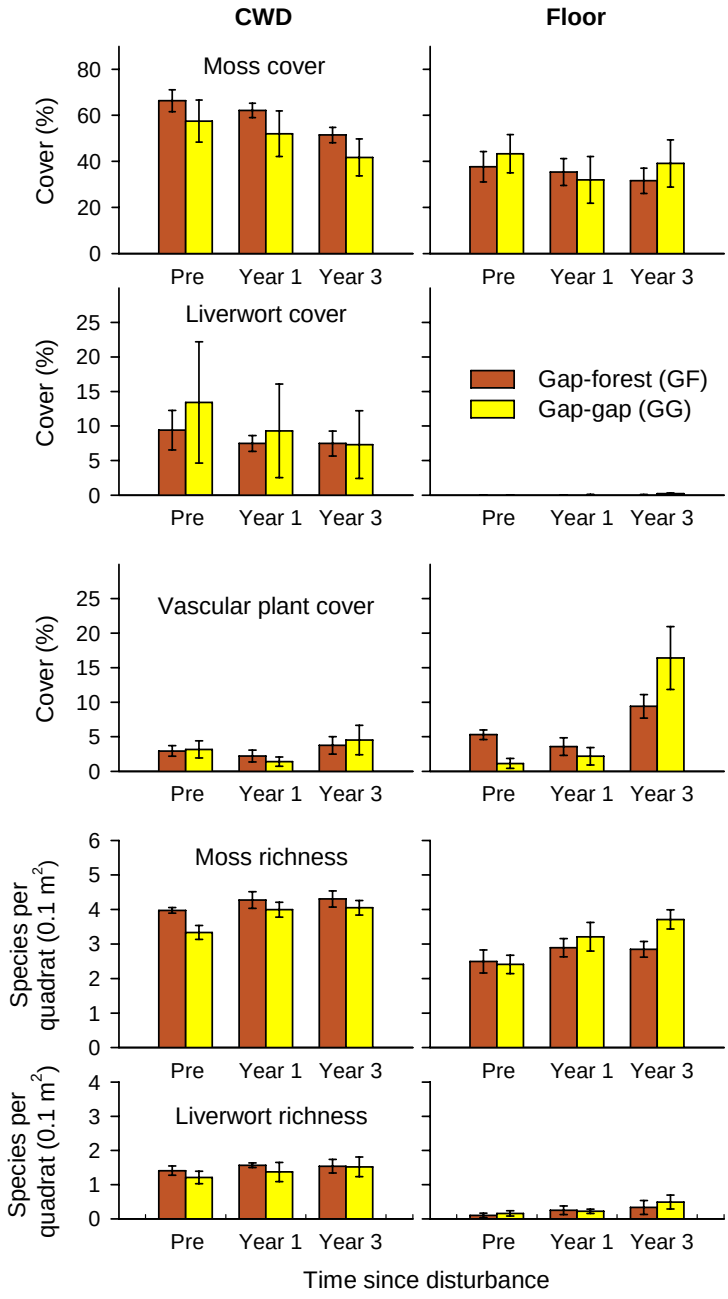

Fig. 31. Changes in cover and richness of bryophytes in gap and adjacent-forest environments.

3.2.3. Bryophyte community composition

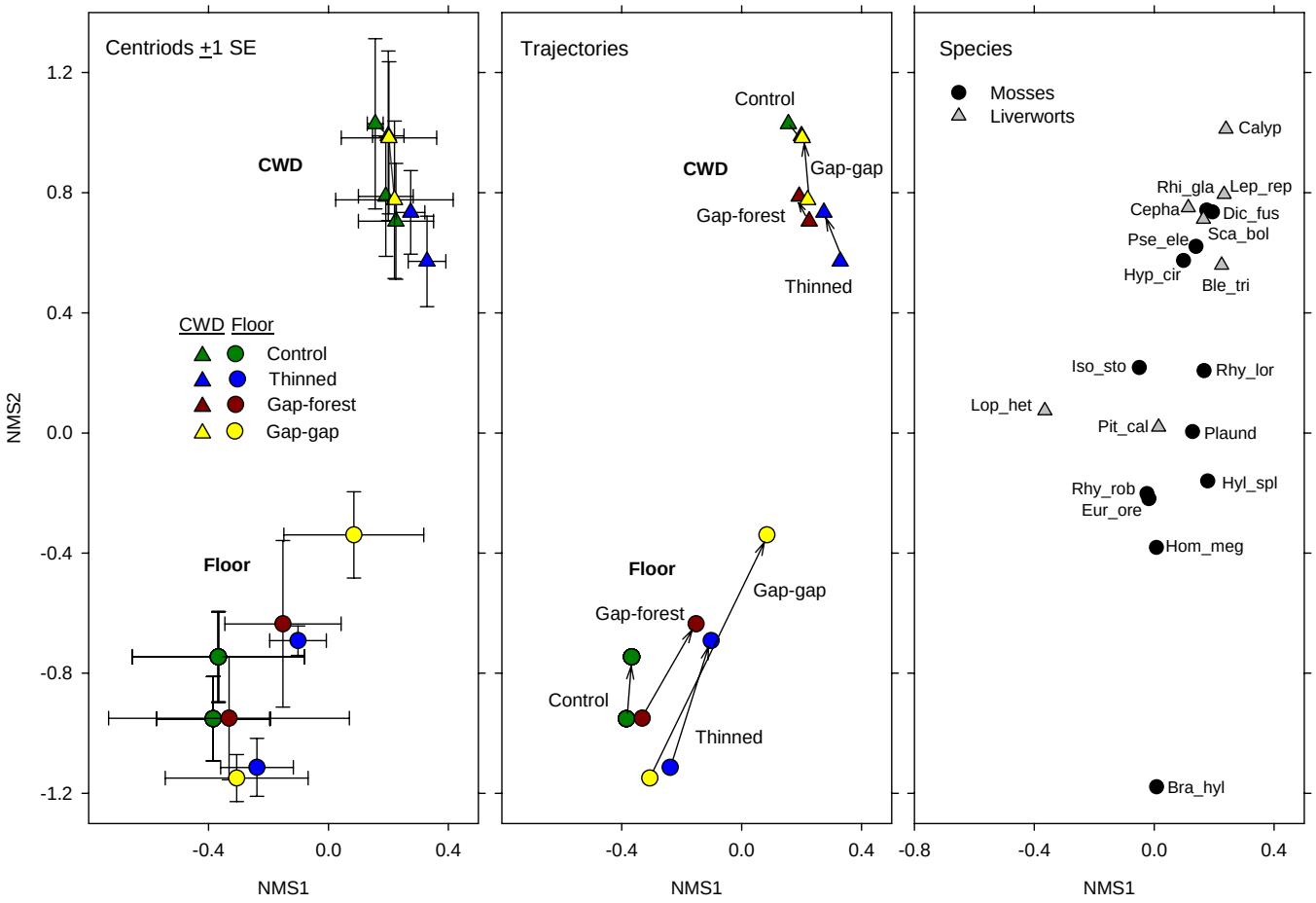

Fig. 32. Nonmetric multi-dimensional scaling (NMS) ordination, illustrating changes in the composition of bryophyte species among experimental treatments over time. Points (samples) represent the centroids (means ±1 SE) of each substrate x treatment x time combination. Samples represent the average species composition (frequency of occurrence) of substrates x experimental units at two points in time (pre-treatment and year 3); gap (gap-gap) and adjacent forest (gap-forest) environments were treated as separate samples. Treatments are coded by color and substrates by symbol. Arrows connect pre- and post-treatment values, illustrating the direction of compositional trends. Species scores are plotted in the third panel (see **Table 5** for a full list of taxa). The analysis was based on 64 samples and 18 taxa. NMS was implemented in PC-ORD (v. 4.41) using the "slow and thorough" autopilot setting, Bray-Curtis as the distance measure, maximum number of iterations of 500 (250 runs with real and randomized data), with a random start, and an instability criterion of 0.000001 (McCune and Grace 2002). A two-dimensional solution was chosen with a final stress value of 13.39.

Results.— The results of NMS ordination highlight the distinct compositional differences between CWD and forest-floor substrates. They also suggest that compositional changes in response to treatments were greater on the forest floor than on CWD. For both substrates, changes were greatest within gaps. However, the magnitude of change was greater for communities on the forest floor. Compositional trends suggest increasing similarity of forest floor with CWD substrates due to the addition of liverwort species (see third panel). In contrast, compositional changes on CWD were relatively small and largely indistinguishable among treatments.

3.2.3. Bryophyte community composition (continued)

Fig. 33. Changes in frequency of occurrence of selected bryophyte species among experimental treatments. Changes in % frequency represent the differences between year 3 and pre-treatment values. For the gap treatment, means were computed separately for quadrats representing four post-treatment environments: forest south of gap, southern portion of gap, northern portion of gap, and forest north of gap. Each bar represents the mean of four replicates, each sampled with 16 to 24, 0.1 m^2 quadrats (for control and thinned treatments), or 2 to 7 quadrats (for gap treatments). Liverwort species are noted in parentheses. See **Table 5** for a complete list of taxa.

Results.— Bryophyte species showed a complex array of responses to treatments, environments within treatments (gap), and substrates. Frequencies of most species changed minimally in the controls, but increased elsewhere. Some species showed small to large increases in all treatments (*Dicranum fuscescens*, *Isothecium stoloniferum*, and *Rhytidiadelphus loreus*); others showed minimal change (*Hylocomium splendens* and *Rhizomnium glabrescens*).

Responses within gap treatments also varied. Some species showed positive responses across the continuum of gap and adjacent-forest environments on both substrates (*Dicranum fuscescens*, *Hypnum circinale, Isothecium stoloniferum*, and *Rhytidiadelphus loreus*). Others showed contrasting responses in the southern and northern portions of gap treatments (*Plagiothecium undulatum, Rhytidiopsis robusta,* and *Lepidozia reptans*) characterized by distinctly different light environments. For most species, responses were similar between substrates, but occasionally they were not (*Plagiothecium undulatum* and *Scapania bolanderi*).

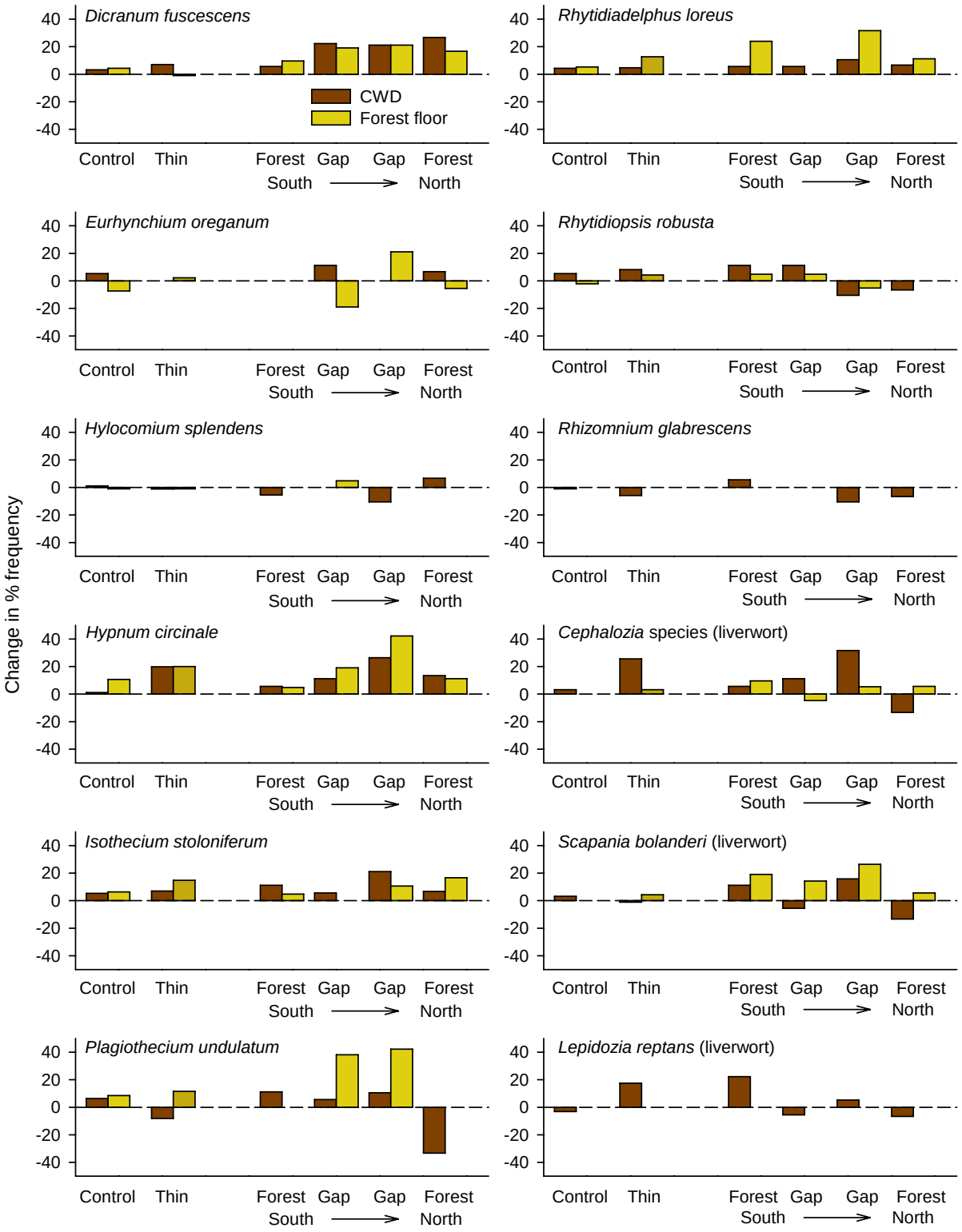

Fig. 33. Changes in frequency of occurrence of selected bryophyte species among experimental treatments.

3.3. CWD Experiment

3.3.1. Forest structure

Table 6. Density and basal area of trees before and after treatment. "Columns" correspond to experimental units; treatment averages follow. The targeted basal area reduction was 30% in both treatments.

			Density (stems ha^{-1})			Basal area (m^2 ha^{-1})		
Site	Treatment	Column	Before	After	% Decrease	Before	After	% Decrease
Bear	- CWD	1	925	304	67	68.5	35.6	48
		3	1,067	421	61	70.7	45.7	35
		4	1,063	454	57	68.3	43.9	36
		7	1,259	625	50	67.3	45.3	33
		Average	1,078	451	59	68.7	42.6	38
	+ CWD	2	938	538	43	73.7	55.9	24
		5	1,071	456	57	70.8	52.6	26
		6	1,042	463	56	61.1	47.3	23
		8	1,650	813	51	68.6	47.0	31
		Average	1,175	567	52	68.5	50.7	26

Results.— Greater density and basal area were removed from -CWD treatments than from +CWD treatments. Basal area reduction exceeded the 30% removal target in -CWD (mean of 38%), but was below target in +CWD (mean of 26%). Much of the excess removal was attributable to a single replicate (column 1; 48% decrease).

3.3.2. Ground-surface characteristics, tree seedling density, bryophyte cover, and vascular plant species abundance and diversity

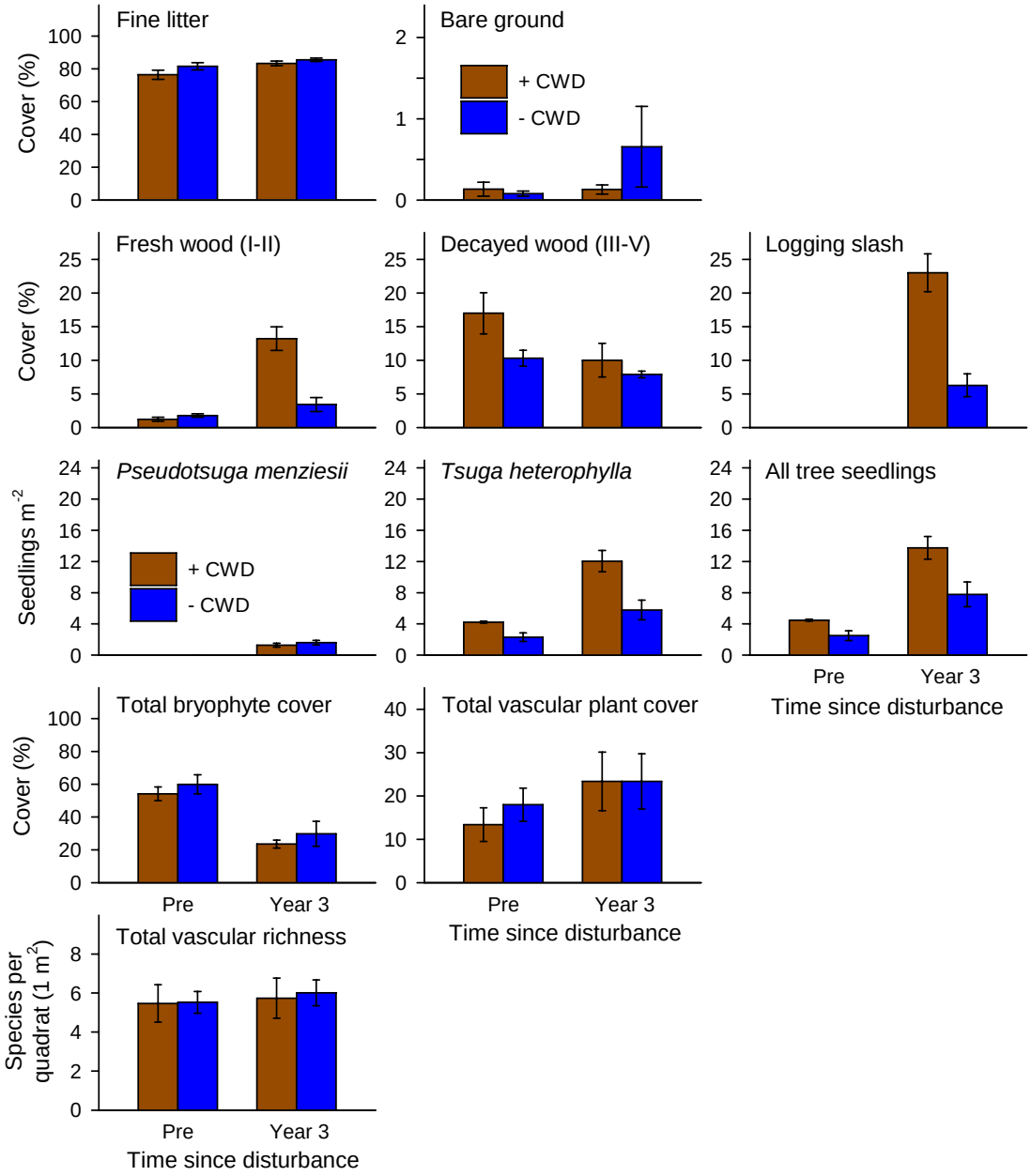

Fig. 34. Changes in ground-surface characteristics, tree seedling density, bryophyte cover, and total cover and richness of vascular plants in thinned treatments in which CWD was retained or removed. Means (±1 SE) are based on four replicates of each treatment: +CWD = retained; -CWD = removed. Each EU was sampled with 51, 1 x 1 m quadrats. Post-treatment data were collected in year 3 only.

Results.— Retention of CWD following thinning had large and predictable effects on ground-surface conditions. Cover of fresh wood and slash were four times greater than on removal sites, although values averaged only 13 and 23%, respectively. Tree seedlings (primarily *Tsuga heterophylla*) responded positively to retention of CWD (nearly a doubling of density), but bryophytes and vascular plants did not.

4. Synthesis

Our experiments were designed to test the potential to enhance understory structure and diversity in dense, second-growth forests by altering overstory structure, and to assess the consequences of retaining, rather than removing trees felled during thinning. In the PNW, there has been a long history of similar studies of vegetation response to structural manipulations in young coniferous forests. These range from studies of plantation stands thinned for silvicultural objectives (growth of crop trees; Doerr and Sandburg 1986, Alaback and Hermann 1988, Bailey et al. 1998, Thomas et al. 1999, Lindh and Muir 2004), to those in which thinning prescriptions incorporate—or emphasize—ecological objectives (e.g., enhancing habitat complexity or accelerating forest structural development; Thysell and Carey 2001, Fahey and Puettmann 2007, 2008, Wilson and Puettmann 2007, Ares et al. 2009, 2010, Davis and Puettmann 2009, Wilson et al. 2009). The results of these studies have shown that it is not possible to generalize broadly about understory responses to thinning. Thinning can have either negative or positive effects on abundance over short or longer time frames; negative, neutral, or positive effects on species diversity; positive or neutral effects on establishment of early seral species or invasion of non-natives; and a broad range of effects on regeneration densities of shade-tolerant conifers. The diversity of responses and conditions under which they occur clearly indicate that many factors can influence vegetation response: some can be manipulated or controlled (e.g., timing, intensity, or spatial pattern of thinning), but others cannot (e.g., site productivity, initial structure or composition, or disturbance history and its influence on the soil seed bank).

4.1. Novel Aspects of Our System and Studies

Within the context of this past research, there are two novel aspects of our system that provide strong justification for testing responses to thinning. First, the forests of interest are not only dense, but heavily dominated by *Tsuga heterophylla*, which creates uniformly low levels of understory light (5-8% of that above the canopy). Most previous research on vegetation responses to thinning has been conducted in *Pseudotsuga*-dominated stands whose canopy architecture and lower leaf areas allow for greater penetration of light to the forest floor. Second, vascular understory communities were extremely depauperate before treatment, with total plant cover averaging <3%. This probably reflects an extended and intense period of stem exclusion in these stands. Given this low cover and diversity of species, responses to stand manipulation are not easily predicted. Initial responses could be shaped more by properties of the seed bank than by characteristics of the above-ground community.

Our experiments are also unique in several important ways. First, we use a randomized block design with each treatment replicated four or five times at each of three sites. Replication within sites, which is lacking in most previous studies, allows for more robust conclusions about the generality of treatment effects. Second, we interpret post-treatment responses relative to pre-treatment conditions. Pre-treatment sampling is lacking in most studies of vegetation response to thinning (e.g., Thomas et al. 1999, Thysell and Carey 2001, Lindh and Muir 2004, Fahey and Puettmann 2007, 2008, Ares et al. 2009, 2010, Davis and Puettmann 2009). Limited replication, combined with the absence of pre-treatment data, can make it difficult to distinguish treatment effects from those due to variation in the initial abundance or distribution of plants (e.g., Nelson and Halpern 2005). This can be problematic in forests such as ours in which the initial distributions of plants are very patchy. Finally, we consider not only the vascular flora, but also ground-layer bryophytes which contribute significantly to the biological diversity of these forests. Studies of bryophyte responses to thinning in young stands are rare and of limited scope (He and Barclay 2000, Thomas et al. 2001).

4.2. Key Findings

Our analyses point to several general, but consistent trends among the array of understory responses considered in this study.

First, for most measures of vegetation response, effects of treatments were not evident until the third growing season. Had there been greater initial plant cover, first-year responses are likely to have been dominated by declines. Woody plants, whose perennating structures lie above ground, are particularly susceptible to mechanical damage from felling or yarding activities (e.g., Thomas et al. 1999, Halpern et al. 2005, Davis and Puettmann 2009).

Second, the magnitude of response to treatments varied markedly within sites. For example, at Pine, thinning increased quadrat-scale richness by ~30% in one EU, but by more than threefold in another. Likewise, at Pine-N, gap creation increased total plant cover from 1.6 to 4.8% in one EU, but to nearly twice that (8.6%) in an adjacent EU. Variation in soil properties that affect plant growth (e.g., moisture availability and nutrient status) may explain these differences. In both thinned and gap treatments, we detected strong positive correlations between local density of *Thuja plicata* and changes in plant cover and richness. Presence of *Thuja* is often indicative of moist, rich soils. However, *Thuja* also tends to raise soil cation exchange capacity, pH, and exchangeable calcium (Alban 1969), which may enhance the cover and diversity of herbaceous species compared to soils under *Tsuga* (Turner and Franz 1986). Thus, it is possible that the factors that enhance *Thuja* establishment and growth similarly affect understory responses to thinning. Regardless of the mechanism(s), our results suggest that local density of *Thuja* may be a useful indicator of the potential for understory response to stand manipulation.

Third, variation among sites was even greater than variation within sites. Except for bryophytes, understory responses were mostly neutral at Bear, but strongly positive at Pine and Pine-N. What factors might contribute to this variation? *Thuja* density is consistently low at Bear, as it is in the less responsive EUs of Pine and Pine-N. The same factors that lead to within-site variation in Pine and Pine-N may be responsible for the large differences among sites. However, we hesitate to ascribe variation among sites entirely, or even largely, to this factor because there are potentially other differences that separate Bear, Pine, and Pine-N. For example, differences in vegetation response could also reflect variation in disturbance intensity or in post-treatment light availability. However, although ground disturbance was greater at Pine and Pine-N than at Bear (the latter protected by snow at the time of harvest), the magnitude of disturbance was generally low at all sites. Similarly, post-harvest light availability was higher at Pine and Pine-N, but the differences among sites were small. Differences in vegetation response could also reflect variation in the soil seed bank, shaped by past disturbance. Post-harvest burn history—evident in the presence/absence of charred wood—differed at Bear and Pine. However, differences in disturbance history among sites should be expressed primarily in the ruderal flora because most forest understory species do not retain viable seeds in the soil (Archibold 1989, Halpern et al. 1999). Although the composition and diversity of ruderals varied among sites (greater development at Pine and Pine-N), ruderal cover remained generally low. Site differences were driven to greater degree by the responses of forest species, including both clonal and non-clonal species. The potential for significant variation among sites, or for significant site x treatment interactions among ostensibly similar forests, has important implications for broader application of these treatments. Short-term responses to thinning and gap creation can be unpredictable, even in forests in which pre-treatment structure is simple.

Finally, our results suggest that gap creation has a stronger effect on plant cover than it does on diversity. Effects were manifested primarily within the physical openings of the gaps, although gap influence extended into adjacent forest for some measures of response (e.g., herbaceous forest species). Similar localization of gap response has been observed in previous studies, even when gaps are

significantly larger (Fahey and Puettmann 2007, 2008). Gap creation resulted not only in a greater mean increase in cover, but in a broader distribution of local (quadrat-scale) responses.

Changes in species richness also suggest stronger responses to gap creation than to thinning, but regression analyses indicated that treatment effects were confounded by other sources of variation within sites (see above). Despite random assignment of treatments to experimental units, gap treatments tended to be assigned to EUs with higher *Thuja* density, thus to sites with greater potential for response. In contrast, at similar *Thuja* density, gap creation and thinning had similar effects on species richness.

Greater heterogeneity of resource availability or physical environments is thought to promote greater diversity of species with differing resource or environmental requirements (Huston 1994, Rosenzweig 1995). Although the spatial distribution of light (or soil moisture) may be more heterogeneous or complex in thinned treatments (e.g., see light maps in **Figs. 2 and 3**), there was no indication in the short term that this resulted in greater diversity of species, or of groups of species with differing environmental or resource requirements. Both treatments resulted in an increase in species number and in the equitability of species' abundance—responses that were further enhanced by variation in site characteristics.

4.3. Measures of Response

Physical effects.—Tree removal had strong and predictable effects on light availability. However, simulations suggest the potential for substantial variation among treatment replicates both in the amount and spatial distribution of light on the forest floor. This was not particularly surprising for the structured ecological thin given the random placement of removal circles, but was not necessarily expected for the gap treatment. Typically, thinning resulted in a greater proportion of the forest floor exposed to moderate levels of light, whereas gap creation produced a greater proportion of higher light values. However, light maps for Bear and Pine illustrated that in some instances, thinning may create spatial distributions of direct light very similar to those in gap treatments. Because tree removal also results in below-ground "gaps" (Gray et al. 2002, Griffiths et al. 2010), effects on soil moisture and nutrient availability may be similar to effects on light, and the benefits for understory plants may even be greater (Lindh et al. 2003). Studies of variation in light, soil moisture, and vegetation response across thinned and gap treatments may provide insight into the relative importance of increased light and soil resources for understory plants in these forests (Ketcheson, unpublished data).

Tree seedlings.— Tree regeneration patterns were dominated by *Tsuga heterophylla*, which was expected given its dominance of the overstory and the abundance of decayed wood on the forest floor. Responses to treatments (and preferential establishment on CWD) were consistent with the ecophysiological traits of *Tsuga* (e.g., tolerant of shade but susceptible to drought) and its distributions in natural, older forests (in gaps and on CWD; Christy and Mack 1984, Harmon and Franklin 1989, Spies et al. 1990, Gray and Spies 1997). Establishment was greater in thinned than in gap treatments, but in the latter, densities were higher in gaps than in adjacent forest. Within these openings, however, seedling densities at Bear and Pine were highly skewed to the south, in areas shaded by forest, and declined steeply to the north. Gray and Spies (1996) observed similar patterns in experimental gaps in mature and older forests. Surprisingly, *Pseudotsuga* and *Alnus*—typically viewed as shade-intolerant, "pioneering" species—displayed spatial distributions within the gaps that were very similar to *Tsuga*. This contrasts with theoretical predictions and empirical observations in other systems that suggest that tree species with differing life histories and regeneration requirements show niche segregation, or spatial partitioning of gaps in response to the environmental and resource gradients that characterize these forest openings (Denslow 1980, Gray and Spies 1996, Raymond et al. 2006). Moreover, *Pseudotsuga* showed consistently greater establishment in thinned than in gap treatments. In the

absence of ground disturbance, seedlings that germinate in areas of intense direct radiation appear unable to move root systems quickly enough through deep moss and organic layers to avoid summer desiccation (Gray and Spies 1997). In contrast, in areas of elevated diffuse light and (presumably) increased water availability, survival is enhanced, leading to greater density and diversity of tree species.

It is critical to acknowledge that current seedling populations are dominated by 1- to 3-yr-old individuals, and thus may continue to show high rates of mortality. We observed significant temporal variability within the controls—particularly at Bear—potentially obscuring variation among treatments. Cyclical patterns of seed availability and annual fluctuations in weather may continue to affect future regeneration patterns—diminishing or further magnifying the effects of treatments.

Vascular plant groups.— Changes in diversity and abundance of vascular plant communities were primarily attributable to the regeneration and growth of species present prior to disturbance, and only secondarily to colonization by ruderals. Although this is consistent with responses to thinning and gap creation in other systems (e.g., Fahey and Puettmann 2007, 2008, Davis and Puettmann 2009), we anticipated that ruderals would play a larger initial role in these forests—particularly in gaps—given the depauperate nature of the understory.

The ruderals that did invade included taxa with a diversity of regenerative strategies, but two modes of dispersal were common. The most abundant herbs included those with seeds that are transported long distances by wind (*Anaphalis margaritacea, Epilobium* spp., and *Lactuca muralis*). Thus, the limited presence (or absence) of these species at Bear was surprising. Ruderals also included genera such as *Rubus* and *Sambucus* which are known to maintain long-lived seeds in the soil (Olmstead and Curtis 1947, Livingston and Allessio 1968, Kellman 1970), suggesting former presence in the vegetation (synchronous with the early stages of regeneration in these stands), or more recent dispersal by frugivores (Kellman 1970, Haeussler and Coates 1986). Differences in the presence of these species among sites could be explained by variation in disturbance history or the stochastic nature of animal-mediated dispersal. As with the herbaceous species, however, they were noticeably absent from Bear. Other ruderal herbs characterized by more limited dispersal included the exotics, *Digitalis purpurea*, *Chrysanthemum leucanthemum*, and *Plantago major*. These were less frequent in thinned and gap treatments and are likely to have dispersed from local roadside vegetation, where they are fairly common.

It is possible that ruderals will contribute increasingly to the abundance and vertical structure of the understory in the near term (although this is unlikely at Bear). For example, *Epilobium angustifolium* can undergo clonal expansion for many years if overstory conditions remain open (Halpern 1989). Likewise, ruderals may become more prominent as shorter statured herbs are replaced by taller, longer-lived shrubs such as *Sambucus and Rubus* species.

As expected, ruderals showed significantly greater development in gaps than in thinned treatments. However, colonization was largely limited to the physical openings of gaps, with both cover and diversity tending to peak toward the centers of gaps. Similar distributional patterns have been observed in other studies of gap creation in young stands, including gaps of significantly larger size with presumably greater influence on surrounding forests (Fahey and Puettmann 2007, 2008). If a goal of gap creation is to enhance the abundance of early seral shrubs that produce berries or contribute to the structural development of the understory, any such effects are likely to be restricted to gap openings and not to extend into adjacent forest. Our results also suggest that the openings created by structured ecological thinning are not as efficient in stimulating germination of these species.

We expected that clonal herbs would show greater expansion than non-clonal species, given their potential for lateral growth under conditions of enhanced resource availability (Ashmun and Pitelka 1984, Lezberg et al. 1999, 2001). Clonal expansion was evident for some forest species that are typically

responsive to increases in light (e.g., *Trientalis latifolia* and *Galium triflorum*) (Anderson and Loucks 1973, Halpern 1989, Lindh 2008, Davis and Puettmann 2009). Relative increases in cover, however, were no larger than those of non-clonal species which, as a group, were more abundant and diverse. Expansion of clonal species may simply lag behind changes in resource availability given limited rhizome development in these formerly dense, dark stands (Lezberg et al. 2001).

Increases among non-clonal species may reflect both the growth of existing plants and the establishment of new individuals via sexual reproduction. Flowering and seed production in these species are uncommon in dense forests under conditions of severe resource limitation (McCall and Primack 1987, Lezberg et al. 2001). We did not quantify patterns of reproduction, but we did note increases in the frequency of flowering of many forest herbs, particularly under more open canopy conditions. Greater frequency of flowering among forest understory herbs and shrubs has been observed after thinning and in areas of lower density in untreated stands (Lindh and Muir 2004, Wender et al. 2004, Lindh 2008). We also observed dramatic increases in the frequency of occurrence of non-clonal ferns characteristic of moist, highly productive sites (*Athyrium* and *Blechnum*). We attribute these increases to recruitment, potentially from a spore bank (Cousens et al. 1985, Dyer and Lindsay 1992), rather than to growth of existing plants.

Bryophyte communities.— Forest bryophytes are rarely considered in studies of silvicultural or ecological thinning (but see Thomas et al. 1999, He and Barclay 2000, Davis and Puettmann 2009). Our studies provide unique opportunities to explore relationships among changes in overstory structure, light, substrates, and the population- and community-level responses of mosses and liverworts.

In contrast to herbaceous and woody species in this system, bryophytes showed consistently negative or neutral responses to treatments. Dramatic declines in the northern halves of gaps, where direct radiation and desiccation stress are greatest, are consistent with expectation. However, declines in cover in the controls (which were particularly large at Bear) make interpretation of treatment effects problematic. Declines were evident in both the main experiment and on CWD and forest-floor substrates in the bryophyte study. The latter confirmed that the broader decline affected both mosses and liverworts on both substrates. However, declines in cover were accompanied by increased richness of moss and liverwort species (even within gaps) and, for the vast majority of species, increases in frequency of occurrence. These trends suggest that declines in cover of community dominants (*Eurhynchium oreganum* and *Rhytidiopsis robusta*) led to competitive releases among subordinate species. However, we cannot explain the magnitude of decline in the controls, unless it relates to annual variation in climate (temperature, precipitation, or humidity) that affects plant performance or appearance. Future measurements of these plots should provide insight into the nature and persistence of these effects.

4.4. Effects of Retaining CWD After Thinning

Results of the CWD experiment suggest neutral to positive effects of retaining wood in the short term. Greater cover of fresh wood (and associated slash) resulted in greater density of conifer establishment (primarily *Tsuga*), possibly through the beneficial effects of shading. Although wood addition has the potential to suppress plant cover on the forest floor, there were no detectable effects of CWD on bryophytes (which declined substantially in both treatments), or on the cover or richness of vascular plants. The ecological roles of CWD are likely to change over time. Shading effects may be important immediately after thinning, but as canopies close and logs fragment or decay, they may contribute increasingly as rooting substrates for bryophytes, herbs, and woody plants; as reservoirs of moisture during summer drought; and as sources of soil nutrients (Harmon et al. 1986, Rambo and Muir 1998a, Six and Halpern 2008).

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6. Data Files and Documentation

In the pages that follow, we provide detailed documentation (metadata) about the core set of field data. All data are stored in MS Excel files, each containing one or more worksheets. The documentation tables below provide brief descriptions of the types of data, file and worksheet names, variable names and definitions, meanings of variable codes, and units of measurement. Previous data files described in the initial establishment report (Halpern et al. 2009) should replaced with the current data.

6.1. Data Files and Documentation for the Main Restoration Experiment

6.1.1. Main Restoration Experiment: Mapped overstory trees

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

File Name(s): Bear complete tree data 2005-2009.xls
Pine complete tree data 2005-2009.xls
Pine-N complete tree data 2005-2009.xls

File Contents:

Worksheet 1: Bear trees 2005-2009, Pine trees 2005-2009, or Pine-N trees 2005-2009

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	—	Numeric species code
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	Row	No	—	Row number of EU
I	Column	No	—	Column number of EU
J	Treatment	Yes	—	Type of treated or non-treated EU
K	StatusPre	Yes	—	Tree status prior to treatment (live or dead)
L	Status2007	Yes	—	Tree status after treatment (2007). Stems are noted as dead, alive, prone/tipped/snapped (live or dead), or as stumps. Used to create post-treatment stem maps.
M	Status2009	Yes	—	Tree status in 2009 (live or dead). Used to account for post-harvest tree fall (but not standing mortality). Only trees marked as prone, tipped, or snapped in 2007 were relocated and rechecked in 2009.
N	Cond2009	Yes	—	Tree condition in 2009. Used to describe the condition of trees marked as prone, tipped, or snapped in 2007 and to identify treefall since that time.

* 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.

— Continued on next page —

6.1.1. Main Restoration Experiment: Mapped overstory trees (continued)

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.

1	*Abies amabilis*	9	*Prunus emarginata*
2	*Abies procera*	10	*Abies amabilis* or *A. procera*
4	*Pseudotsuga menziesii*	11	*Acer macrophyllum*
5	*Thuja plicata*	14	*Taxus brevifolia*
6	*Tsuga heterophylla*	15	Unknown species
7	*Alnus rubra*	16	*Tsuga mertensiana*
8	*Populus trichocarpa*	17	Unknown hardwood species

Note: Sp.No. codes 3, 12, and 13 are not used.

Variable: Treatment

C	Control
G	Gap
T	Thin
X	area of the tree plot not used in the experiment

Variable: StatusPre

0	dead
1	alive

Variable: Status2007

0	dead
1	alive
2	prone, tipped, or snapped
5	stump
blank	not assessed (trees in areas of the tree plot not used in the experiment)

Variable: Status2009

0	dead or snag
1	alive
Blank	not assessed

Variable: Cond2009

1	standing (inferred if value recorded in the field was not 2-5)		
2	snapped	3	tipped
4	prone	5	stump
blank	not assessed		

6.1.2. Main Restoration Experiment: Post-treatment hemispherical photos

Description: Results of GLA analysis (light transmission) of post-treatment hemispherical photos (2007 photos reanalyzed in 2009).

File Name(s): All hemispherical photos 2010.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; negative numbers represent distances SW or SE of gap center; positive numbers represent 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 (Apr-Sep) transmitted by the canopy
R	Trans Dif	No	mols/m^2/day	Amount of diffuse solar radiation (Apr-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 (Apr-Sep) transmitted by the canopy
U	% Trans Dif	No	%	% of above-canopy diffuse solar radiation (Apr-Sep) transmitted by the canopy
V	% Trans Tot	No	%	% of above-canopy total solar radiation (Apr-Sep) transmitted by the canopy

* Site = Pine for EUs located in column 8 at Pine-N

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6.1.2. Main Restoration Experiment: Post-treatment hemispherical photos (continued)

File Contents: (continued)

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

6.1.2. Main Restoration Experiment: Post-treatment hemispherical photos (continued)

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 (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 (Apr-Sep) transmitted by the canopy
P	Trans Dif	No	mols/m^2/day	Amount of diffuse solar radiation (Apr-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 (Apr-Sep) transmitted by the canopy
S	% Trans Dif	No	%	% of above-canopy diffuse solar radiation (Apr-Sep) transmitted by the canopy
T	% Trans Tot	No	%	% of above-canopy total solar radiation (Apr-Sep) transmitted by the canopy

* Site = Pine for EUs located in column 8 at Pine-N

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

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6.1.2. Main Restoration Experiment: Post-treatment hemispherical photos (continued)

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

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

6.1.3. Main Restoration Experiment: Ground-surface characteristics

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

File Name(s): Bear ground cover 2006-2009.xls
Pine ground cover 2006-2009.xls
Pine-N ground cover 2006-2009.xls

File Contents:

Worksheet 1: Ground 2006 (pre-treatment)
Worksheet 2: Ground 2007 (post-treatment, year 1)
Worksheet 3: Ground 2009 (post-treatment, year 3)

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, ≥10 cm diameter)
O	DECAY	No	%	Cover of decayed wood (decay classes III-V, ≥10 cm diameter)
P	LITTER	No	%	Cover of fine litter (foliage or wood <10 cm diameter)

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6.1.3. Main Restoration Experiment: Ground-surface characteristics (continued)

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

* Site = Pine for EUs located in column 8 at Pine-N

† 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)

6.1.4. 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 2006-2009.xls
Pine understory species 2006-2009.xls
Pine-N understory species 2006-2009.xls

File Contents:

Worksheet 1: Species 2006 (pre-treatment)
Worksheet 2: Species 2007 (post-treatment, year 1)
Worksheet 3: Species 2009 (post-treatment, year 3)

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 → DX	Species cover	No	%	Projected canopy cover of the species listed in the column heading (cover of understory tree species was first recorded in 2009)

* Site = Pine for EUs located in column 8 at Pine-N

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

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6.1.4. Main Restoration Experiment: Understory plant composition (continued)

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 7, next page, for a full list of species codes and scientific names

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6.1.4. Main Restoration Experiment: Understory plant composition (continued)

Table 7. Database codes and scientific names of vascular plant species present in sample quadrats. Cover of understory tree species was sampled only in 2009. Nomenclature follows Hitchcock, C. L., and A. Cronquist. 1973. *Flora of the Pacific Northwest*. University of Washington Press, Seattle.

Code	Scientific name	Code	Scientific name
ACCI	*Acer circinatum*	HODI	*Holodiscus discolor*
ACRU	*Actaea rubra*	HYMO	*Hypopitys monotropa*
ACTR	*Achlys triphylla*	LAMU	*Lactuca muralis*
ADBI	*Adenocaulon bicolor*	LIBO2	*Linnaea borealis*
AGSC	*Agrostis scabra*	LICA3	*Listera caurina*
ANMA	*Anaphalis margaritacea*	LICO3	*Listera cordata*
ARSY	*Aruncus sylvester*	LILIAC	Liliaceae (unknown)
ASCA3	*Asarum caudatum*	LUCA2	*Luzula campestris*
ATFI	*Athyrium filix-femina*	LUPA	*Luzula parviiflora*
BENE	*Berberis nervosa*	LUZUL	*Luzula* species
BLSP	*Blechnum spicant*	LYCL	*Lycopodium clavatum*
CADE	*Carex deweyana*	MADI2	*Maianthemum dilatatum*
CAME2	*Carex mertensii*	MEFE	*Menziesia ferruginea*
CAREX	*Carex* species	OPHO	*Oplopanax horridus*
CASC2	*Campanula scouleri*	OSCH	*Osmorhiza chilensis*
CHLE2	*Chrysanthemum leucanthemum*	PLMA	*Plantago major*
CHME	*Chimaphila menziesii*	POGL4	*Polypodium glycyrrhiza*
CIAL	*Circaea alpina*	POLYPO	*Polypodiaceae* species
CIBR2	*Cirsium brevistylum*	POMU	*Polystichum munitum*
CIVU	*Cirsium vulgare*	PRVU	*Prunella vulgaris*
CLUN	*Clintonia uniflora*	PTAQ	*Pteridium aquilinum*
COCA	*Cornus canadensis*	PYCH	*Pyrola chlorantha*
COME	*Corallorhiza mertensiana*	PYMI	*Pyrola minor*
DEEL	*Deschampsia elongata*	PYROL	*Pyrola* species
DIFO	*Dicentra formosa*	PYSE	*Pyrola secunda*
DIPU	*Digitalis purpurea*	PYUN	*Pyrola uniflora*
DISPO	*Disporum* species	RIBES	*Ribes* species
DRAU2	*Dryopteris austriaca*	ROGY	*Rosa gymnocarpa*
EPAN	*Epilobium angustifolium*	RUBUS	*Rubus* species
EPILO	*Epilobium* species	RULA	*Rubus lasiococcus*
EPWA	*Epilobium watsonii*	RULE	*Rubus leucodermis*
EQUIS	*Equisetum* species	RUPA	*Rubus parviflorus*
GASH	*Gaultheria shallon*	RUPE	*Rubus pedatus*
GATR	*Galium triflorum*	RUSP	*Rubus spectabils*
GOOB	*Goodyera oblongifolia*	RUUR	*Rubus ursinus*
GRAMIN#	Unknown graminoid species	SADO	*Satureja douglasii*
GYDR	*Gymnocarpium dryopteris*	SARA	*Sambucus racemosa*
HAOR	*Habenaria orbiculata*	SESY	*Senecio sylvaticus*
HIAL	*Hieracium albiflorum*	SMST	*Smilacina stellata*

6.1.4. Main Restoration Experiment: Understory plant composition (continued)

Table 7. Continued.

Code	Scientific name	Code	Scientific name
STAM	*Streptopus amplexifolius*	**Tree species***	
STCR	*Stellaria crispa*	ABAM	*Abies amabilis*
STREP	*Streptopus* species	ABIES	*Abies* species
TAOF	*Taraxacum officinale*	ABPR	*Abies procera*
TITR	*Tiarella trifoliata*	ACER	*Acer* species (tree or shrub)
TRCA3	*Trautvetteria caroliniensis*	ACMA	*Acer macrophylum*
TRLA2	*Trientalis latifolia*	ALRU	*Alnus rubra*
TROV	*Trillium ovatum*	PIMO	*Pinus monticola*
UNKN#	Unknown species	POTR2	*Populus trichocarpa*
VAPA	*Vaccinium parvifolium*	PREM	*Prunus emarginata*
VEOF	*Veronica officinalis*	PSME	*Pseudotsuga menziesii*
VIGL	*Viola glabella*	SOSC2	*Sorbus scopulina*
VISE	*Viola sempervirens*	THPL	*Thuja plicata*
		TSHE	*Tsuga heterophylla*

* Sampled for cover in 2009 only

6.1.5. Main Restoration Experiment: Tree seedling counts

Description: Pre- and post-treatment counts of tree seedlings (<1.4 m tall) by height class.

File Name(s): Bear tree seedlings 2006-2009.xls
Pine tree seedlings 2006-2009.xls
Pine-N tree seedlings 2006-2009.xls

File Contents:

Worksheet 1: Seedlings 2006 (pre-treatment)
Worksheet 2: Seedlings 2007 (post-treatment, year 1)
Worksheet 3: Seedlings 2009 (post-treatment, year 3)

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). Negative numbers represent 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 → CL	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

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

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6.1.5. Main Restoration Experiment: Tree seedling counts (continued)

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

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
T	all classes combined

6.2. Data Files and Documentation for the Bryophyte Study

6.2.1. 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 2006-2009.xls

File Contents:

Worksheet 1: Bryophyte attributes 2006 (pre-treatment)
Worksheet 2: Bryophyte attributes 2007 (post-treatment, year 1)
Worksheet 3: Bryophyte attributes 2009 (post-treatment, year 3)

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 (X) for a quadrat reestablished in a new location in after logging due to disturbance
J	Dropped	Yes	—	Indicator (X) for a quadrat dropped from the analysis because it was reestablished after disturbance, data were missing, or there were other uncertainties about data quality
K	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 thinned treatments (2007 worksheet only)
L	U/D/G/F	Yes	—	General location within EU
M	Post X	No	m	The X coordinate (meters) within the EU of the reference post (PVC) to which quadrat was surveyed
N	Post Y	No	m	The Y coordinate (meters) within the EU of the reference post (PVC) to which quadrat was surveyed
O	D_to_post	No	m	Distance from center of quadrat to reference post

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6.2.1. Bryophyte Study: Quadrat locations, growth-form cover data (continued)

Excel column	Variable name	Coded	Units	Definition
P	Az_to_post	No	deg	Azimuth from center of quadrat to reference post
Q	X(site)	No	m	Distance along the X axis of the full tree plot
R	Y(site)	No	m	Distance along the Y axis of the full tree plot
S	X(EU)	No	m	Distance along the X axis within the EU
T	Y(EU)	No	m	Distance along the Y axis within the EU
U	MOSS	No	%	Total cover of mosses
V	LIVER	No	%	Total cover of liverworts
W	VASCUL	No	%	Total cover of vascular plant species
X	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 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)

Variable: Dropped

blank	quadrat retained for analysis
X	quadrat dropped from analysis because it was reestablished after disturbance, data were missing, or there were other uncertainties about data quality

6.2.2. Bryophyte Study: Disturbance

Description: Disturbance to substrates and slash cover data (post-treatment dates only; 2007 data were reassessed in 2009).

File Name(s): Bryophyte disturbance 2007-2009.xls

File Contents:

Worksheet 1: Bryophyte disturbance 2007 (post-treatment, year 1)
Worksheet 2: Bryophyte disturbance 2009 (post-treatment, year 3 [disturbance reassessed])

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 (estimated for forest floor quadrats only)
J	FRESH	No	%	Cover of fresh wood (decay class 1-2; ≥ 10cm diameter)
K	SLASH	No	%	Cover of logging slash, needles twigs, fine branches (<5 cm diameter)
L	%MISS	No	%	Percentage of CWD quadrat missing (removed) due to logging disturbance
M	%SCRAPED			Percentage of log surface scraped clean
N	%SMASHED			Percentage of surface of CWD quadrat smashed/ broken into pieces, or pulverized due to logging disturbance
N	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

6.2.3. Bryophyte Study: Bryophyte species

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

File Name(s): Bryophyte species 2006-2009.xls

File Contents:

Worksheet 1: Bryophyte species 2006 (pre-treatment)
Worksheet 2: Bryophyte species 2007 (post-treatment, year 1)
Worksheet 3: Bryophyte species 2009 (post-treatment, year 3)

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)

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6.2.3. Bryophyte Study: Bryophyte species (continued)

Coded Variables:

Variable: Species

(See Table 8, below, for a full list of species codes and scientific names)

Table 8. Codes and scientific names of bryophyte species recorded in quadrats at the Bear site.

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

† Includes at least *Calypogeia muelleriana* and *Calypogeia suecica*

* Includes *Cephalozia lunulifolia* and *Cephalozia bicuspidata*

6.2.4. Bryophyte Study: Tree seedling counts

Description: Tree seedling counts within bryophyte quadrats.

File Name(s): Bryophyte tree seedlings 2006-2009.xls

File Contents:

Worksheet 1: Bryophyte tree seedlings 2006 (pre-treatment)
Worksheet 2: Bryophyte tree seedlings 2007 (post-treatment, year 1)
Worksheet 3: Bryophyte tree seedlings 2009 (post-treatment, year 3)

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*
TABR	*Taxus brevifolia*
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

6.3. Data Files and Documentation for the CWD Experiment

6.3.1. CWD Experiment: Overstory trees

Description: Diameters (dbh) of all overstory trees (≥1.4 m tall).

File Name(s): Bear CWD complete tree data 2006-2009.xls

File Contents:

Worksheet 1: Bear CWD tree data 2006 (pre-treatment)
Worksheet 2: Bear CWD tree data 2009 (post-treatment, year 3)

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*

6.3.2. CWD Experiment: Ground-surface characteristics

Description: Cover of ground-surface characteristics and bryophytes.

File Name(s): Bear CWD ground cover 2006-2009.xls

File Contents:

Worksheet 1: Bear CWD ground cover 2006 (pre-treatment)
Worksheet 2: Bear CWD ground cover 2009 (post-treatment, year 3)

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 bryophyte cover
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)
ROCK	bare rock (2009 only)
SLASH	logging slash (<10 cm diameter) (2009 only)
STUMP	stump
BRYOP	bryophytes (mosses and liverworts)

6.3.3. CWD Experiment: Understory plant composition

Description: Cover of vascular plant species.

File Name(s): Bear CWD understory species 2006-2009.xls

File Contents:

Worksheet 1: Bear CWD understory spp 2006 (pre-treatment)
Worksheet 2: Bear CWD understory spp 2009 (post-treatment, year 3)

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

6.3.4. CWD Experiment: Tree seedling counts

Description: Counts of tree seedlings (<1.4 m tall) by height class.

File Name(s): Bear CWD tree seedlings 2006-2009.xls

File Contents:

Worksheet 1: Bear CWD tree seedlings 2006 (pre-treatment)
Worksheet 2: Bear CWD tree seedlings 2009 (post-treatment, year 3)

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)