Fuel treatment effects in ponderosa pine and dry mixed conifer forests: 17 Years after the Fire-Fire Surrogate Study

May 31, 2018

- **Ilana Abrahamson**, Supervisory Ecologist, Rocky Mountain Research Station - Fire, Fuel and Smoke Science Program
- **Cory Cleveland**, Professor of Terrestrial Ecosystem Ecology, W.A. Franke College of Forestry and Conservation, University of Montana
- **Justin Crotteau**, Graduate Student, W.A. Franke College of Forestry and Conservation, University of Montana
- **Tom DeLuca**, Dean and Professor, W.A. Franke College of Forestry and Conservation, University of Montana
- **Carl Fiedler**, Research Professor of Silviculture, W.A. Franke College of Forestry and Conservation, University of Montana
- **Mick Harrington**, Research Forester (Retired), Rocky Mountain Research Station - Fire, Fuel and Smoke Science Program
- **Sharon Hood**, Research Ecologist, Rocky Mountain Research Station - Fire, Fuel and Smoke Science Program
- **Chris Keyes**, Research Professor of Silviculture, W.A. Franke College of Forestry and Conservation, University of Montana

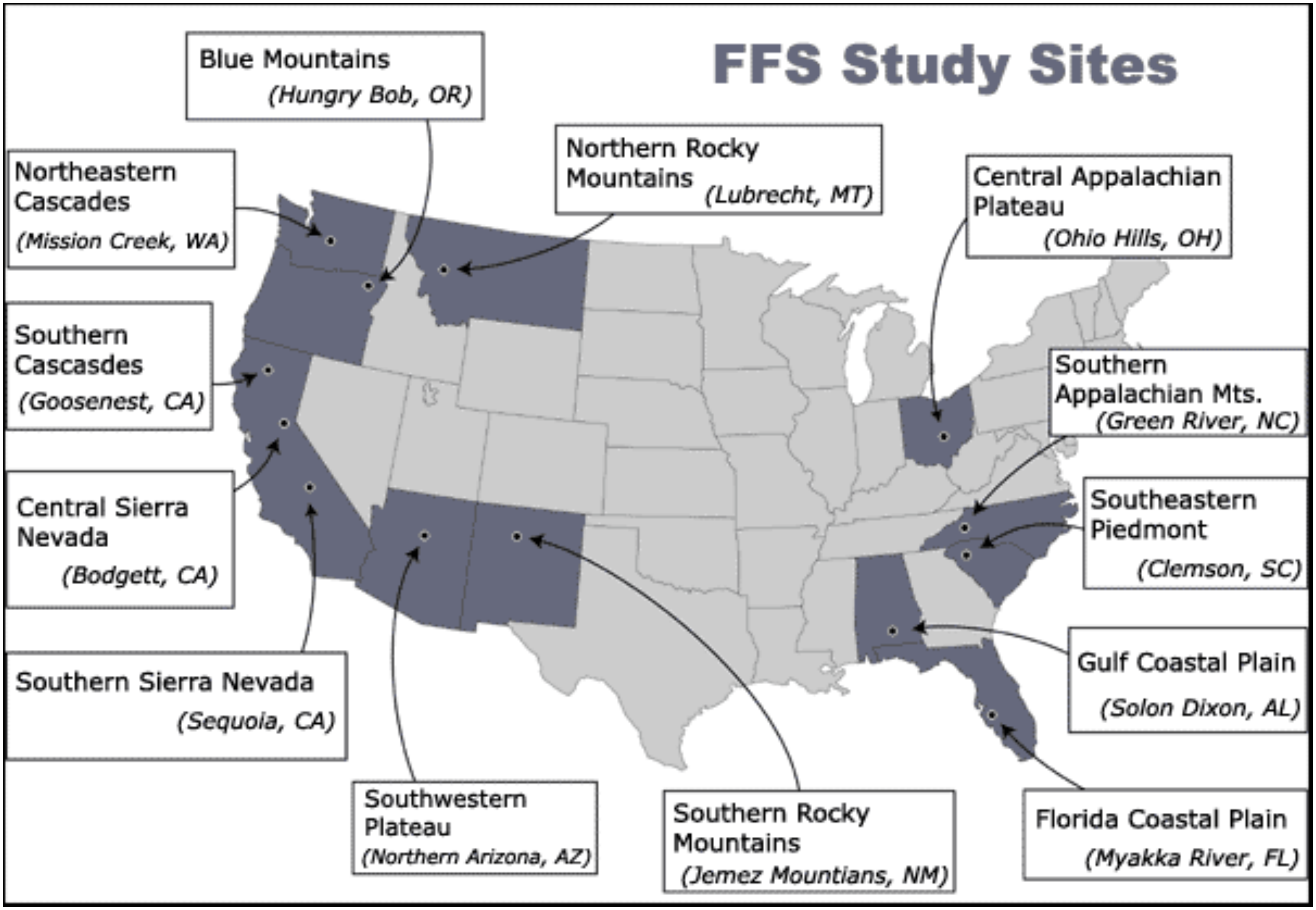
Additional resources provided by Kerry Metlen, Forest Ecologist, The Nature Conservancy, and Diana Six, Professor, W.A. Franke College of Forestry and Conservation, University of Montana

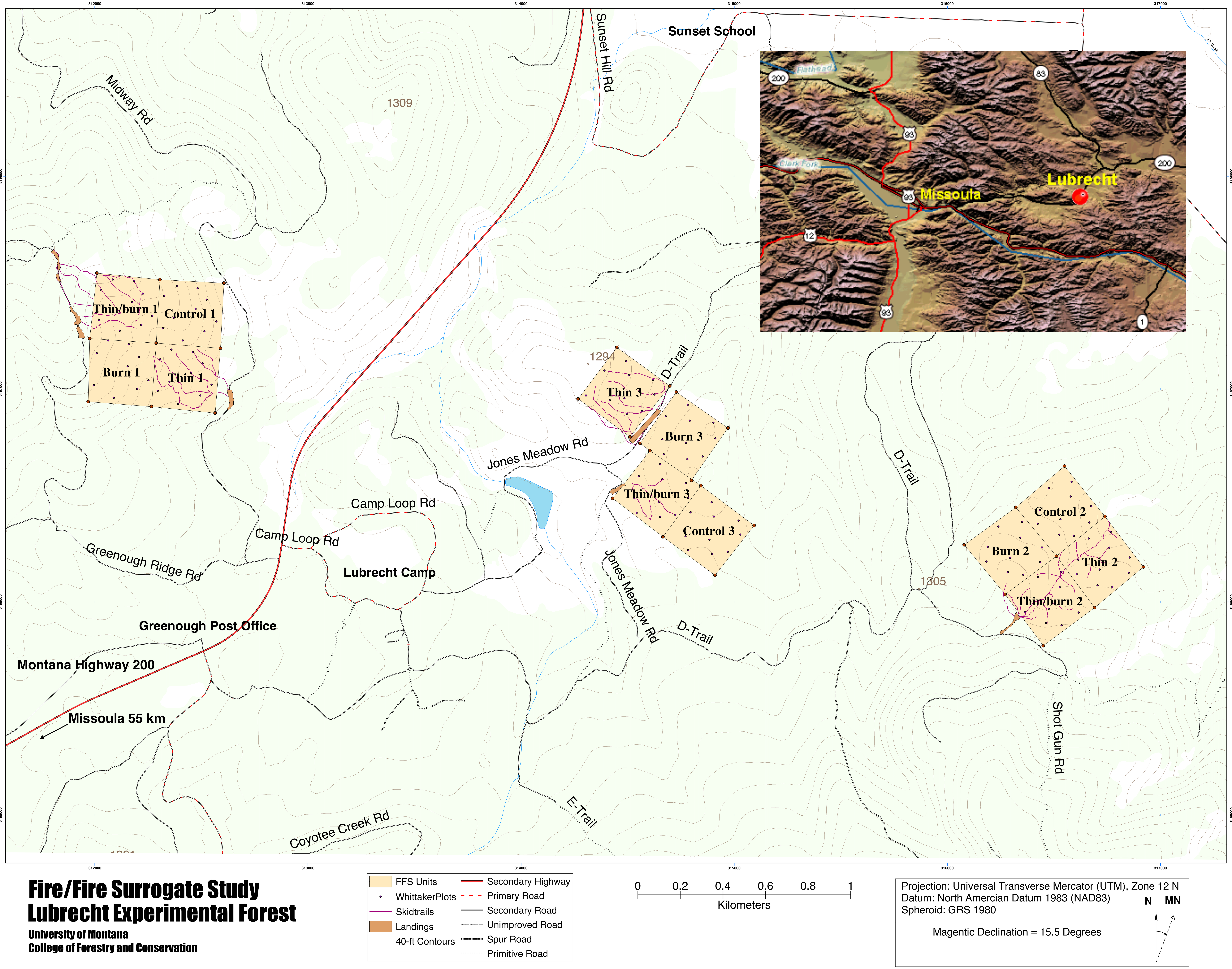
NORTHERN ROCKIES FIRE SCIENCE NETWORK A JFSP Knowledge Exchange Consortium

JOINT FIRE SCIENCE PROGRAM

Rocky Mountain Research Station

W.A. FRANKE COLLEGE OF FORESTRY & CONSERVATION UNIVERSITY OF MONTANA

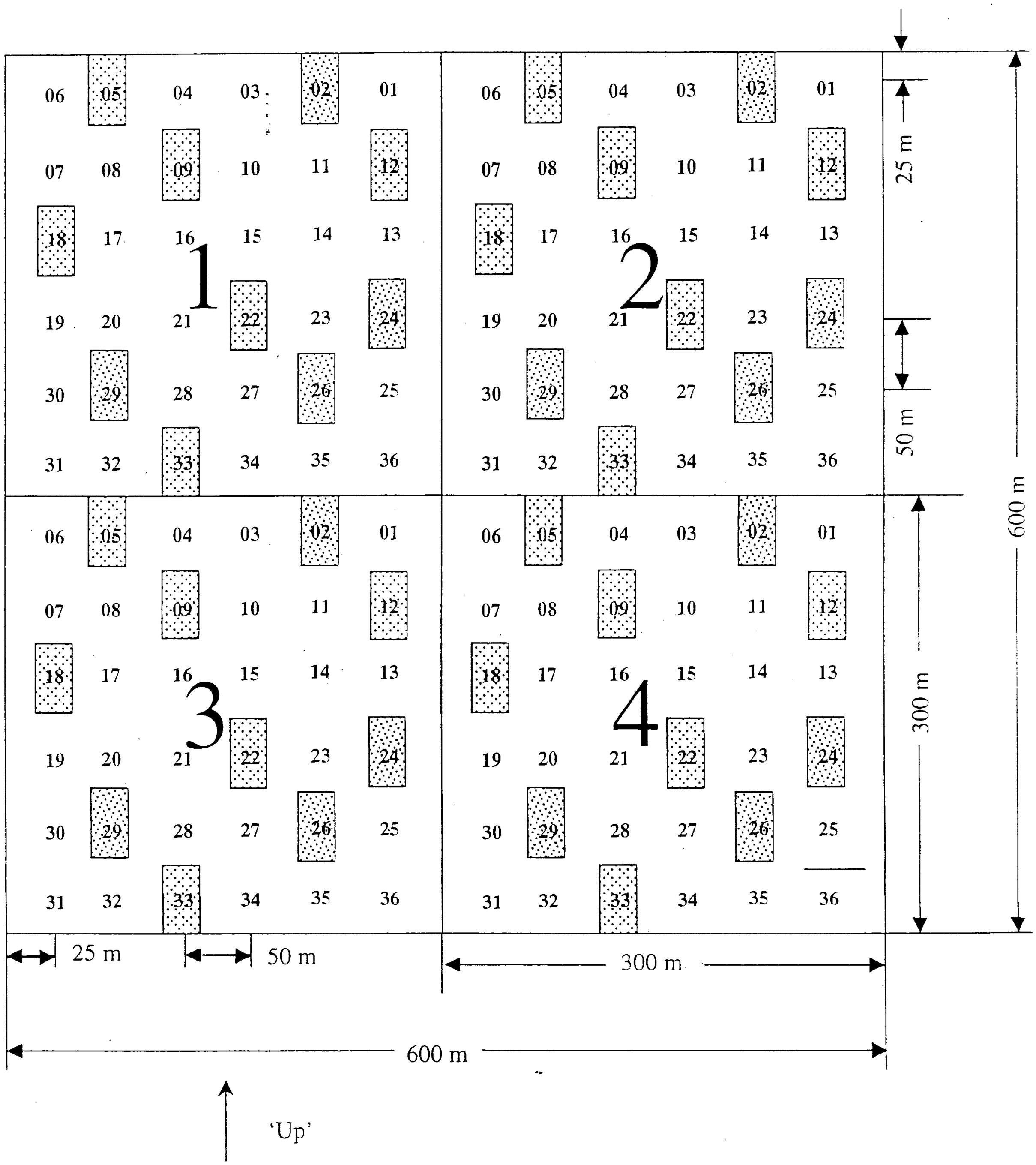

FFS Study Sites
Blue Mountains
(Hungry Bob, OR)
Northern Rocky Mountains
(Lubrecht, MT)
Northeastern Cascades
(Mission Creek, WA)
Central Appalachian Plateau
(Ohio Hills, OH)
Southern Cascasdes
(Goosenest, CA)
Southern Appalachian Mts.
(Green River, NC)
Central Sierra Nevada
(Bodgett, CA)
Southeastern Piedmont
(Clemson, SC)
Southern Sierra Nevada
(Sequoia, CA)
Gulf Coastal Plain
(Solon Dixon, AL)
Southwestern Plateau
(Northern Arizona, AZ)
Southern Rocky Mountains
(Jemez Mountians, NM)
Florida Coastal Plain
(Myakka River, FL)



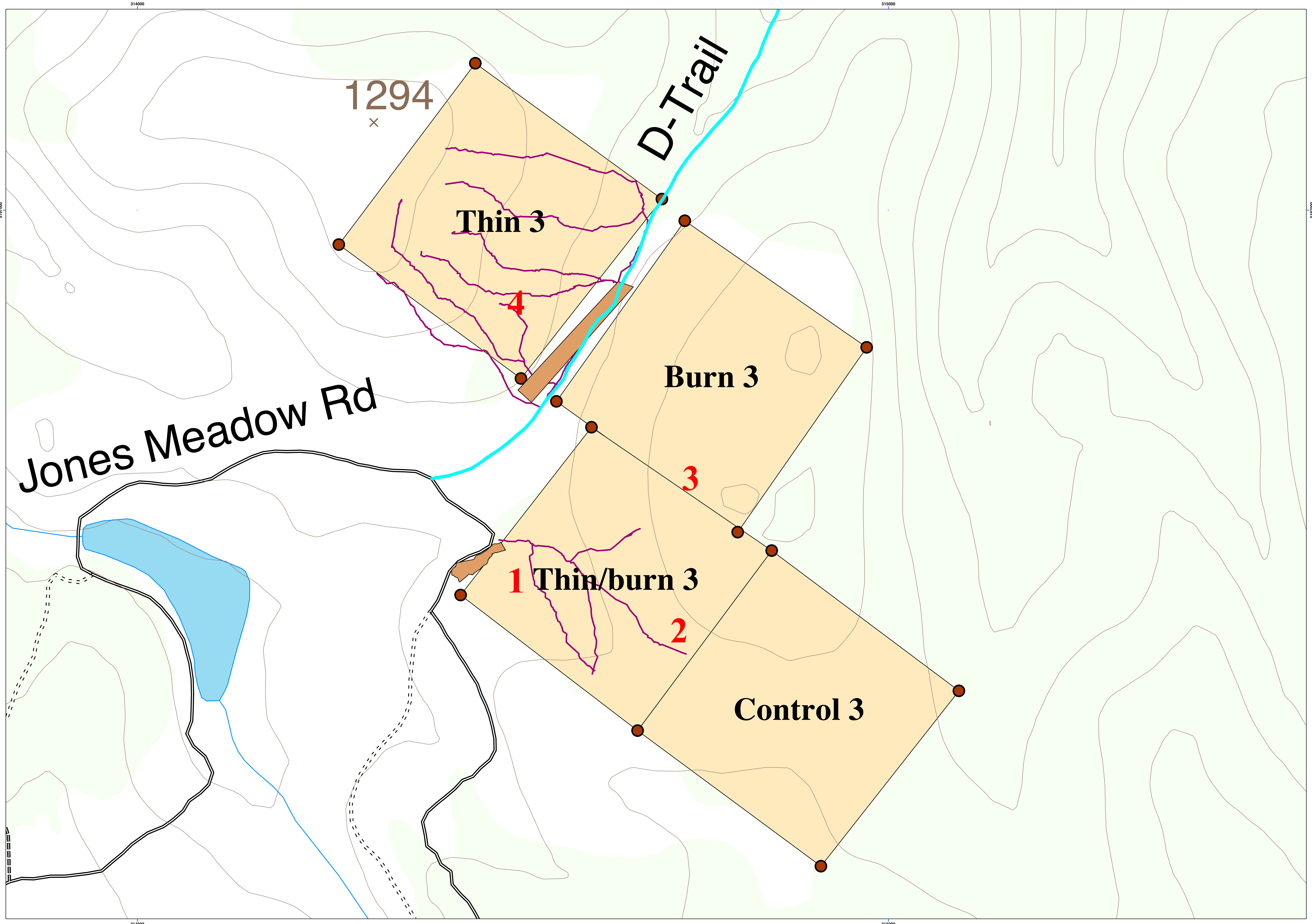
Fire/Fire Surrogate Study
Lubrecht Experimental Forest

University of Montana
College of Forestry and Conservation

Figure 1: Each block is comprised of four units. Within each unit there are 36 points and ten Whitaker plots (⬚ = Whitaker Plots) centered on their respective points. Fuel Transects are located at each point. Coarse woody debris transects are located at every other point (odd-numbered points).



Block 1 'up' = 268 degrees Block 2 'up' = 50 degrees Block 3 'up' = 39 degrees



Block 3 - Fire/Fire Surrogate Study
Lubrecht Experimental Forest
University of Montana
College of Forestry and Conservation

FFS Units
Skidtrails
Landings
40-ft Contours
Secondary Highway
Primary Road
Secondary Road
Unimproved Road
Spur Road
Primitive Road

0 0.06 0.12 0.18 0.24 0.3
Kilometers

Projection: Universal Transverse Mercator (UTM), Zone 12 N
Datum: North Amercian Datum 1983 (NAD83)
Spheroid: GRS 1980

Magnetic Declination = 15.5 Degrees

N MN

Lubrecht Fire-Fire Surrogate (FFS) Study: Treatment Overview

Silvicultural Cutting Treatments
Four treatments (*control*, *burn-only*, *thin-only*, and *thin-burn*) were evaluated for their effectiveness in moving stands toward desired future conditions (i.e., relatively open, large-tree dominated, primarily ponderosa pine/seral species composition, uneven-aged, randomly arranged, with scattered openings).

- The *control* treatment involved no thinning or burning.
- The *burn-only* treatment involved prescribed broadcast burning in the spring.
- The treatment referred to as *thin-only* (for consistency with FFS terminology) included low thinning and improvement/selection cutting.
- The *thin-burn* treatment included low thinning and improvement/selection cutting, followed by broadcast burning the following spring.

All treatment units were leave-tree marked to the target basal area (BA) density before treatments were assigned so that a subset of similar trees could be directly compared among treatments in the future (target BA = 48 ft^2/ac over each 25-ac treatment unit, although density varied considerably over any given acre). Marking favored healthy, larger (≥16-in DBH) trees in the following order: PP>WL>LP>DF. Modest numbers of healthy, medium-sized and smaller ponderosa pines were also marked for leave, if available, until the target reserve basal area density was achieved, and to make progress toward the desired uneven-aged structure.

Treatments Evaluated
- *Control* (no treatment; ~105 ft^2/ac BA in existing uncut stand)
- *Burn-only* (spring broadcast burn)
- *Thin-only* (48 ft^2/ac reserve BA; PP>WL>LP>DF)
- *Thin-burn* (48 ft^2/ac reserve BA; PP>WL>LP>DF); spring broadcast burn)

Burning Treatments
- All six burn units were scheduled for treatment in the spring of 2002 after slash from the cut units had one season of drying.
- The six burns were conducted between May 1 and June 25, 2002.
    - The May and early June dates coincide well with typical low-elevation prescribed underburning in this region.
    - The last burn was outside of the normal seasonal burning window with significant ‘greenup’ and the progression towards the classic wildfire season.
- Controlled strip-headfires were used on all burns by 3-5 igniters directed by an ignition specialist. Typically, slow ignition with short strips (15-20ft) was used in the Cut/Burn units to reduce flame lengths in slash concentrations and minimize tree injury, contrasted to rapid, continuous ignition (30-40ft strip widths) in lighter fine fuel loadings in the Burn Only units to increase flame lengths to kill trees.

Table 1. Timing, weather, and fuel moisture conditions for the Lubrecht FFS burns.

Parameters	Unit 1-2	Unit 1-1	Unit 3-3	Unit 2-4	Unit 3-2	Unit 2-3
Treatment	Cut/Burn	Burn	Cut/Burn	Cut/Burn	Burn	Burn
Date	5/1/02	5/15/02	5/31/02	6/6/02	6/14/02	6/25/02
Burn Times	1020-1800	1100-1530	1100-1700	1300-1830	1030-1600	1100-1600
Temp. Range (F)	53-56	48-53	64-80	57-64	67-83	67-83
R.H. Range (%)	28-42	35-46	20-29	27-45	20-41	26-48
Wind sp. (mph)	2-5	1-3	3-6 g=8	4-8 g=13	1-3	1-3
Fuel Moisture (%)						
Litter	9	13	7	10	9	11
1-Hour	14	13	13	15	10	12
10-Hour	21	12	21	23	22	11
100-Hour	33	23	29	24	51	16
1000-Hr sound	55	50	44	44	60	36
1000-Hr rotten	63	77	80	63	131	38
Duff	38	28	44	94	40	40

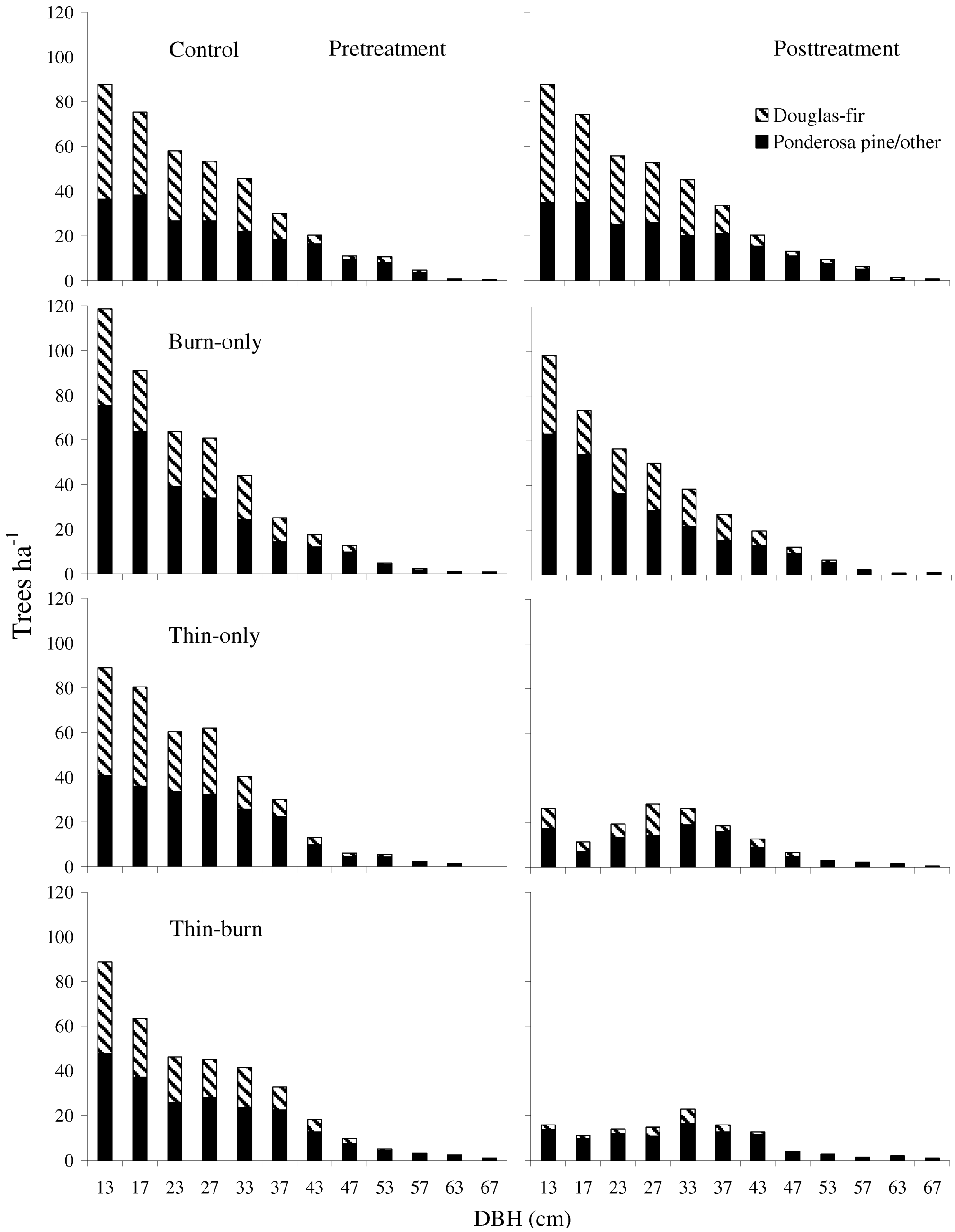


Figure 1. Pretreatment (2001) and post-treatment (2005) tree density (trees/ha >10 cm dbh), by 5-cm diameter class and treatment.

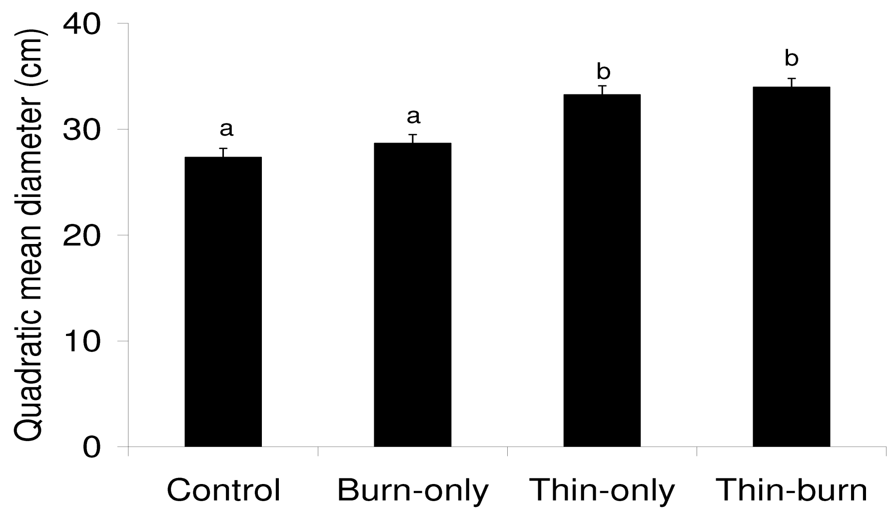


Figure 2. Change in quadratic mean diameter (QMD) from pretreatment to 2005, by treatment, for trees >10cm dbh.

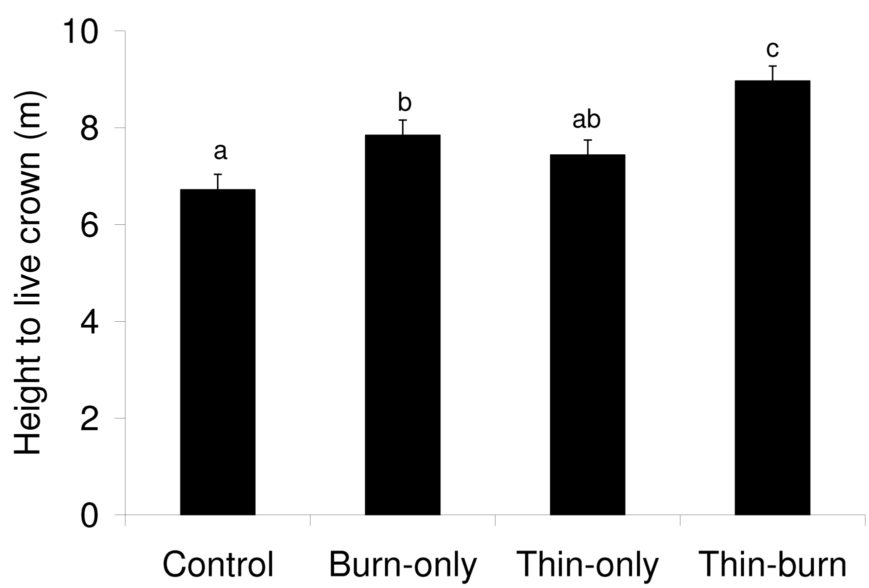


Figure 3. Change in height to live crown (HLC) from pretreatment to 2005, by treatment, for trees >10cm dbh.

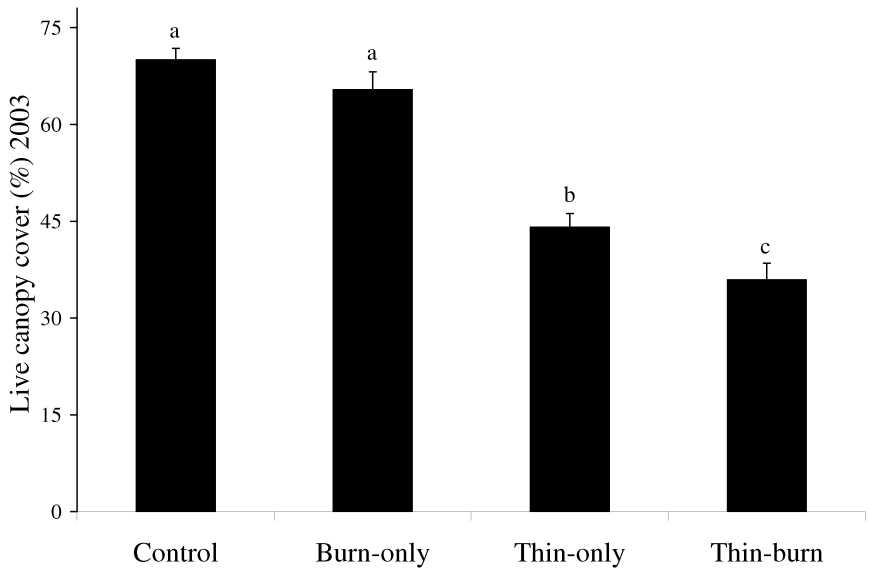


Figure 4. Post-treatment live canopy cover (CC) in 2003, one year after burning and two years after thinning, by treatment.

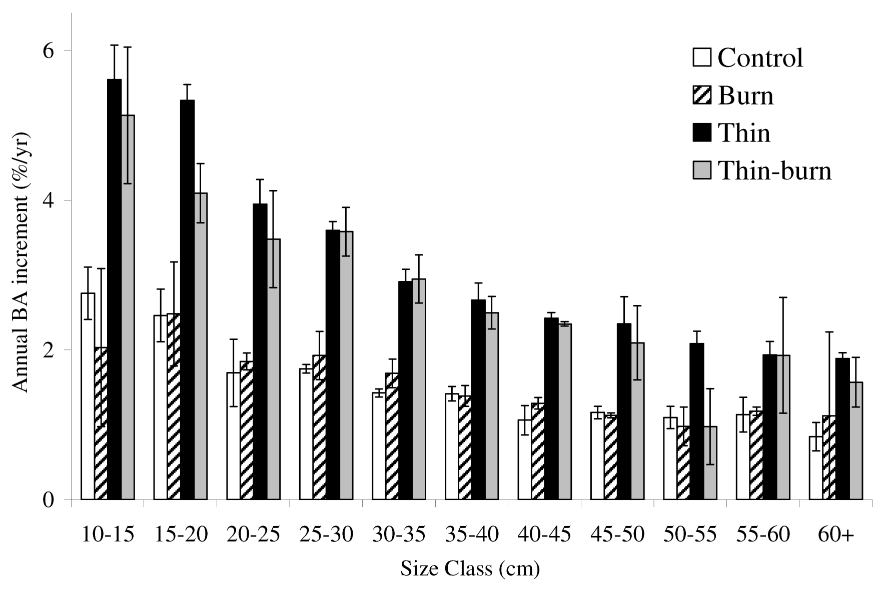


Figure 5. Average annual basal area increment (BAI) for leave trees, by treatment and initial 5-cm diameter class.

Short-Term Thinning and Burning Effects on Fuels – Mick Harrington

Objectives
To assess live and dead, surface and ground fuel loadings prior to treatments, after thinning, and after prescribed burning to determine the effects of these activities on fuel quantity and quality. Additionally, fuel consumption will be an independent variable for explaining fire impacts on other site attributes.

Methods
Pretreatment biomass of surface down and dead woody fuels was estimated along two 50ft long Brown transects at each of the 36 grid points. Duff depth was measure at 2 points, shrub biomass in 2 subplots, and small tree biomass in 1 subplot. Accurate depth measurements of the shallow litter layer were not possible, so it was destructively sampled from 2, 1ft^2 subplots at each of the 36 grid points per unit (72 total). A depth to loading regression for each block of 4 units was developed for the duff layer by destructively sampling 13 points per unit or 52 points per block. The regressions were somewhat similar among blocks but were more accurate by keeping the blocks separate. Most duff layers were less than 2 inches deep so layer separation was not necessary. This fuel sampling methodology was also followed for post-burn assessment in the burn only units.

It became apparent that Brown's transect method would be inaccurate in the Cut/Burn and Cut Only units. The cut-to-length processor that cut and limbed the trees deposited the branch wood in piles and then drove over them causing significant compaction. Accurately counting intercepts within these piles was tested and found to be challenging and disruptive to the fuel bed. A new technique was used in which one, 1ft^2 sample of all fuels less than 1 inch in diameter (litter, 1-hour, and 10-hour) were collected on each transect, separated into different fuel components, and oven-dried. Fuels larger than 1 inch (100-hour and 1000-hour) were counted along each transect as in pretreatment sampling.

Duff depth reduction in the burn units was measured with four, 8-inch spikes located around each grid point. The top of the spike was placed at the top of the duff beneath the litter layer. After the burns, the exposed spike length equaled the duff depth consumed and the length of the spike to mineral soil equaled total duff depth.

To assess burn severity, each foot along the 50ft transects was given 1 of 4 qualitative ratings; no burn, light burn (surface little burned, little duff consumed), moderate burn (duff mostly consumed, much charred material remaining), severe burn (all fuels consumed, no organic matter remaining, soil color changed). This resulted in burn severity ratings along 3600 linear feet in each unit.

Preliminary results
Pre- and post-treatment fuel loadings by treatment are shown in Table 1. Quantities of pretreatment fine fuels (litter + 1Hr, 10-Hr, and 100-Hr) were similar among treatments with the exception of the litter which was twice as high in the control units as the others.

Table 1. Pre-and post-treatment surface fuel loadings (tons/acre) and duff depths (inches) by treatment (shrub and small tree biomass is not reported).

		Litter+1Hr	10-Hr	100-Hr	1000-Hr	Duff Depth
Burn	preburn	1.00	0.73	0.82	6.07	0.77
Only	postburn	0.30	0.44	0.48	2.02	0.55
Cut	preharvest	0.95	0.74	0.71	4.19	0.98
Only	postharvest	2.76	3.33	3.31	4.24	0.84
Cut/	preharvest	0.87	0.71	0.66	3.79	1.14
Burn	postharvest	4.18	3.28	3.87	5.28	0.90
	postburn	0.43	0.93	2.06	2.59	0.72
Control		2.07	0.73	1.01	8.05	1.33

Duff was also deeper in the controls by 15 to 42%. One-thousand-Hr fuels ranged from about 4 to 8 tons/acre with 65 to 85% classified as rotten material.
Harvesting increased fine fuels 4 to 5 fold. One-thousand-Hr fuels increased modestly because, even though new material was added, a general reduction of rotten logs occurred with destruction by logging equipment. A slight decrease in duff depth resulted from harvesting.
Burning reduced fine fuels by 50% in Burn Only units and 70% in Cut/Burn units, where 10-Hr and 100-Hr fuels remained above pretreatment levels. Duff depths decreased by 20 to 30% with burning.
Burn severity was quite variable between and within treatments. Treatment comparisons follow:

Treatment	None	Low	Moderate	High
Burn only	37%	52%	6%	5%
Cut/burn	32%	50%	15%	4%

Both burn treatments left about 1/3 of the area unburned on average but, for example, one Cut/Burn unit had 48% unburned and another had only 15%. In this latter unit, 29% of the 3600ft of transect length was occupied with slash, compared to about 15% on the other two Cut/Burn units. The Cut/Burn units experienced 19% in the combined high and moderate burn severity range compared to 11% for the Burn Only. This indicates that even though the cut/burn units had a greater average duff depth remaining (Table 1), they had more places with no duff.

454 ILANA L. ABRAHAMSON ET AL. Ecological Applications Vol. 21, No. 2

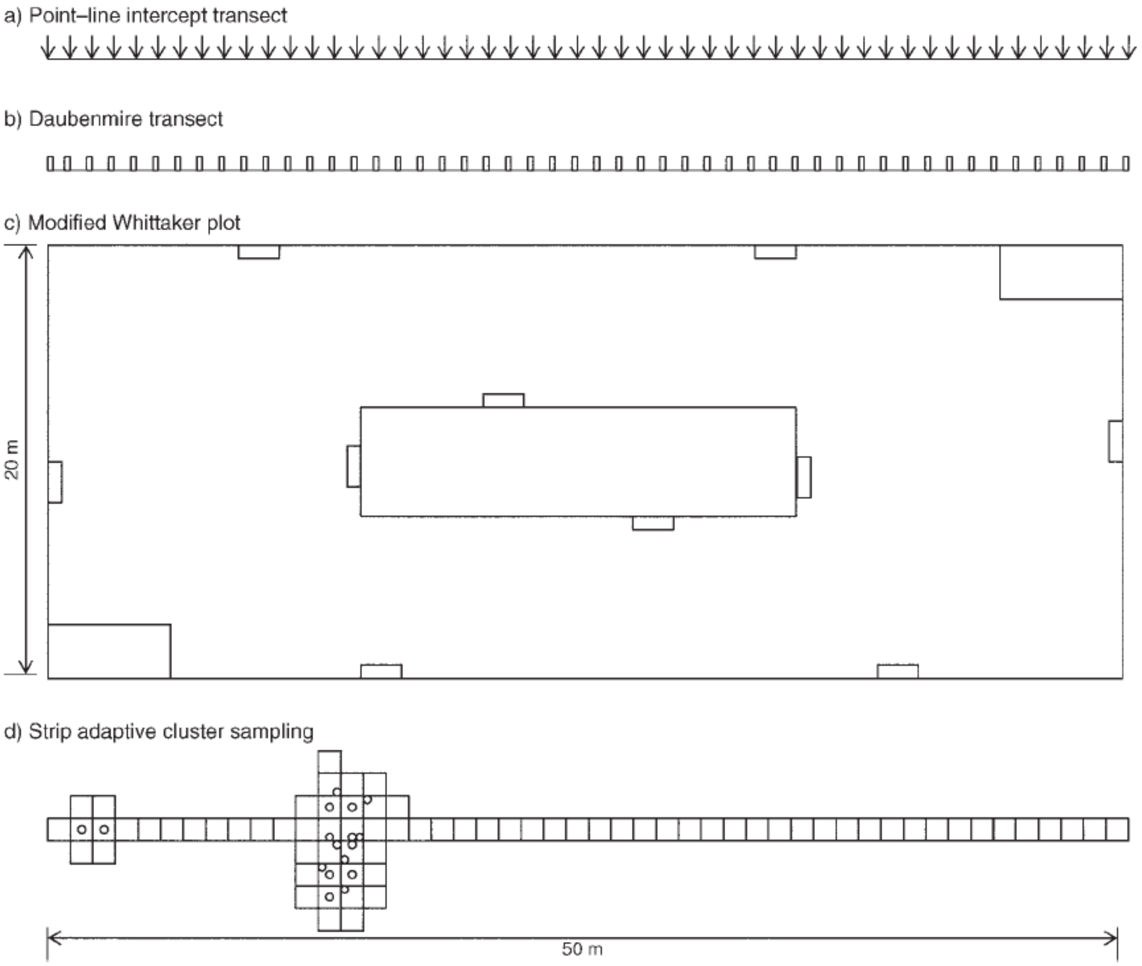


FIG. 1. The four sampling designs tested for estimating cover of forest understory plants in western Montana, USA: (a) point–line intercept transect, 166 points spaced every 30 cm; (b) Daubenmire transects, fifty 20 × 50 cm subplots; (c) modified Whittaker plots, ten 1-m^2 quadrats, two 10-m^2 subplots, one 100-m^2 subplot, within full 20 × 50 m plot; (d) strip adaptive cluster sampling initial transect, fifty 1 × 1 m subplots.

We tested conventional (modified Whittaker plots and Daubenmire and point–line intercept transects) and novel (strip adaptive cluster sampling [SACS]) approaches to sampling understory plants to determine their efficacy for quantifying abundance on control and thinned-and-burned treatment units.

For species grouped by growth-form and for common species, all three conventional designs were capable of estimating cover with a 50% relative margin of error with reasonable sample sizes (3–36 replicates for growth-form groups; 8–14 replicates for common species); however, increasing precision to 25% relative margin of error required sample sizes that may be infeasible (11–143 replicates for growth form groups; 28–54 replicates for common species).

All three conventional designs required enormous sample sizes to estimate cover of nonnative species as a group (29–60 replicates) and of individual less common species (62–118 replicates), even with a 50% relative margin of error. SACS was the only design that efficiently sampled less common species, requiring only 6–11% as many replicates relative to conventional designs.

Conventional designs may not be effective for estimating abundance of the majority of forest understory plants, which are typically patchily distributed with low abundance, or of newly establishing nonnative plants. Novel

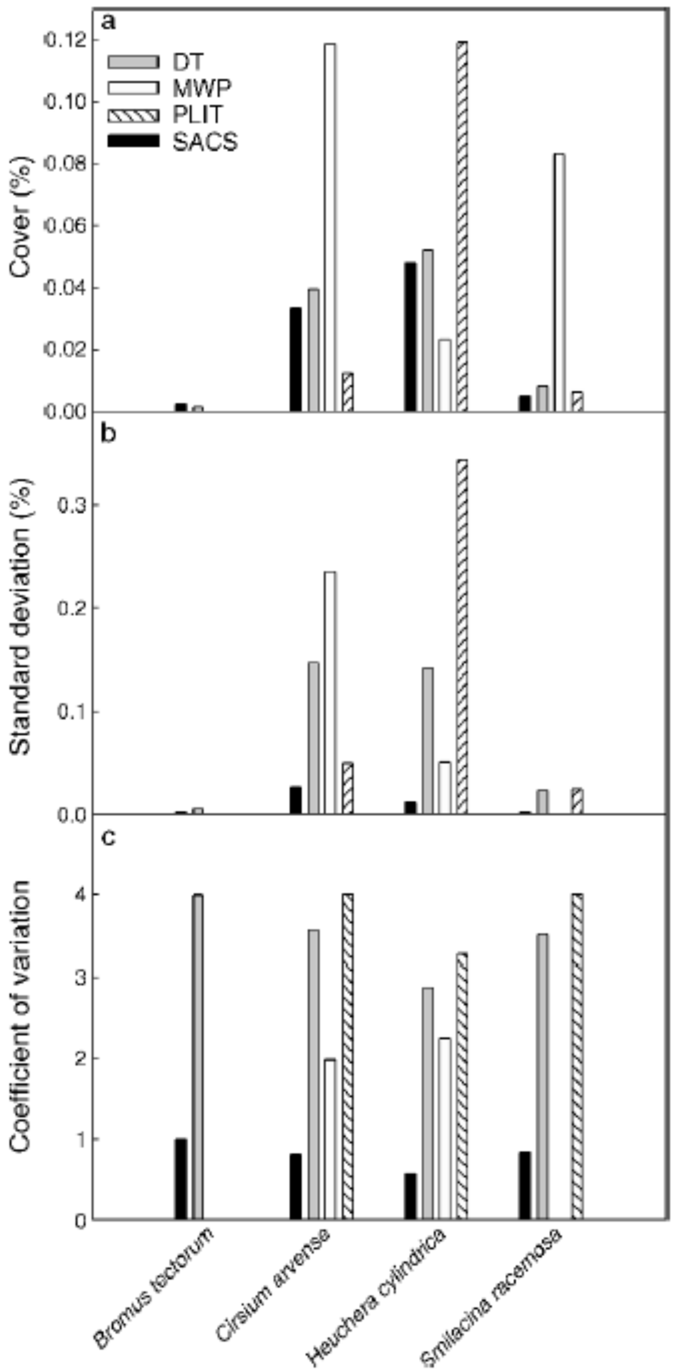


FIG. 4. Sampling results for the four species sampled using strip adaptive cluster sampling (SACS). (a) Percent cover, (b) within-stand standard deviation, and (c) coefficient of variation for the four species sampled using SACS as well as the three multispecies designs (DT, MWP, and PLIT; see Fig. 3 legend for sampling abbreviations). Coefficient of variation for *Bromus tectorum* and *Cirsium arvense* is based on data only from the thinned-and-burned stands; these species were absent or present on only one control stand.

Abrahamson, I. L., Nelson, C. R. and Affleck, D. L. R. (2011), Assessing the performance of sampling designs for measuring the abundance of understory plants. Ecological Applications, 21: 452–464. doi:10.1890/09-2296.1

Vegetation Response to Fire and Fire Surrogate Treatments – Kerry Metlen

Early, ugly vegetation crew. Blame these guys.

Site Leader Meeting, Blackfoot Montana 2004. Who's Who?

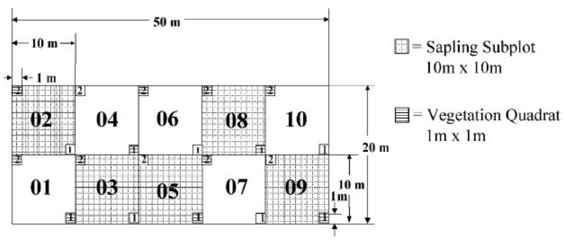


Fig. 3. Schematic of a modified Whittaker plot used to sample vegetation at the FFS site at Lubrecht Forest. Understory species richness was sampled on the entire plot. Understory richness and cover were sampled on twelve 1 m × 1 m quadrats dispersed throughout the plot. Saplings were tallied on five subplots.

Metlen & Fiedler 2006

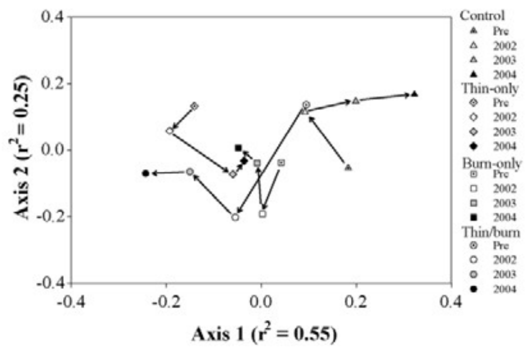
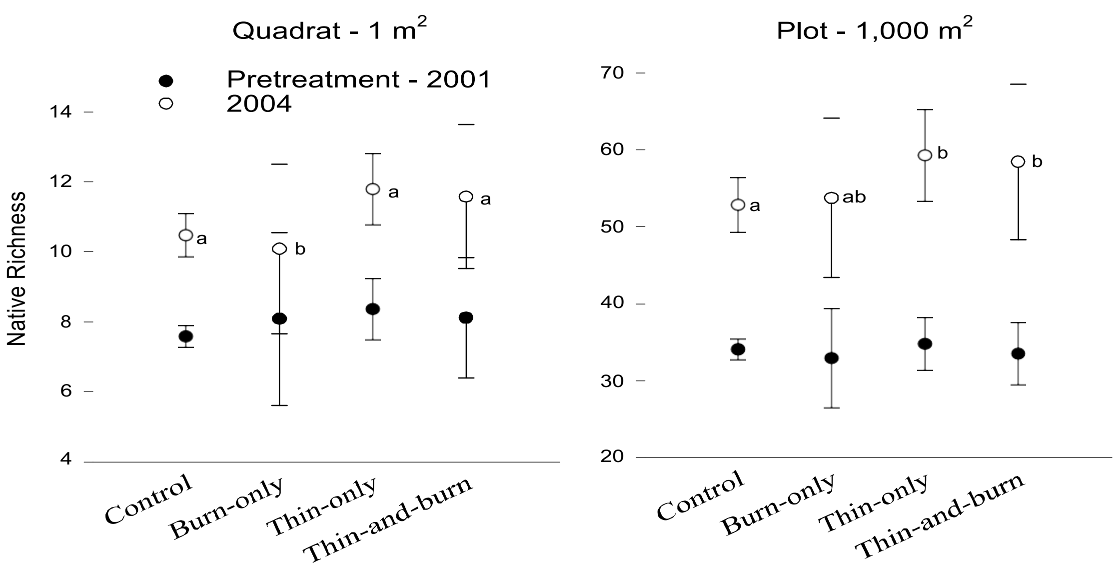


Fig. 4. NMS ordination of the understory plant community at the Lubrecht Forest FFS site before treatment and in the three subsequent years. Individual species covers were aligned to the block median cover (for each species) before analysis.



New Figure: Native richness (mean +/- 2 standard error, N=3) at two scales, the 1 m^2 quadrat and the 1,000 m^2 plot, before (2001) and after fire and fire surrogate treatments (2004) at Lubrecht forest. Letters indicate significant differences within the year of measurement from Metlen & Fiedler (2006).

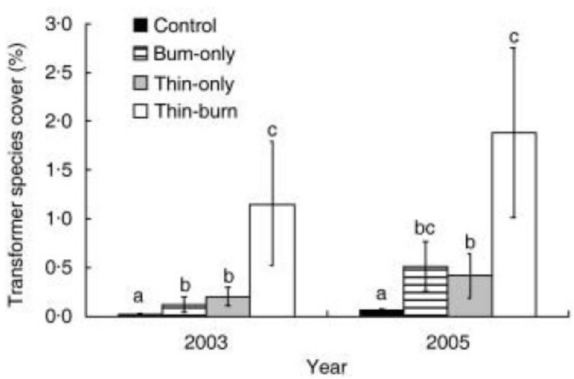


Fig. 1. Treatment means and standard errors (n = 3) for transformer species cover at the subplot level (100 m^2) in each treatment in 2003 and 2005. BMRPP was used to test for treatment differences within years (n = 3). Where differences occurred, pair-wise MRPP tests of plot-level data (n = 30) were used to test for between-treatment differences (represented by different letters). Pair-wise comparisons were adjusted by a Bonferroni procedure.

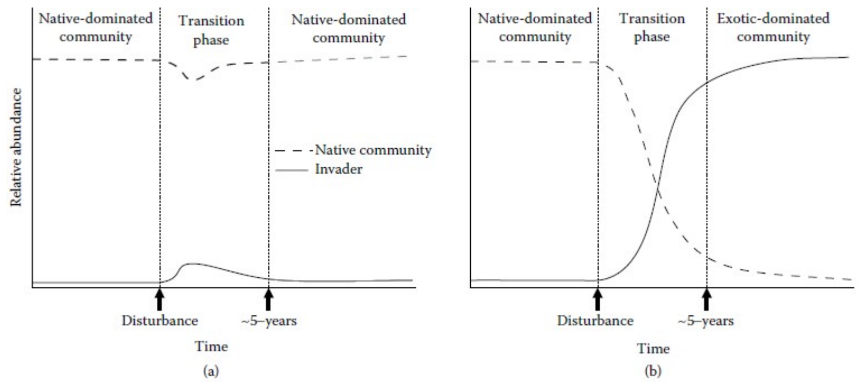


Figure 8.2 (a) Typical short-term (≤5 years) response of exotic species to thinning and burning (restoration) treatments, based on ongoing experiments at numerous locations across the West. These studies provide evidence that exotic invaders are not transforming native plant communities during the first few years after treatment, as exotic species cover average <2% at nearly all sites. Dashed lines (in gray) extended after the fifth year indicate expected native and exotic relative abundances based on current trends. (b) Hypothesized transformation of the plant community by exotics if changing environment or propagule pressure allows exotic species to increase and dominate the community over longer time periods (i.e., >5 years).

Dodson & Fiedler 2006

Fiedler, Dodson, & Metlen 2010

Abella & Springer (2015)

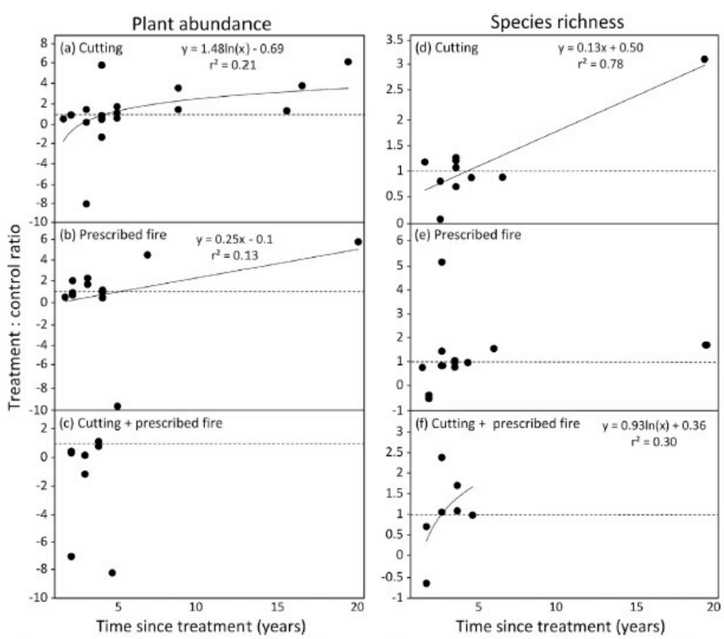


Fig. 3. Relationship between time since treatment and response of total understory plant abundance (cover, biomass, or density) and species richness among treatments in mixed conifer forests of western North America. Treatment : control ratios exceeding 1.0 (above broken horizontal lines) indicate that treatments increased understory measures. Note how the longest-term studies, exceeding 6 years post-treatment, usually found that treatments increased understory measures. Coefficients of determination (r^2) are given when they exceeded 0.10 (note for [d], the high r^2 largely results from the single long-term study).

Citations

Abella, S. R., and J. D. Springer. 2015. Effects of tree cutting and fire on understory vegetation in mixed conifer forests. Forest Ecology and Management **335**:281-299.

Dodson, E. K., and C. E. Fiedler. 2006. Impacts of restoration treatments on alien plant invasion in Pinus ponderosa forests, Montana, USA. Journal of Applied Ecology **43**:887-897.

Fiedler, C. E., E. K. Dodson, and K. L. Metlen. 2010. Invasive Plant Response to Forest Disturbance in the Western United States. *in* S. Jose and H. P. Singh, editors. Invasive Plant Ecology. CRC Press, Boca Raton, FL.

Metlen, K. L., and C. E. Fiedler. 2006. Restoration treatment effects on the understory of ponderosa pine/Douglas-fir forests in western Montana, USA. Forest Ecology and Management **222**:355-369.

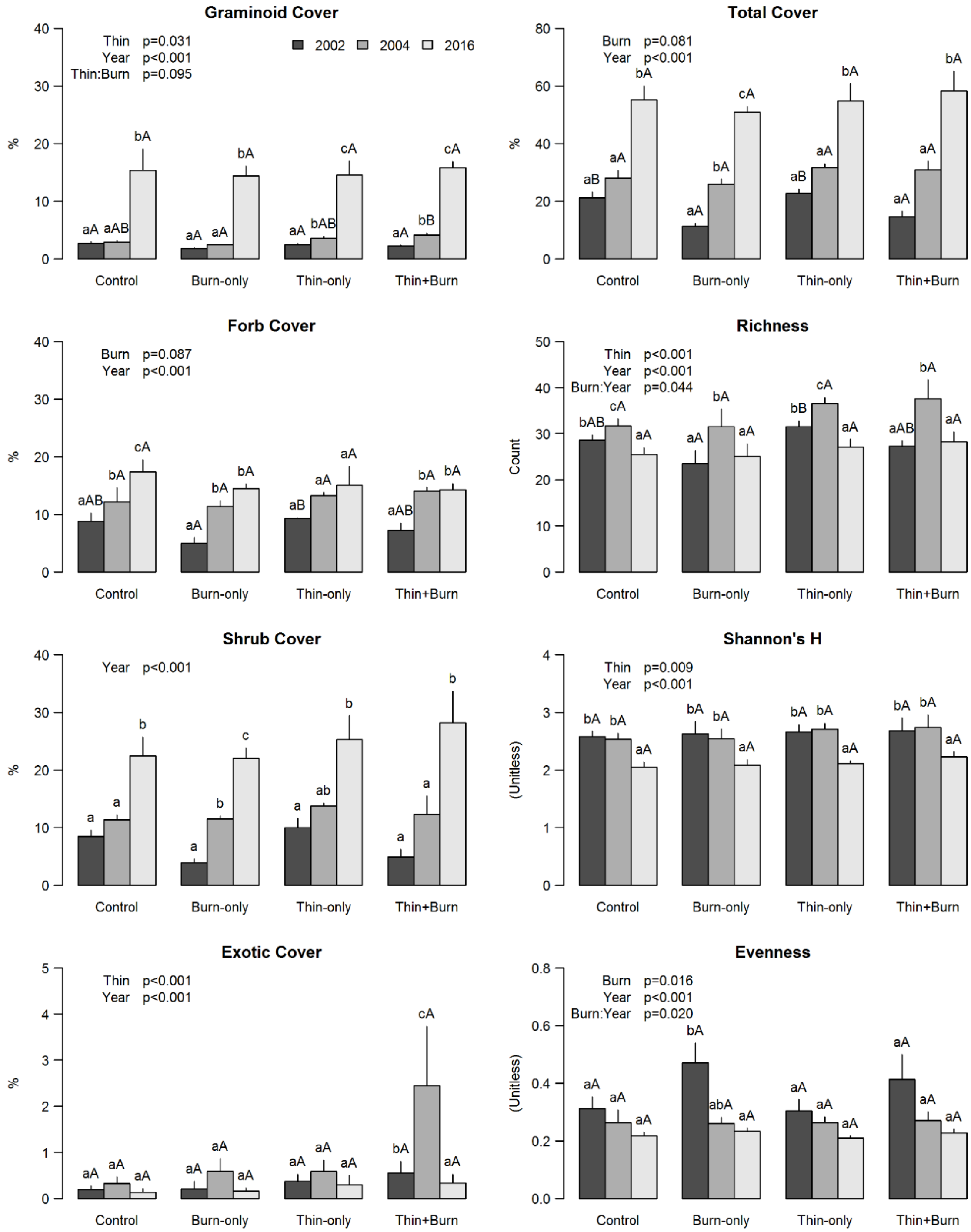


Figure 4. Non-tree vegetation cover and diversity at Lubrecht's Fire & Fire Surrogate Study. Bars show treatment means and standard error by year: 2002 (immediately after treatment), 2004, and 2016. Significant ANOVA factors (p-values < 0.1) are shown with text at the top of each panel. Letters above bars show pairwise differences (α=0.05) within treatment between years (lowercase) and within year between treatments (uppercase).

Available online at www.sciencedirect.com
SCIENCE DIRECT
Forest Ecology and Management 213 (2005) 25–38
Forest Ecology and Management
www.elsevier.com/locate/foreco

Restoration treatments in a Montana ponderosa pine forest: Effects on soil physical, chemical and biological properties

Michael J. Gundale [a], Thomas H. DeLuca [a,*], Carl E. Fiedler [a], Philip W. Ramsey [b], Michael G. Harrington [c], James E. Gannon [b]

[a] *College of Forestry and Conservation, University of Montana, Missoula, MT 59812, USA*
[b] *Department of Biological Science, University of Montana, Missoula, MT 59812, USA*
[c] *USDA, Forest Service, Fire Sciences Laboratory, Missoula, MT 59807, USA*

Received 16 November 2004; received in revised form 22 March 2005; accepted 23 March 2005

Abstract

Low-elevation ponderosa pine ecosystems of the inland northwestern United States experienced frequent, low-severity fire that promoted open stands dominated by large diameter ponderosa pine (*Pinus ponderosa*). Fire exclusion has led to increased stand densities, often due to proliferation of less fire-tolerant species and an increased risk of stand-replacing wildfire. These fundamental changes have spurred interest in forest restoration treatments, including thinning, prescribed burning and thinning combined with prescribed burning. We examined the response of numerous soil physical, chemical and biological parameters to these treatments 1 and 3 years post-treatment, using a replicated field experiment. Individual restoration treatments were implemented in 9 ha units. We observed significantly lower C:N in the O horizon and higher O horizon and mineral soil NH_4^+ concentrations in both BURN and THIN/BURN treatments during year 1. Soil NH_4^+ remained elevated through year 3 in the THIN/BURN treatment. Net N mineralization, nitrification and NO_3^- concentration were significantly greater in the THIN/BURN than all other treatments during year 1 and net nitrification rates remained elevated through year 3. A high C:N substrate decomposed more rapidly in both BURN treatments relative to the unburned treatments. Treatments had no immediate effect on the soil microbial community; however, phospholipid fatty acid profiles differed 16–18 weeks following treatments due to higher actinomycetes in the THIN/BURN treatment. The large scale of our treatment units resulted in significant variation in fire severity among prescribed burns as a function of variation in fuel quantity and distribution, and weather conditions during burn days. Correlation analysis revealed that variation in fine fuel consumed was tightly correlated with net N mineralization and net nitrification. These differences in soil characteristics may influence stand productivity and understory species composition in the future.

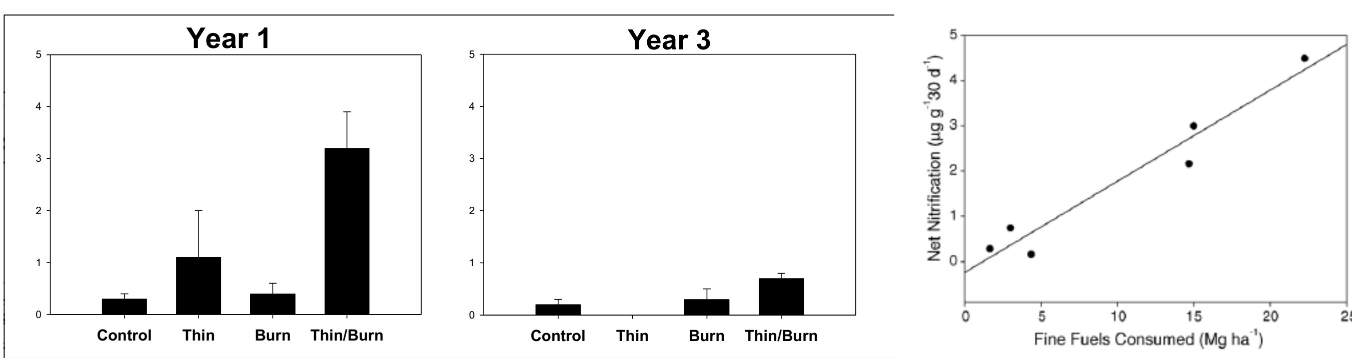


Figure 1. Net nitrification in a 30 day aerobic incubation (yr 1 and 3) and net nitrification vs fine fuel consumption from the Lubrecht Fire, Fire Surrogates study.

Long-Term Treatment Effects on Soil Nutrient Cycling – Cory Cleveland

Ecological Applications, 26(5), 2016, pp. 1503–1516

Forest restoration treatments have subtle long-term effects on soil C and N cycling in mixed conifer forests

Peter W. Ganzlin,[1,4] Michael J. Gundale,[2] Rachel E. Becknell,[3] and Cory C. Cleveland[1,5]

[1]*Department of Ecosystem and Conservation Sciences, College of Forestry and Conservation, University of Montana, Missoula, Montana 59812 USA*
[2]*Department of Forest Ecology and Management, Swedish University of Agricultural Sciences, Umeå, 90183 Sweden*
[3]*Department of Biology, University of Missouri–St. Louis, St. Louis, Missouri 63121 USA*

Abstract. Decades of fire suppression following extensive timber harvesting have left much of the forest in the intermountain western United States exceedingly dense, and forest restoration techniques (i.e., thinning and prescribed fire) are increasingly being used in an attempt to mitigate the effects of severe wildfire, to enhance tree growth and regeneration, and to stimulate soil nutrient cycling. While many of the short-term effects of forest restoration have been established, the long-term effects on soil biogeochemical and ecosystem processes are largely unknown. We assessed the effects of commonly used forest restoration treatments (thinning, burning, and thinning + burning) on nutrient cycling and other ecosystem processes 11 yr after restoration treatments were implemented in a ponderosa pine (Pinus ponderosa var. scopulorum)/Douglas fir (Pseudotsuga menziesii var. glauca) forest at the Lubrecht Fire and Fire Surrogates Study (FFS) site in western Montana, USA. Despite short-term (<3 yr) increases in soil inorganic nitrogen (N) pools and N cycling rates following prescribed fire, long-term soil N pools and N mineralization rates showed only subtle differences from untreated control plots. Similarly, despite a persistent positive correlation between fuels consumed in prescribed burns and several metrics of N cycling, variability in inorganic N pools decreased significantly since treatments were implemented, indicating a decline in N spatial heterogeneity through time. However, rates of net nitrification remain significantly higher in a thin + burn treatment relative to other treatments. Short-term declines in forest floor carbon (C) pools have

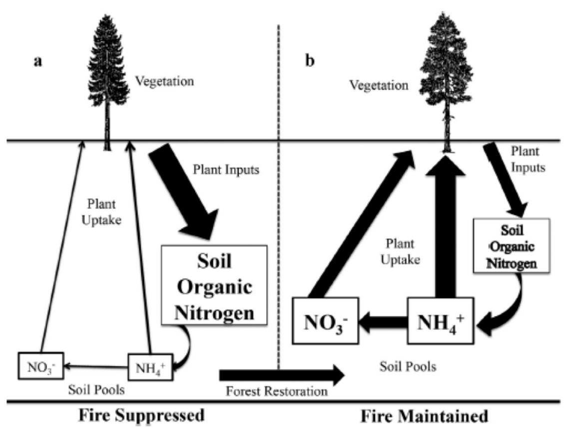


Fig. 1. Simplified conceptual model showing hypothesized impacts of (a) active fire suppression and (b) forest restoration practices involving fire on the N cycle of a semiarid forest ecosystem. The model illustrates how forest restoration can minimize pools and fluxes of soil organic N while enhancing nutrient mineralization and improving availability of inorganic forms of N. Sizes of arrows and boxes represent the relative contribution of the N fluxes and pools, respectively.

Table 2. Total carbon (C), nitrogen (N), and C:N ratio from mineral soil (0–10 cm) and organic (O) horizons and O horizon bulk density (B_d) from summer 2013 sampling.

Variable	Control	Thin-only	Burn-only	Thin + Burn
O Horizon				
B_d (g/cm^2)†	0.093 (0.006)	0.085 (0.003)	0.091 (0.005)	0.097 (0.009)
Total C (g/kg)†	401.36 (16.23)	383.98 (21.41)	414.17 (14.09)	361.90 (17.73)
Total N (g/kg)†	11.88 (0.85)	10.51 (1.17)	12.15 (0.87)	13.90 (1.69)
Total C (Mg/ha)‡, ***	12.36^b (0.50)	12.16^b (0.68)	12.69^b (0.43)	8.21^a (0.40)
Total N (Mg/ha)†	0.37 (0.03)	0.33 (0.04)	0.37 (0.03)	0.32 (0.04)
C:N Ratio†	34.66 (2.76)	38.91 (4.54)	35.05 (2.80)	27.16 (2.12)
Mineral soil				
Total C (g/kg)†	17.59 (3.77)	12.59 (2.36)	12.36 (2.18)	21.62 (4.13)
Total N (g/kg)†	0.95 (0.19)	0.72 (0.15)	0.77 (0.12)	1.17 (0.14)
C:N ratio†	18.61 (2.49)	17.44 (1.33)	16.15 (0.87)	18.90 (0.85)

Notes: Data presented as mean with SE, n = 3 from sampling in summer 2013. Means followed by the same superscripted letter are not significantly different at $P < 0.05$ (Dunnett-Tukey-Kramer post hoc test).
*P <0.05; **P <0.01; ***P<0.001.
†Significance determined via ANOVA
‡Significance determined via nonparametric Kruskal-Wallis test.

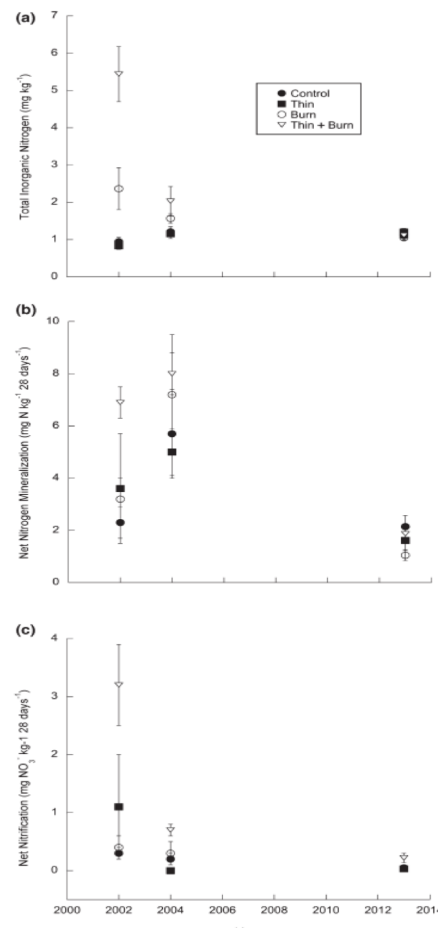


Fig. 2. (a) Total inorganic N (TIN) concentrations, (b) net N mineralization rates, and (c) net nitrification rates in 2002, 2004, and 2013. Treatments include control (solid circles), thin-only (solid squares), burn-only (open circles), and thin + burn (open triangles). Data are presented as mean ± standard error (SE), and data from 2002 and 2004 are from Gundale et al. (2005).

Fuel Treatment Effectiveness During Mountain Pine Beetle Outbreak – Sharon Hood

Take Home Messages:

- A mountain pine beetle (MPB) outbreak occurred ~5 years after treatment implementation (2005-2012).
- Ponderosa pine mortality from MPB was highest in the control (50%) and burn-only (39%) treatments, compared to almost no mortality in the thin-only and thin-burn treatments.
- After the outbreak, ponderosa pine remained dominant in the thin and thin-burn treatments, but the control and burn-only shifted in species dominance to Douglas-fir.
- The high Douglas-fir component in the control and burn-only treatments due to 20th century fire exclusion, coupled with high pine mortality from MPB, has likely reduced resilience of this forest beyond the ability to return to a ponderosa pine-dominated system in the absence of further fire or mechanical treatment.
- Treatments designed to increase resistance to high-severity fire in ponderosa pine- dominated forests in the Northern Rockies can also increase resistance to MPB, even during an outbreak.

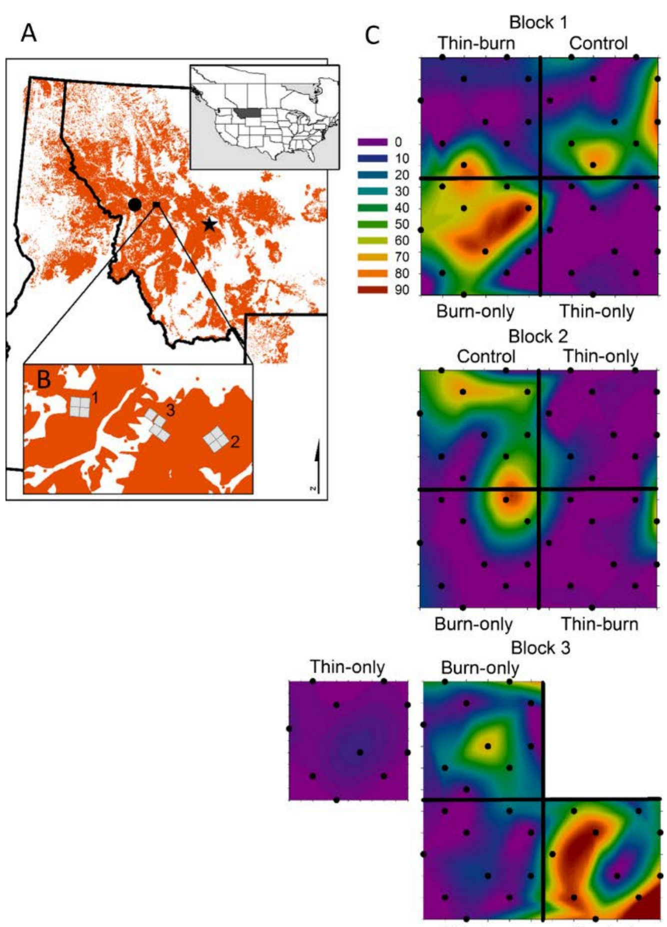


Figure 1. (A) An area in western Montana impacted by mountain pine beetle between 2000 and 2013. Source: USDA Forest Service Aerial Detection Survey Data. The black square shows the study site, the black star shows Helena, state capital of Montana, and the black circle shows Missoula. The upper right box shows the location of Montana in relation to USA and Canada. (B) The inset shows the location of the Fire and Fire Surrogate study site on Lubrecht Experimental Forest. (C) MPB attack intensity (% of MPB host trees killed by MPB) patterns shown in each block by treatment. Black circles indicate location of 0.1-ha plots where attack data was collected.

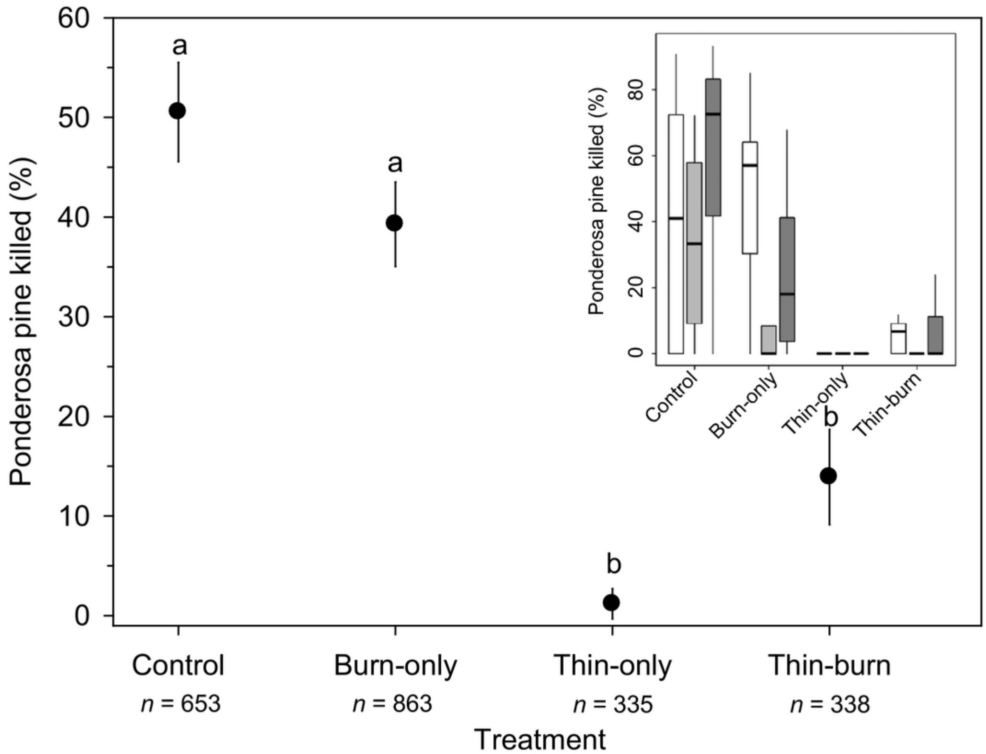


Figure 2. Mean (SE) of percent of ponderosa pine killed by mountain pine beetle between 2005 and 2012. Different letters indicate mortality is significantly different between treatments (α = 0.05). Study total number of host trees noted below treatment. The inset shows the percentage of ponderosa pine killed by mountain pine beetle between 2005 and 2012 by experimental block. Block 1 is white; block 2, light gray; and block 3, dark gray. Boxes denote first and third quartiles, lines the median, and whiskers the 1.5 inter-quartile range (IQR).

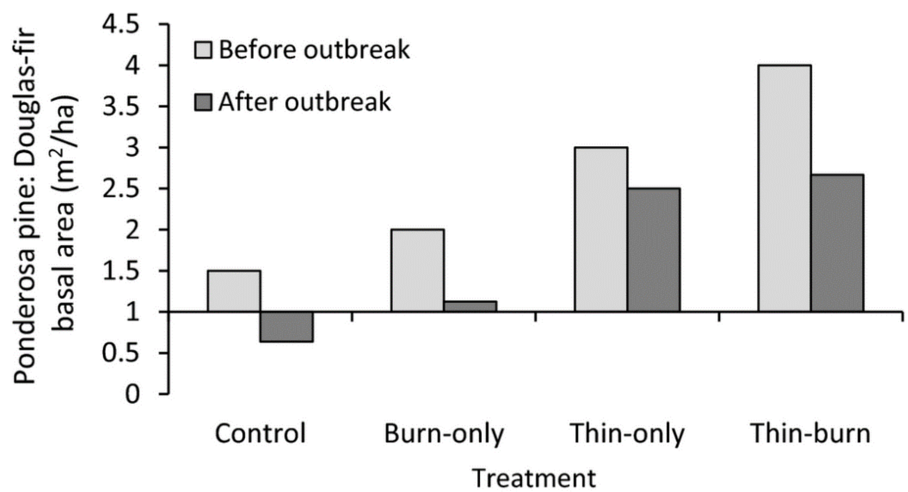


Figure 3. The ratio of host (ponderosa pine) to non-host (Douglas-fir) basal area before (2005) and after (2012) the mountain pine beetle outbreak.

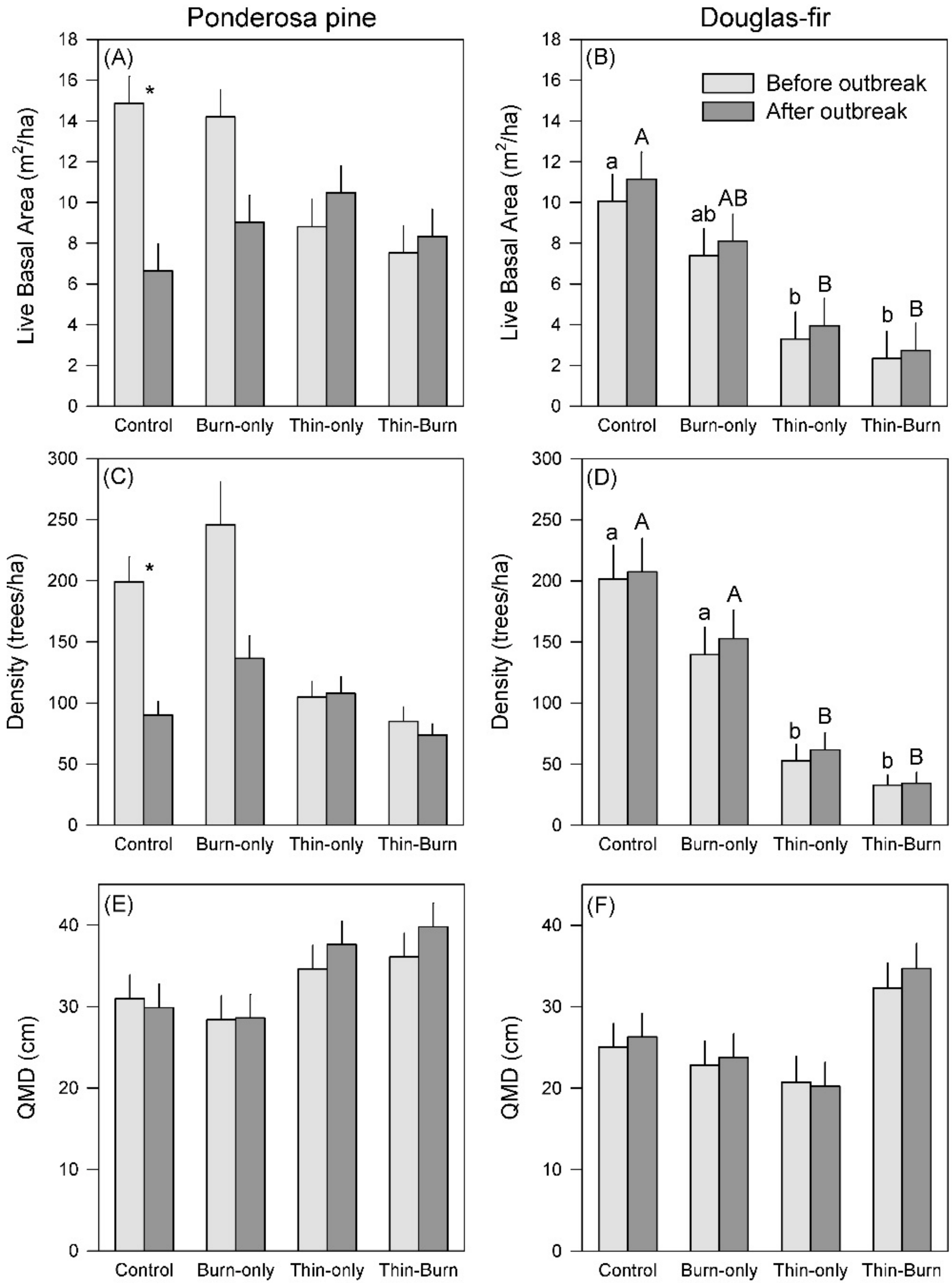


Figure 4. Mean (SE) of forest attributes before (2005) and after (2012) the mountain pine beetle outbreak by host (ponderosa pine) and non-host (Douglas-fir). (A and B) shows basal area, (C and D) shows density, and (E and F) shows quadratic mean diameter (QMD). The asterisk denotes a significant difference before and after the outbreak within a treatment. Lower case letters denote significant treatment differences before the outbreak, and uppercase letters denote significant treatment differences after the outbreak.

Ponderosa Pine Defenses to Mountain Pine Beetle – Sharon Hood

Take Home Messages:

- Resin duct-related traits provide resistance against bark beetles. Trees killed by bark beetles invest less in resin ducts relative to trees that survive attack
- Low-severity fire can induce resin duct production and resin duct production declines when fire ceases.
- Low-severity fire can trigger a long-lasting induced defense.
- At the Lubrecht FFS site, thinning treatments, with or without fire, dramatically increased tree growth and resin ducts relative to control and burn-only treatments.
- Prescribed burning in the Lubrecht FFS study did not increase resin ducts but did cause changes in resin chemistry that may have affected MPB communication and lowered attack success.
- Forest management that encourages healthy, vigorously growing trees will also favor larger resin ducts, thereby conferring increased constitutive resistance to bark beetle attack.

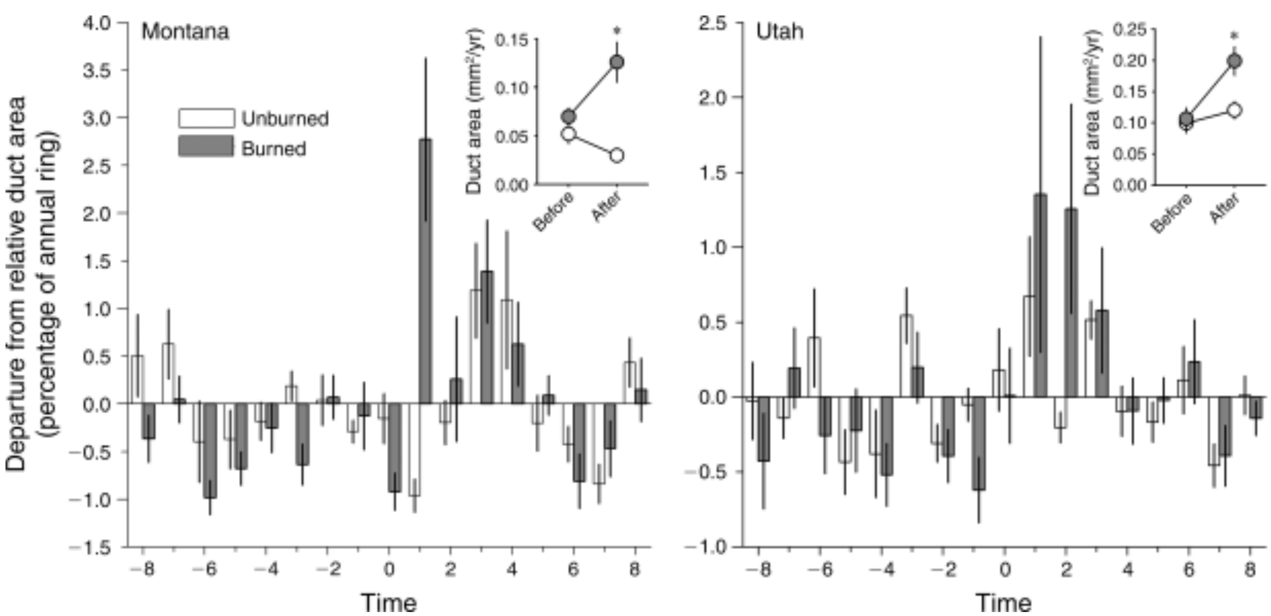


Figure 5. Departure (mean ± SE) from average total axial resin duct area by year for burned and unburned ponderosa pine trees at Montana and Utah sites. Fire occurrence is denoted as time = 0; negative values are years before fire and positive values are years after fire. Insets show total resin duct area (adjusted mean ± SE) after accounting for ring area based on 5 mm wide samples. Inset for the Montana site total duct area is one year before and after fire, and inset for the Utah site total duct area is the second year before and after fire. An asterisk (*) indicates duct area increased after fire on burned trees.

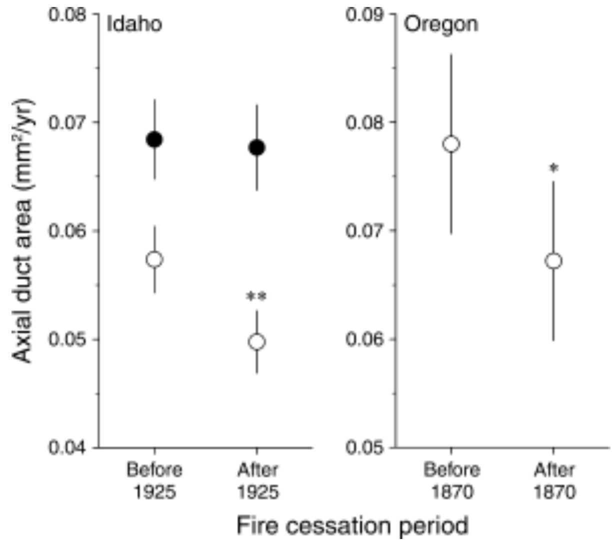


Figure 6. Ponderosa pine axial resin duct area (adjusted mean ± SE) before and after fire cessation in Idaho and Oregon after accounting for ring area based on a 5 mm core diameter. We defined fire cessation as the period following the last recorded fire at a site, determined from tree-ring reconstructions. The Idaho site was divided into two areas: open circles are fires that ceased in the 20th century, solid circles are fires that continued in the 20th century. Asterisks (*) indicate duct area decreased after fire exclusion after 1870 in Oregon and after 1925 in Idaho.
* $P < 0.05$; ** $P < 0.01$

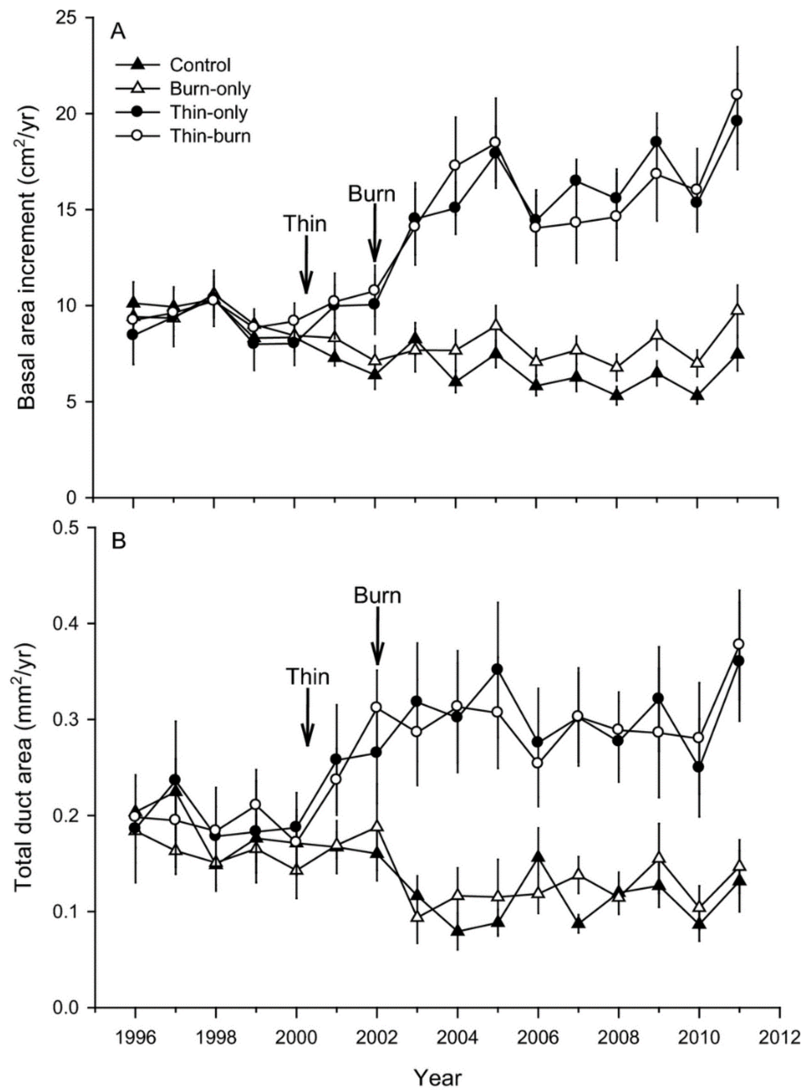


Figure 7. (A) Yearly mean basal area increment and (B) total duct area by treatment. Error bars are standard error. Arrows denote year of thinning (winter 2000/2001) and prescribed burn (Spring 2002).

Further Reading:

Hood, S., Baker, S. & Sala, A. (2016) Fortifying the Forest: Thinning and Burning Increase Resistance to a Bark Beetle Outbreak and Promote Forest Resilience. *Ecological Applications,* **26,** 1984–2000.

Hood, S., Sala, A., Heyerdahl, E.K. & Boutin, M. (2015) Low-severity fire increases tree defense against bark beetle attacks. *Ecology,* **96,** 1846-1855.

Hood, S. & Sala, A. (2015) Ponderosa pine resin defenses and growth: metrics matter. *Tree Physiology,* **35,** 1223-1235.

Six, D.L. and K. Skov. 2009. Response of bark beetles and their natural enemies to fire and fire surrogate treatments in mixed-conifer forests in western Montana. *Forest Ecology and Management* 258: 761-772.

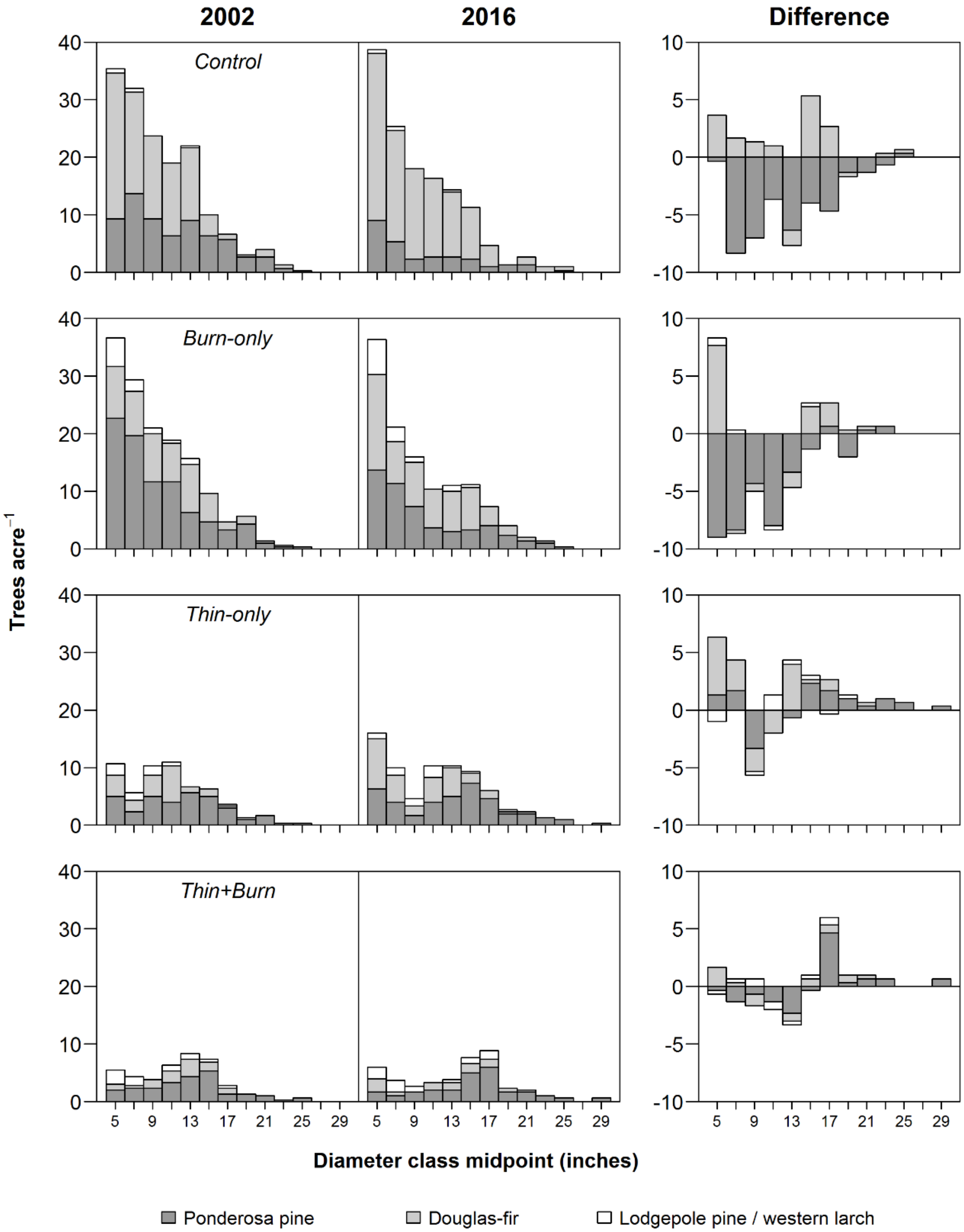


Figure 1. Overstory diameter distribution by species after treatment at Lubrecht's Fire & Fire Surrogate Study. From left to right panels show distribution in 2002 (immediately after treatment), 2016, and then change in distribution between those years.

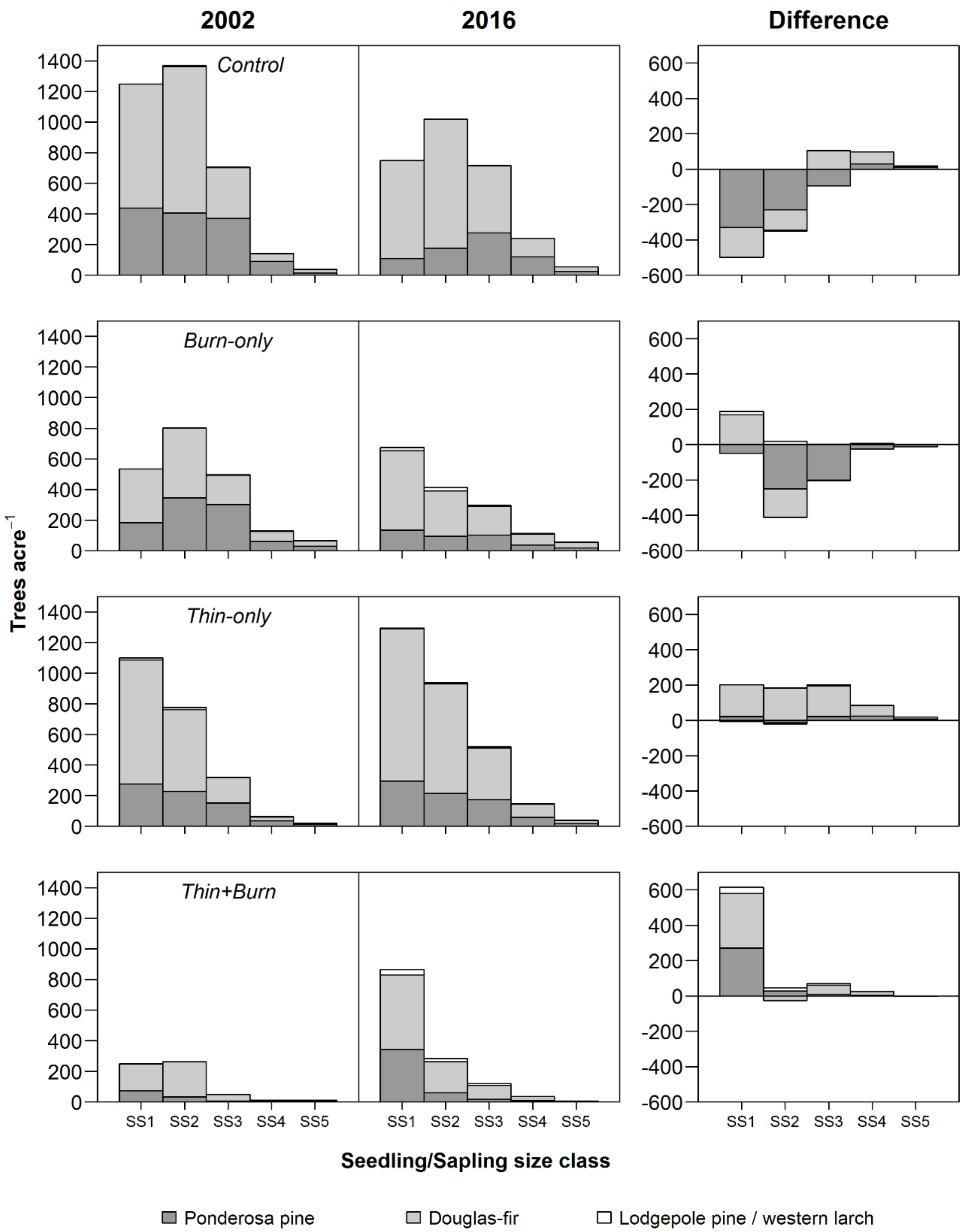


Figure 2. Regeneration size class distribution by species after treatment at Lubrecht's Fire & Fire Surrogate Study. From left to right panels show distribution in 2002 (immediately after treatment), 2016, and then change in distribution between those years. SS1="seedling" (10 cm ≤ height < 50 cm), SS2 ="large seedling" (50 cm ≤ height < 137 cm), SS3="small sapling" (0.1 cm ≤ dbh < 3 cm), SS4="medium sapling" (3 cm ≤ dbh < 6 cm), and SS5="large sapling" (6 cm ≤ dbh < 10.16 cm).

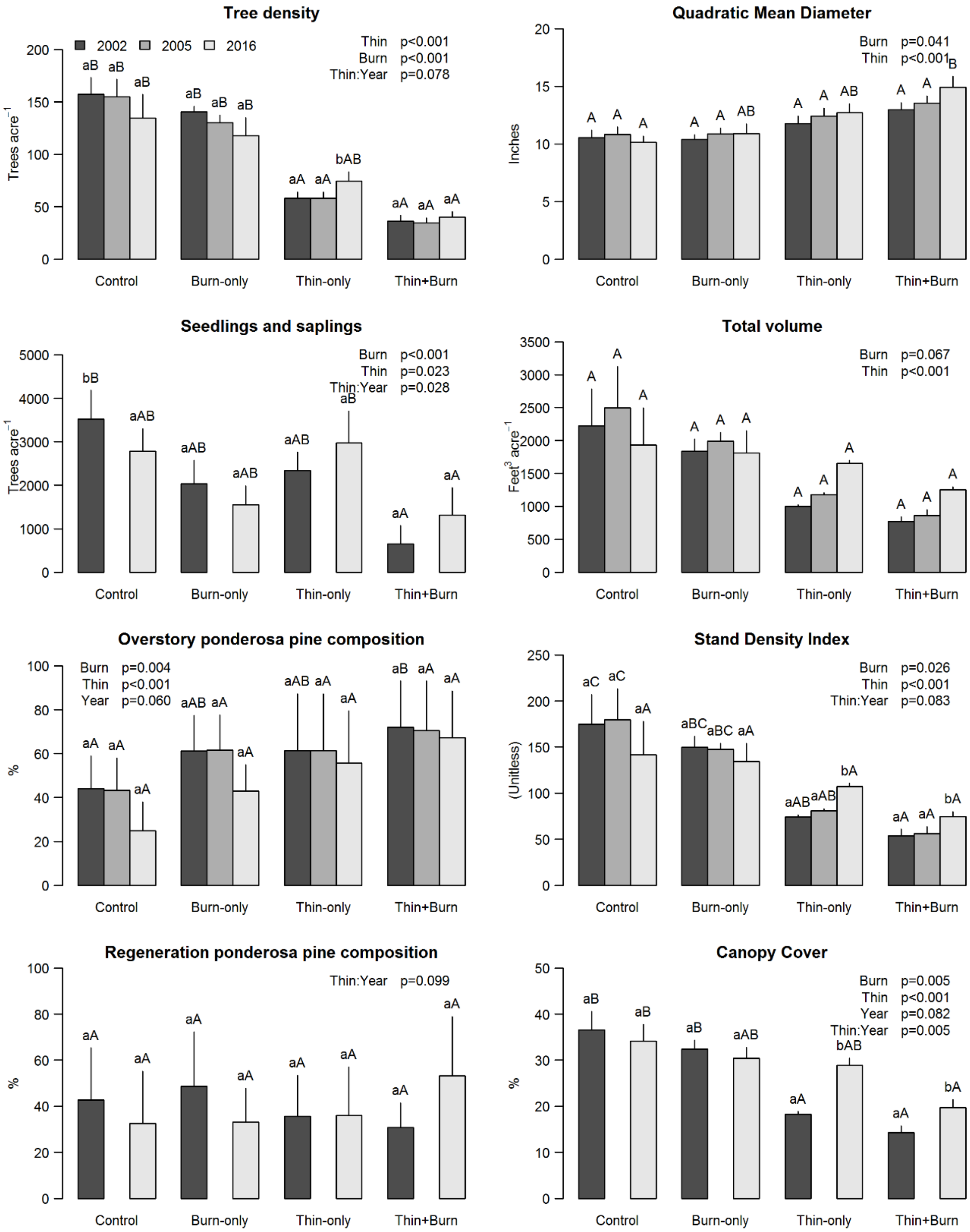


Figure 3. Forest structure and composition at Lubrecht's Fire & Fire Surrogate Study. Bars show treatment means and standard error by year: 2002 (immediately after treatment), 2005, and 2016. Regeneration density, regeneration composition, and canopy cover were not measured in 2005. Significant ANOVA factors (p-values < 0.1) are shown with text at the top of each panel. Letters above bars show pairwise differences (α=0.05) within treatment between years (lowercase) and within year between treatments (uppercase).

Fuel dynamics and crown fire hazard in the F&FS Study – Justin Crotteau

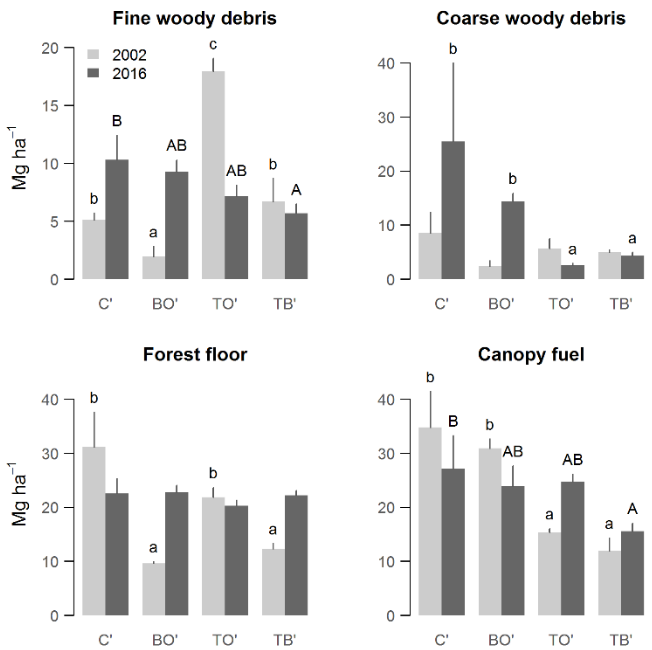


Figure 1. Fuel loads immediately after treatment and in 2016 in the Fire & Fire Surrogate Study. Fine woody debris includes downed woody material < 3" diameter; large woody debris, >3"; forest floor includes litter and duff; canopy fuel includes attached foliage and half of canopy 1-hr fuels.

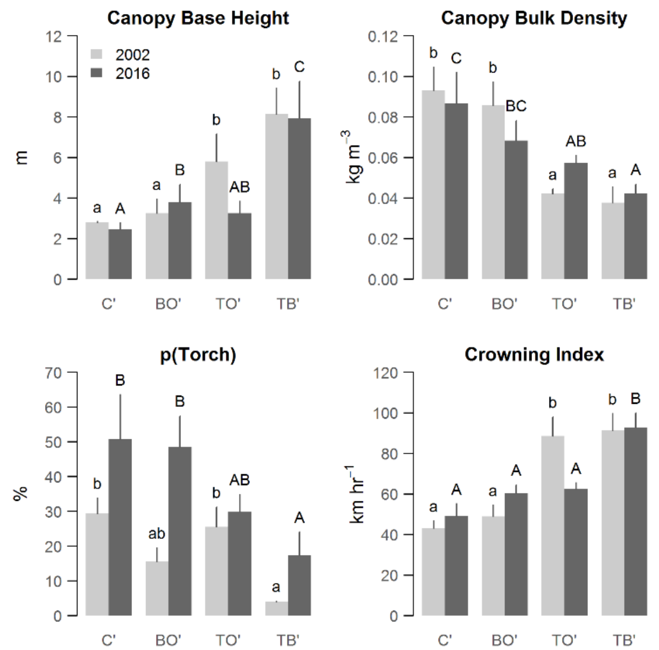


Figure 2. Crown fire hazard metrics immediately after treatment and in 2016 in the Fire & Fire Surrogate Study. p(Torch) is the probability of torching, i.e., fire transition from surface to overstory. Crowning index is the 18 foot windspeed necessary for canopy to actively carry crown fire.

Table 1. Fire modeling details immediately after treatment and in 2016 in the Fire & Fire Surrogate Study. Calculated in FFE-FVS under "severe" conditions (4% 10-hr moisture, 70°F, 20 mph 18-ft windspeed).

		Primary fuel model					Predicted fire type			
Year	Treatment	8	10	12	13	Surface flame length	Surface	Cond'l	Passive	Active
		………………%………………				m	………………%………………			
2002	Control	67 (3)	27 (7)	7 (3)	0 (0)	0.83 (0.01)	63 (13)	23 (12)	13 (3)	0 (0)
2002	Burn-only	93 (3)	7 (3)	0 (0)	0 (0)	0.43 (0.06)	80 (10)	20 (10)	0 (0)	0 (0)
2002	Thin-only	53 (3)	30 (0)	17 (3)	0 (0)	1.54 (0.03)	87 (3)	0 (0)	13 (3)	0 (0)
2002	Thin+Burn	93 (3)	3 (3)	3 (3)	0 (0)	0.71 (0.13)	100 (0)	0 (0)	0 (0)	0 (0)
2016	Control'	33 (20)	40 (15)	23 (19)	3 (3)	1.56 (0.32)	40 (15)	17 (12)	40 (15)	3 (3)
2016	Burn-only'	37 (9)	50 (10)	13 (3)	0 (0)	1.50 (0.13)	70 (12)	7 (7)	23 (7)	0 (0)
2016	Thin-only'	70 (6)	30 (6)	0 (0)	0 (0)	1.11 (0.03)	83 (3)	0 (0)	17 (3)	0 (0)
2016	Thin+Burn'	60 (0)	40 (0)	0 (0)	0 (0)	1.47 (0.11)	90 (6)	0 (0)	10 (6)	0 (0)

Short-Term Response of Bark Beetles to FFS Treatments – Diana Six

The fire and fire surrogate study provided a rare opportunity to study thinning and fire treatment effects in mixed conifer forests in a fully-replicated operational-size controlled experiment. It also, quite by chance, allowed for the first replicated study with these treatments to follow mountain pine beetle through all population phases of an outbreak. The results of the bark beetle study for 2000-2008 are presented in Six, D.L. and K. Skov. 2010. Response of bark beetles and their natural enemies to fire and fire surrogate treatments in mixed conifer forests in western Montana, Forest Ecology and Management 258: 761-772.

Objectives: Short-term: 2000-2004
Assess bark beetle responses to fire and fire surrogate treatments
Assess fire effects on trees (crown and bole scorch, ground char) and correlate those to beetle responses
Assess constitutive tree defenses to bark beetles after treatment
Assess responses of natural enemies of bark beetles to treatments

Short-term results: 2000-2004 beetle responses

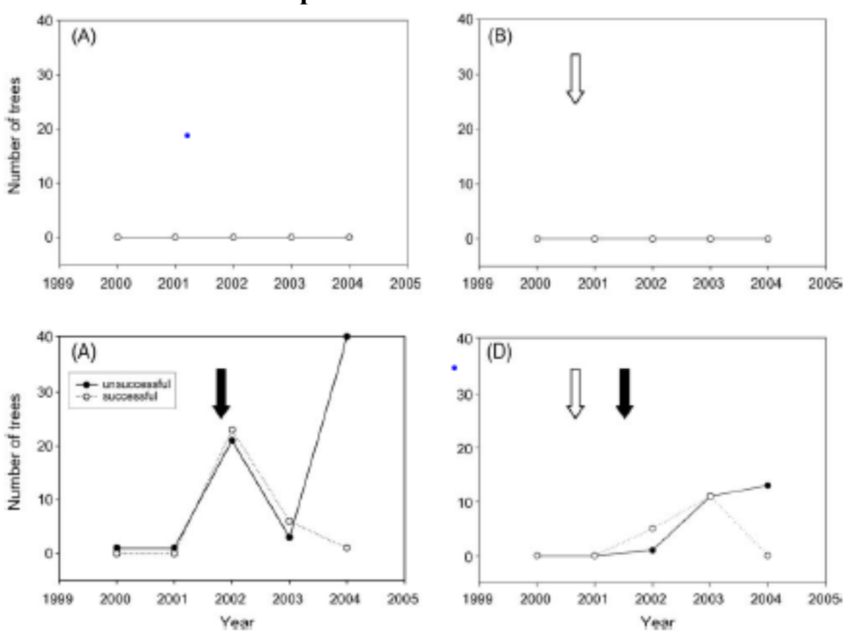


Fig. 1. Number of Douglas-fir killed by Douglas-fir beetle in (A) control, (B) thin-only, (C) burn-only and (D) thin-and-burn treatments at Lubrecht Forest, MT (2000–2004). Open arrows indicate timing of thinning treatments; bold arrows indicate timing of burn treatments.

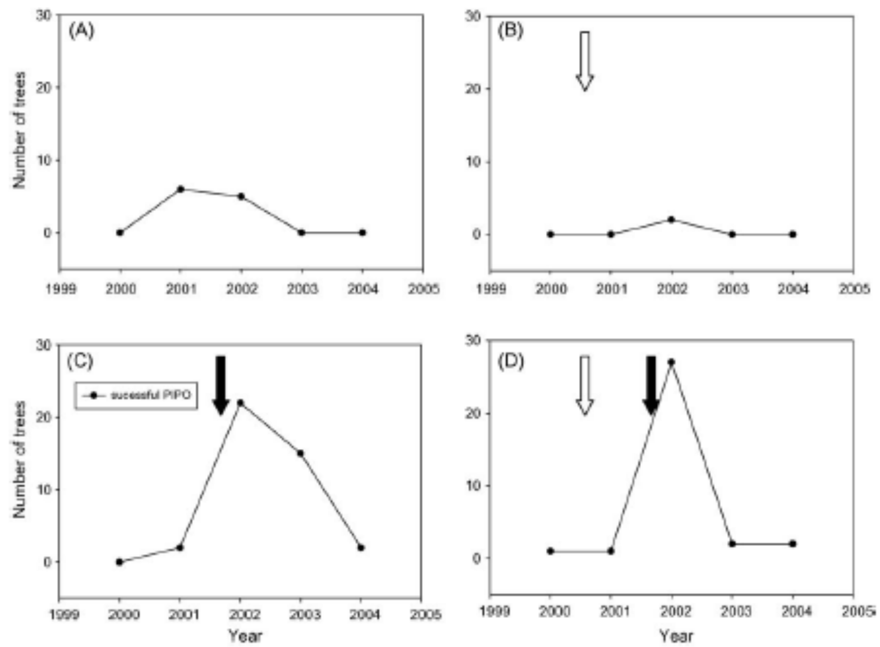


Fig. 2. Number of ponderosa pines (PIPO) killed by pine engraver in (A) control, (B) thin-only, (C) burn-only and (D) thin-and-burn treatments at Lubrecht Forest, MT (2000–2004). Open arrows indicate timing of thinning treatments; bold arrows indicate timing of burn treatments.

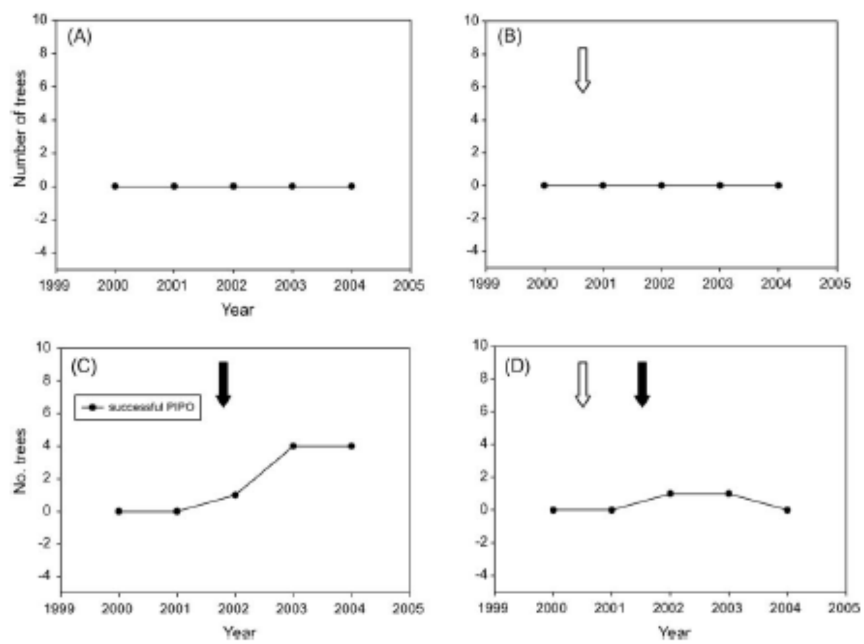


Fig. 3. Number of ponderosa pines (PIPO) killed by western pine beetle in (A) control, (B) thin-only, (C) burn-only and (D) thin-and-burn treatments at Lubrecht Forest, MT (2000–2004). Open arrows indicate timing of thinning treatments; bold arrows indicate timing of burn treatments.

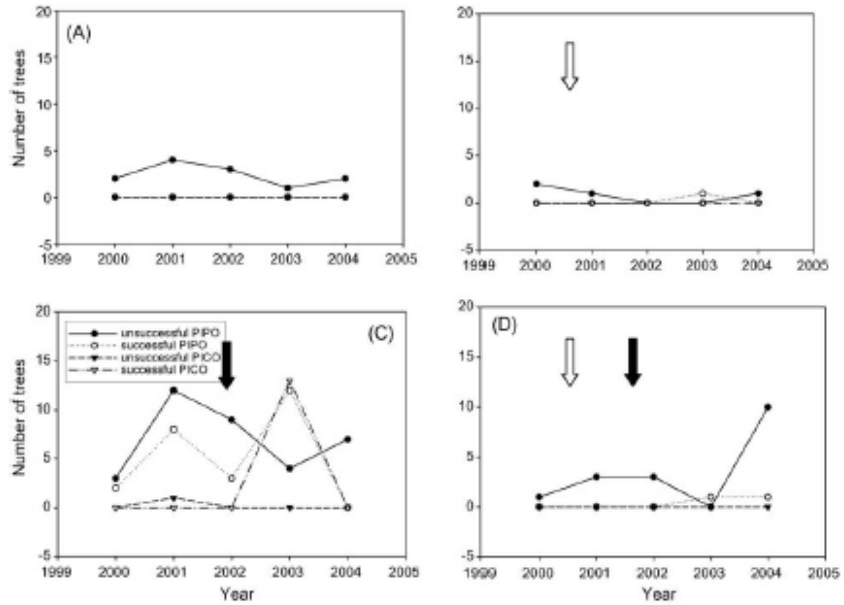


Fig. 4. Number of ponderosa pine (PIPO) or lodgepole pine (PICO) killed by mountain pine beetle in (A) control, (B) thin-only, (C) burn-only and (D) thin-and-burn treatments at Lubrecht Forest, MT (2000–2004). Open arrows indicate timing of thinning treatments; bold arrows indicate timing of burn treatments.

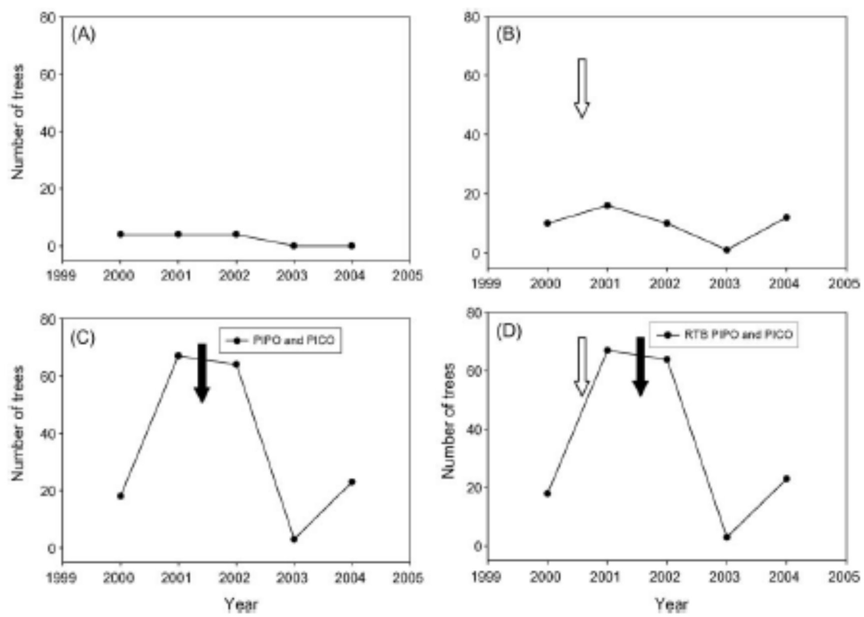


Fig. 5. Number of ponderosa pine (PIPO) or lodgepole pine (PICO) colonized by red turpentine beetle in (A) control, (B) thin-only, (C) burn-only and (D) thin-and-burn treatments at Lubrecht Forest, MT (2000–2004). Open arrows indicate timing of thinning treatments; bold arrows indicate timing of burn treatments.

Short-term effects: 2005-2008

Mortality remained very low. No additional mortality due to Douglas-fir beetle, western pine beetle or pine engraver was observed. Red turpentine beetle continued to attack trees in treated plots but none were observed in trees in control plots. Mountain pine beetle killed 11 trees over the three years (6 in control plots, 4 in burn only, and 1 in thin and burn).