FINAL REPORT

Monitoring Effectiveness of Forest Restoration Treatments: The Importance of Time and Space

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List of Abbreviations & Acronyms

ANOVA	analysis of variance
B	burned treatment
BA	basal area
BACI	Before-After, Control-Impact
DBH	diameter at breast height
CFLRP	Collaborative Forest Landscape Restoration Program
CV	coefficient of variation
cm	centimeter
early	early post-treatment response (2-3 years)
EU	experimental unit
FFS	Fire and Fire Surrogate study
ha	hectare
late	late post-treatment response (10-13 years)
m	meter
post	post-treatment
pre	pre-treatment
SDI	stand density index (square root of product of stand density [trees/ha] and basal area [m^2/ha]
U	unburned treatment

Keywords

ecological metrics, ecological restoration, frequent-fire forests, Fire and Fire Surrogate study, fuel treatments, long-term experiment, mechanical thinning, mixed-conifer forest, mixed-effects models, multi-scale assessment, plant diversity, prescribed burning, spatial scale, species diversity, species richness, temporal scale, thinning intensity, understory diversity, wildfire.

Acknowledgements

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Abstract

Fuel-reduction treatments have been used effectively in dry, fire-adapted forests to reduce risk of high-severity crown fire, but it is less certain if they achieve their ecosystem restoration objectives. To date, there has not been a comprehensive assessment of how the spatial and temporal dimensions of ecological assessments may influence our understanding of the effectiveness of fuel treatments (mechanical thinning, prescribed burning) in meeting ecosystem restoration objectives. We addressed this gap in knowledge through two study components: (1) a systematic review of the peer-reviewed literature that explicitly considers the temporal or spatial aspects of vegetation response to fuel-reduction treatments; and (2) remeasurement of a long-term experiment followed by a multi-scale assessment of how spatial scale of observation, time since treatment, and pre-treatment conditions interact to shape vegetation responses to thinning and prescribed burning.

Our review (Component 1) identified 224 studies examining vegetation responses to thinning and/or burning treatments in western North America. Of these, 46% were 'long-term' examining responses ≥ 5 years since treatment. Consideration of spatial variation was limited and included multi-scale sampling approaches (8% of studies), comparisons of responses among sites differing in biophysical conditions (e.g., soil type; 17%), measures of variability within treatment units (9%), and analyses of spatially explicit patterning in the overstory or understory (e.g., clump-size distributions; 12%). Very rarely did studies consider responses at both multiple temporal and spatial scales. Additionally, only 33% of long-term studies included both control and pre-treatment data as benchmarks for interpreting ecological responses to treatments.

Our analyses of long-term experimental data (Component 2) indicated that species richness was enhanced by burning and, to a lesser extent, by thinning, although the timing, duration, and strengths of these effects varied with spatial and temporal scale, and also varied among components of the understory. Annuals showed an early and persistent increase after burning at the larger scale, but a lagged response at the smaller scale. In contrast, perennial herbs showed lagged responses to thinning at smaller scales and to burning at larger scales, suggesting slower rates of colonization than annuals. Pre-treatment richness was a significant predictor of responses at both spatial scales but had no effect on colonization rate and did not interact with treatment to affect post-treatment richness. Non-natives were unresponsive to treatments, likely because they were uncommon in the landscape. Conclusions about treatment effectiveness can be influenced by basic aspects of the analytical approach, including whether to aggregate data, to treat thinning as a nominal or continuous variable, or to account for pre-treatment variation.

Our research has important implications for monitoring the ecological effectiveness of fuel treatments. It underscores the value – but rarity – of long-term multi-scale assessments. Pre-treatment data are critical for interpreting responses to treatments, documenting the range of conditions that are responsive to treatment, and quantifying the magnitude of response. Conclusions about treatment effectiveness can be sensitive to the temporal and spatial scales at which responses are measured. Short-term studies cannot detect effects that emerge slowly, nor can they document the longevity of responses to treatment. As a consequence, they can lead to false conclusions about treatment effectiveness and could trigger interventions that would not be suggested by results of longer-term studies. Multi-scale designs allow characterization of spatial variation and the scale-dependence of ecological responses. Long-term multi-scale assessments are necessary to ensure that fuel treatments provide desired ecosystem services and are resilient to changes in climate and disturbance regime.

Objectives

Despite widespread application of fuel treatments in dry, pine-dominated and mixed-conifer forests, knowledge of the ecological outcomes of these treatments is limited. Although thinning and burning treatments can effectively reduce surface and ladder fuels, and thus the likelihood of crown fire (Stephens et al. 2012, Fulé et al. 2012, Martinson & Omi, 2013), it is less clear that they meet other ecological objectives. Managers are increasingly interested in the ecosystem-restoration outcomes of fuel treatments, e.g., promoting native understory diversity and limiting establishment of fire-intolerant species, but they are also concerned by possible trade-offs among fuel-reduction and ecological objectives. This uncertainty has been highlighted in recent reviews and meta-analyses of the literature that point to large variation and inconsistency in the responses of forest understories to fuel-reduction treatments (McIver et al. 2013, Abella & Springer 2015, Willms et al. 2017).

This project addressed this uncertainty. It stemmed from a 2013 solicitation for proposals designed to *"… assess the effectiveness of joint vegetation management and fuels treatments in restoring ecosystem composition, structure, and function" (Task Statement 4. Fuels treatment effectiveness: ecosystem restoration*). Our project explored two central themes in *Task Statement 4* that relate to the use and usefulness of ecological metrics and the sensitivity of these metrics to spatial and temporal scales:

- ***Metrics**. What metrics are used to characterize the effectiveness of fuels treatments at meeting ecosystem restoration objectives? What are the characteristics of useful metrics? Which metrics have potential for effective and broad usage?*
- ***Scale**. How do the ecological effects of vegetation management and fuel treatments vary with spatial and temporal scale? At what scales can these treatments be effective at meeting ecosystem restoration objectives?*

To answer these questions, we proposed a research plan comprising two components with complementary objectives and analytical approaches.

Component 1. Document and evaluate the range of metrics used to assess the effectiveness of fuel treatments in meeting vegetation-related, ecosystem restoration objectives. To address this objective, we conducted a *systematic review* to identify (1) the primary vegetation-related ecosystem restoration objectives formulated for fuel treatments in frequent- and mixed-fire regime forests of the western U.S., and (2) the metrics used to evaluate ecological outcomes of fuel treatments, including the temporal and spatial scales at which they are measured.

Component 2. Experimentally evaluate how temporal and spatial scales of observation influence the behavior of vegetation metrics and their utility as ecological indicators of fuel treatment effectiveness. To address this objective, we conducted a *multi-scale analysis of vegetation response to fuel treatments* based on a remeasurement and re-analysis of data from a large-scale restoration experiment established as part of the national Fire and Fire Surrogate (FFS) study (McIver et al. 2013).

We addressed both components successfully, although we modified and expanded some of the analyses originally proposed.

Background

Restoration of frequent- and mixed-fire regime forest ecosystems is a pressing natural resource issue throughout western North America. A century or more of fire exclusion, highgrade logging, and livestock grazing has produced forests with high densities of fire-intolerant species and elevated fuel loadings (Keane et al. 2002, Hessburg & Agee 2003). These changes increase the risk of insect outbreaks, stress-induced mortality, and stand-replacing wildfires that can have profound effects on the ecological functioning and resource values of forests at local to landscape scales (Peterson et al. 2005). In response to these threats, forest managers are applying fuel treatments, typically mechanical thinning and prescribed burning, to achieve multiple objectives. However, these objectives can conflict, either constraining options to achieve fuel reduction or forcing spatial or temporal separation of treatments across the landscape. For example, prescribed burning may achieve a desired future fire behavior but also cause unintended tree mortality or promote spread of non-natives (Zouhar et al. 2008, Sutherland & Nelson 2010, Hood et al 2016).

Recent reviews and meta-analyses of studies devoted to vegetation responses to fuel treatments have uncovered a wide range of outcomes, including positive, negative, and neutral effects on plant abundance and diversity (Metlen et al. 2004, Dodson et al. 2008, Schwilk et al. 2009). Efforts to reconcile these differences point to myriad sources of variation acting prior to, during, or after treatment, including the temporal and spatial scales of ecological measurements (Abella & Springer 2015, Willms et al. 2017).

There are various ways in which conclusions about ecological responses to fuel treatments are sensitive to the temporal scale of measurement. For example, disturbances associated with thinning or burning can reduce species diversity (by damaging or consuming plants), or can increase it (by freeing space or resources) (Halpern 1989, Gundale et al. 2005, Pyke et al. 2010). The longevity of the decline or increase in richness can vary with species' sensitivity to disturbance, treatment severity, or post-disturbance processes that are time-dependent (e.g., litter accumulation, seed dispersal, or vegetative regrowth). Additionally, some responses to fuel treatments may become apparent in the longer term, but only in the context of drought or disturbance (e.g., mortality due to wildfire or insect outbreaks) (van Mantgem et al. 2016). Responses to treatment can thus differ in the short and long term.

Similarly, responses to treatment can vary with spatial scale. For example, species richness is scale-dependent, as are the mechanisms that regulate it (Palmer & White 1994). At local scales (e.g., the sizes of individual plants), dispersal and competition may limit richness or the ability of new species to establish (Huston 1999). However, at larger spatial scales, other mechanisms become important. Larger areas typically encompass greater habitat or resource heterogeneity, thus support a greater diversity of species (Rosenzweig 1995). Larger areas also increase the probability of establishment and reduce the likelihood of extinction. Whether, and at what spatial scales, fuel-reduction treatments enhance (or reduce) richness via colonization (or extinction) may depend on how they alter or interact with these processes. For example, burning may enhance richness at smaller (but not larger) spatial scales by creating open space and reducing competition, promoting recruitment from the local species pool (**Fig. 1**, **scenario 1**). Conversely, burning may enhance richness at larger (but not smaller spatial scales) by increasing habitat heterogeneity, allowing species with different regeneration requirements to colonize from the regional species pool (**scenario 2**). Alternatively, burning may enhance richness at both spatial scales, concurrently (**scenario 3**) or over time (**scenario 4**), depending on the proximity of seed sources. Finally, some effects may be transient (**scenario 5**), if colonists are short-lived or outcompeted.

Given this background, the primary goals of our project were to characterize the range of vegetation metrics commonly used to assess the ecological effectiveness of fuel-reduction

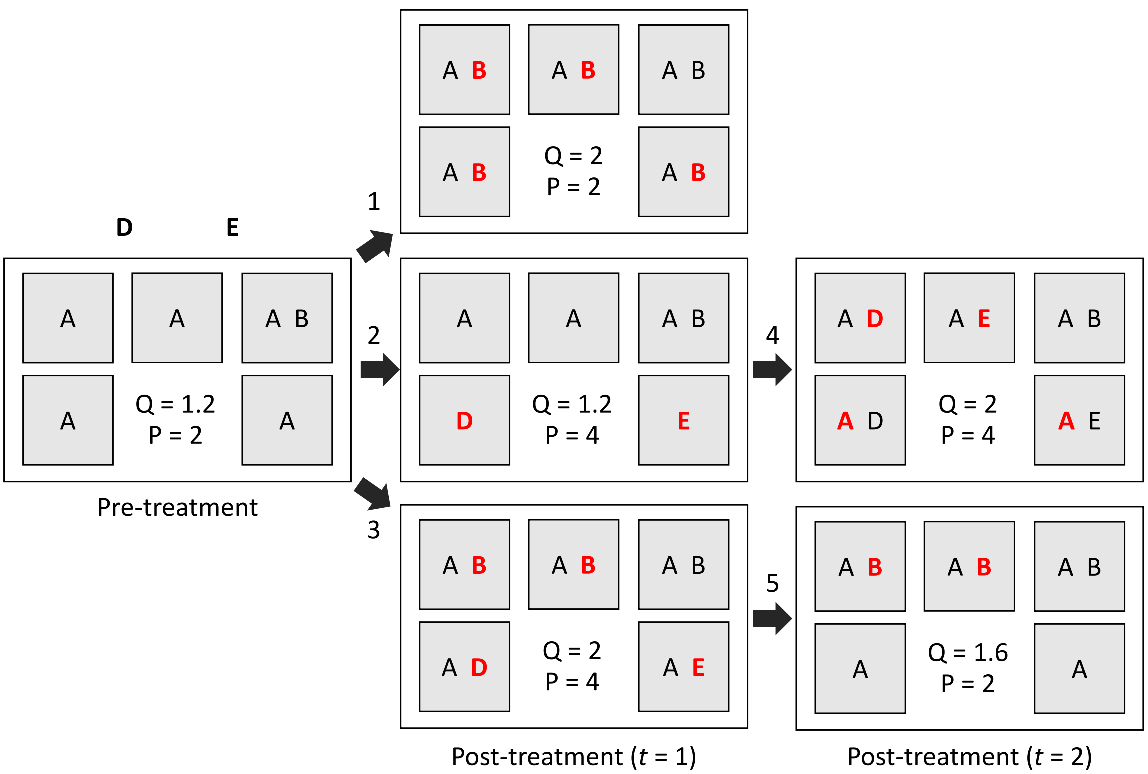


Fig. 1. Alternate scenarios in which treatments enhance richness at different spatial scales and times via colonization or loss from the local or regional species' pools. Spatial scales are 'small' quadrats (Q, grey squares) and 'large' plots (P, white rectangles). Q = mean number of species/quadrat; P= cumulative number of species/plot. Letters are different species; red font indicates colonization. (**1**) Quadrat richness increases via local dispersal; plot richness does not. (**2**) Quadrat richness does not change; plot richness increases via dispersal from the regional species pool (D, E). (**3**) Richness increases at both scales. (**4**) Richness increases at both scales, but more slowly in quadrats. (**5**) Initial increase in plot richness is transient.

treatments, and to determine whether conclusions about treatment effectiveness are sensitive to issues of temporal and spatial scale. The two components of our research were designed to address questions of fundamental importance to scientists and managers who seek to balance the multiple resource objectives of fuel-reduction treatments, including:

- What vegetation-related metrics have been used to evaluate ecological responses to fuel-reduction treatments in pine- and mixed conifer forests of western North America? How do these metrics relate to the primary management objectives in these systems?
- In what ways, and to what extent, have relationships with space and time been considered in research designed to assess the ecological effectiveness of fuel treatments?
- How do temporal and spatial scales of observation influence the behavior of key vegetation metrics, and thus shape conclusions about the effectiveness of treatments?
- How are conclusions about ecological effectiveness influenced by the analytical approach(es) used to assess responses to fuel treatments?

Materials & Methods

Component 1. Review & Synthesis of the Literature

We first identified the primary vegetation-related ecosystem restoration objectives formulated for fuel treatments in frequent- and mixed-fire regime forests of the western U.S. These were generated from interviews with stakeholders and analysis of planning documents from collaboratives associated with the USFS Collaborative Forest Landscape Restoration Program (CFLRP). For details on methodology see Urgenson et al. (2017, *in press*).

Next, we conducted a systematic review of the peer-reviewed literature to identify studies that address vegetation responses to fuel treatments in frequent- and mixed-fire regime forests in western North America. We considered studies published through October 2017. We implemented a Boolean search using the following combination of terms:

> ("Dry Forest" OR "Fire-Prone Forest" OR "Mixed conifer forest" OR "Fire-adapted forest") AND ("Fuel Reduction" OR "Fuels Reduction" OR "Thinning" OR "Prescribed Burning") AND ("Overstory" OR "Understory" OR "Vegetation" OR "Forest")

Data sources included Google Scholar (first 1000 citations), JSTOR, Scopus, and Web of Science. We then followed citation trails, adding documents citing or cited in papers generated by the initial searches. We considered only field-sampling studies (not simulation, modelling, or remote sensing studies) and those focused on understory or overstory responses (not studies of fuels, fire, microclimate, soil, carbon, wildlife, insects, or hydrology).

For each paper, we recorded the geographic location and forest type. We also characterized key aspects of the study design: range of treatments; replication; whether treatments were compared to pre-treatment conditions, controls, and/or historical reference information; temporal approach (longitudinal, retrospective, chronosequence, or dendroecological); and the temporal and spatial scale(s) of observation. We used a hierarchical classification to tally vegetation metrics. Primary divisions in the classification include vegetation stratum (overstory, understory, or seeds) and metric type (structure/abundance, diversity, composition, disturbance, growth or physiological performance). The complete list of papers with details on study characteristics, response variables, and definitions is available as a data archive (Urgenson et al. 2018).

Component 2. Multi-scale Assessment of Treatment Effects

Study Area

Our study area, Mission Creek, was part of the Fire and Fire Surrogates (FFS) study, a JFSP-funded study that began in 2000 and tested thinning and burning treatments at multiple sites around the U.S. (McIver et al. 2013). Mission Creek was chosen to represent dry forests of the interior Columbia River basin (Agee & Lehmkuhl 2009). It is in the northeastern Cascade Mountains of Washington (47'25' N, 120'32'W; **Fig. 2**) and encompasses a wide variation in physical environment, forest structure, and understory vegetation (**Table 1**). The climate is characterized by cool, wet winters and warm, dry summers. Minimum temperatures average -7˚C (January) to 9˚C (July) and maximum temperatures, 1˚C (January) to 28˚C (July) (NCDC monthly normals, 1937-2016, Plain, WA, 570 m; Western Regional Climate Center, https://wrcc.dri.edu/cgi-in/cliMAIN.pl?wa6534). Annual precipitation averages 67 cm; most falls as snow from October through April.

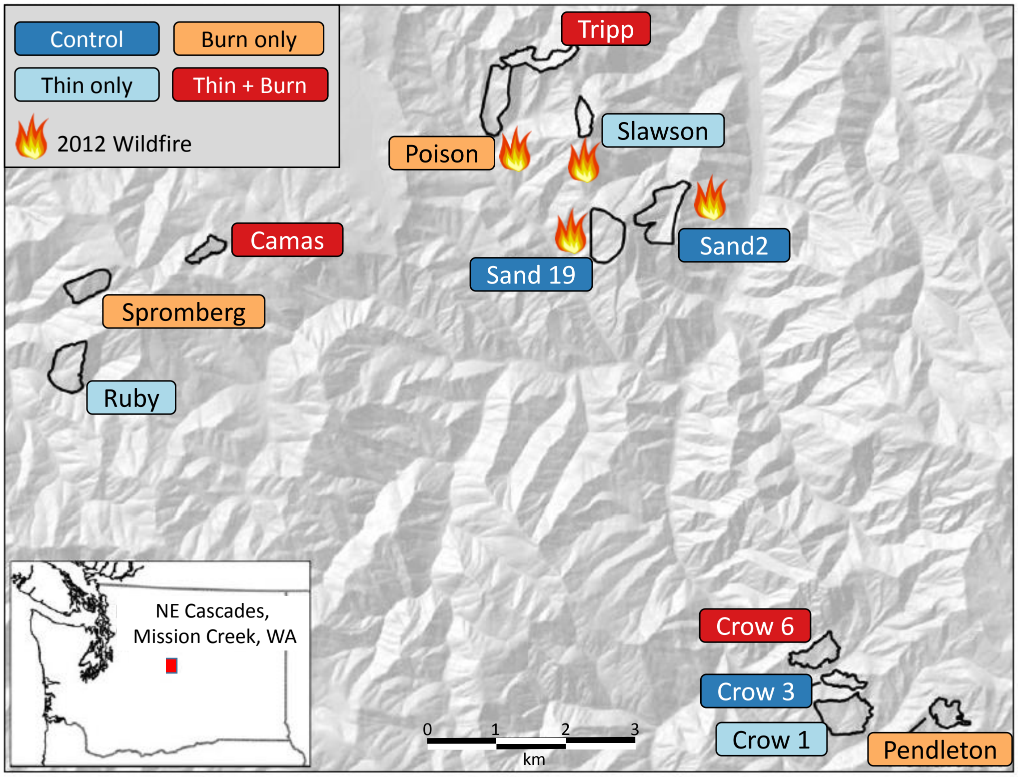


Fig. 2. Locations and treatment assignments of the 12 original experimental units at Mission Creek. Four units were affected by the Wenatchee Complex wildfire in 2012.

Forests are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), with lesser amounts of grand fir (*Abies grandis*). Common shrubs are serviceberry (*Amelanchier alnifolia*), snowberry (*Symphoricarpos albus*), and rose species/hybrids (*Rosa* spp.). Common herbaceous species include elk sedge (*Carex geyeri*), pinegrass (*Calamagrostis rubescens*), and heartleaf arnica (*Arnica cordifolia*).

Over the past century, fire suppression, logging and, to a lesser extent, domestic grazing have substantially altered the structure and composition of these forests. Prior to Euro-American settlement, fire-free intervals ranged from 6-21 years (Agee & Lehmkuhl 2009). Long-term suppression of fire has greatly increased the interval, promoted establishment of shade-tolerant species, and shifted the fire regime from low- to mixed- or high-severity (Agee & Lehmkuhl 2009). With selective logging of large-diameter stems, relatively open stands have been replaced by forests with multi-layered canopies and higher densities of smaller stems (Harrod et al. 1999).

Thinning & Burning Treatments

From a larger set of potential units, twelve 10-ha experimental units (EUs) were selected in 2000, meeting the following criteria: primarily *Pseudotsuga menziesii* series (Lillybridge et al. 1995), forested over >90% of the EU, and slopes averaging <50%. Two treatments, *mechanical thinning* and *prescribed burning*, were assigned randomly to each of three replicates in a balanced factorial design (thinning, burning, thinning and burning, and control) (**Table 1**, **Fig. 2**). In 2012, the Wenatchee Complex wildfire burned through four EUs, compromising the design. We measured these EUs and included them in analyses of overstory-understory relationships, but excluded them from analyses of spatial and temporal variation in understory response to treatments. In contrast, these units were included in previous analyses of overstory

Table 1. Environmental characteristics, pre-treatment structural attributes, and thinning intensities of the 12 original experimental units (EUs). Values are the means of six plots per EU. SDI (stand density index), is computed as √(stand density × basal area). Asterisks denote units affected by the 2012 Wenatchee Complex wildfire.

Name	Treatment	Elevation (m)	Slope (%)	Density (trees/ha)	Basal area (m^2/ha)	SDI	Thinning intensity: SDI of cut trees	Thinning intensity: % of initial SDI
Crow 3	Control	747	38	488	33.5	127.8	–	–
Sand19*	Control	780	43	517	34.1	132.8	–	–
Sand2*	Control	683	58	805	34.2	165.9	–	–
Crow 1	Thin	738	21	492	29.6	120.7	82.8	69
Ruby	Thin	975	43	532	39.0	144.0	67.6	47
Slawson*	Thin	838	35	870	35.6	176.0	79.7	45
Pendleton	Burn	841	16	352	23.1	90.2	–	–
Poison*	Burn	768	40	472	31.2	121.3	–	–
Spromberg	Burn	848	57	493	31.9	125.4	–	–
Camas	Thin & Burn	1097	43	588	33.7	140.8	74.5	53
Crow 6	Thin & Burn	718	26	488	29.0	119.0	84.3	71
Tripp	Thin & Burn	765	67	937	36.2	184.2	76.9	42

and understory response (Dodson et al. 2008, Harrod et al. 2009, Dodson and Peterson 2010).

Thinning was conducted between fall 2002 and spring 2003. Thinning was designed to reduce basal area to 10-14 m^2/ha (from initial values of 23-42 m^2/ha), minimize risk of high-severity fire, retain most large trees, and maintain or enhance structural heterogeneity by retaining trees in clumps. Due to variation in initial stand structure, thinning intensity varied markedly within and among EUs (**Table 1**).

Prescribed burning was conducted in spring 2004 in four burn units. Due to high fuel moisture, fire severity was low and consumption was patchy, failing to meet most fuel-reduction objectives (Agee & Lolley 2006). The two remaining burn units were not treated until spring 2006 (due to unfavorable weather/fuel conditions), when burned under drier conditions. Previous publications used data collected before these units were burned (Dodson et al. 2008, Harrod 2009, Dodson and Peterson 2010). Details on treatment implementation, weather conditions, fuel moisture, and fire behavior can be found in earlier publications (Agee & Lolley 2006, Agee & Lehmkuhl 2009, Harrod et al. 2009).

Measurement History & Sampling Design

We designed this project using a multi-scaled sampling design that facilitates analysis of vegetation responses over a range of spatial and temporal scales that are relevant to management (**Fig. 3**). Vegetation was sampled before treatment ('*pre*', 2000/2001) and twice after treatment, '*early*' (2005/2007) and '*late*' (2015, with funds from this grant). The post-treatment dates equate to 2-3 and 10-13 years after thinning or burning. A core set of measurements was made at each date, and additional measurement were made in 2015, as described below. Vegetation in each *experimental unit (EU)* was sampled using 6, 20 × 50 m (1000 m^2) modified-Whittaker *plots*. Nested within each plot are 10, 5 × 10 m (50 m^2) shrub *subplots* and 20, 1 × 1 m (1 m^2) herb *quadrats*. Field work in 2015 included the following:

<u>*Plots* (1000 m^2): overstory trees, snags, and saplings</u>. Within each *plot*, all live overstory

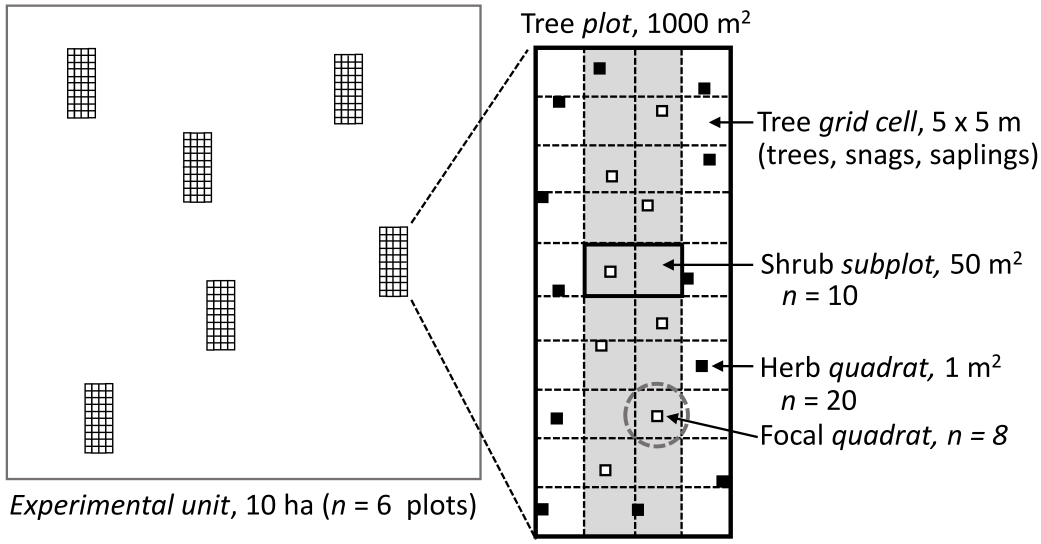


Fig. 3. Multi-scaled design for sampling overstory and understory vegetation.

trees (>7.5 cm DBH) were re-tagged at DBH (tags had been basal) and re-measured for diameter, height, and height to live crown. Previous snags, and live stems that had died since the last measurement, were measured for diameter and height. In addition, we assigned each dead stem a condition code (intact, broken above BH, broken below BH, or down) to enable more detailed assessment of snag dynamics. Saplings ($\leq$7.5 cm DBH) were tallied by species and height class (0.3-1.37 m or >1.37 m). To facilitate analyses of overstory structure and to explore the scale-dependence of overstory-understory relationships, we also established a 5 × 5 m grid in each plot and recorded presence of all live and dead stems by grid cell (**Fig. 3**). Finally, in all plots affected by the 2012 Wenatchee Complex wildfire, we recorded char height on each stem as a potential predictor of recent mortality.

Subplots (50 m^2): shrubs (non-coniferous woody plants). Presence and foliar cover of each shrub species were recorded in each 50 m^2 *subplot*. We also censused the *tree plot* (1000 m^2) for additional species to estimate shrub richness at this larger spatial scale.

Quadrats (1 m^2): herbs, conifer seedlings, and ground conditions. Presence and foliar cover of each herb species were recorded in each 1 m^2 *quadrat*. We also inventoried one *subplot* (50 m^2) and the full *tree plot* (1000 m^2) for species to estimate herb richness at these larger spatial scales. Quadrats were also used to estimate cover of bare ground and other substrates, and to tally conifer seedlings (<0.3 m tall). Finally, at each of the eight centrally located (*focal*) quadrats (**Fig. 3**), we estimated local basal area with a prism and canopy cover with a convex densiometer as metrics for exploring the scale-dependence of overstory-understory relationships.

Repeat photographs. We repeated photographs at permanent photo points established prior to treatment, to document changing vegetation conditions. Two types of photos were taken: plot-scale views and close-ups of individual quadrats (**Fig. 4**).

Compilation, Assessment, and Availability of Historical & New Data

As a critical step in preparing for the 2015 remeasurement and subsequent analyses, we comprehensively assessed the content and quality of historical data (2000-2007). We compiled all available paper records (field sheets, protocols, reference materials) and electronic data

Fig. 4. A thinned and burned plot before (Aug 2000) and 12 years after treatment (May 2015).

(spreadsheets, photos, associated documents). Paper records were inventoried and scanned to pdfs. Electronic data were compared to field sheets and data-entry errors were corrected. Data were then subjected to QA/QC protocols (data limits, checks for missing data, relational checks, legitimate codes, comparisons of codes among plots/years). Inconsistencies or unresolved issues were added to a "notes" column on the field forms to be resolved during the 2015 remeasurement. These included (1) uncertainty about whether tagged trees were in or adjacent to plots; (2) unaccounted for tag numbers; (3) discrepancies in diameter, height, or status (live, dead, or cut trees); and (4) potential discrepancies in species' identification. These issues were described in a field manual (Halpern et al. 2017), along with remeasurement protocols, data-recording procedures, example data forms, and reference materials.

Following collection, entry, and verification of the 2015 data, inconsistencies were revisited, resolved (if possible), and documented in the final database. For example, because it was not possible to ensure consistent identification of some taxa, an "analysis code" was added to each record in the database, allowing some taxa to be grouped at the genus level. Historical codes and species nomenclature were updated to USDA Plants standards (http://plants.usda.gov), but both are preserved in the database to enable cross-referencing. Vouchers of unknown or difficult-to-identify species collected in 2015 are stored in the Bakker lab at the University of Washington. Additional details on data management are included, with the raw data, in a data archive (Bakker et al. 2018).

We have also contributed long-term data to another JFSP-sponsored project that is using a national database on tree mortality to validate existing models of post-fire tree mortality and to explore relationships between pre-fire climate and post-fire mortality (*Mortality reconsidered: Testing and extending models of fire-induced tree mortality across the US*; JFSP Project ID 16-1-04-8, S. Hood-PI). Bakker (PI) will be actively engaged in this ongoing collaboration.

Species' Identification & Data Reduction

Given the sensitivity of our results to species' turnover, we took a conservative approach to species identification. Several taxa that could not be reliably identified to species were grouped at the genus level (two shrubs, eight herbs). In addition, a small number (0.1%) of plant records could not be identified and were removed from the analyses. A full list of species, including family and common names, is provided in Rossman (2017) and Rossman et al. (*in review*).

Plant Groups & Vegetation Metrics

To characterize the contributions of different plant groups to the broader response of the understory, all species were classified by *growth form* (tree, shrub, or herb). In addition, herbs were classified by *life history* (annual/biennial vs. perennial) and geographic *origin* (native vs. non-native). These groupings were used to generate sets of ecological metrics (e.g., cover of shrubs or herbs; richness of herbs, annuals, natives, non-natives, etc.) for each sampling unit at each *spatial scale* (quadrat, subplot, or plot) and *time* (pre, early, and late). We generated two additional *post-treatment* metrics to interpret changes in herbaceous species richness: number of species that *colonized* and number of species that were *lost.*

Statistical Analyses

1. Variation in time and space. We used linear mixed-effects models to explore how temporal and spatial scales of observation influence vegetation responses to treatments. Using *species richness* as the metric, models tested a series of hypothesized responses of key understory plant groups to treatments, time, spatial scale, and pre-treatment conditions. The hypotheses are briefly summarized here; see Rossman et al. (*in review*) for the ecological bases for each hypothesis.

H1. General responses to thinning and burning. Species richness will be enhanced by thinning intensity and burning, reflecting greater post-treatment colonization than loss of species.

H2. Plant life history and origin. Annuals and non-natives (groups that benefit from disturbance) will be more responsive to burning than will perennials and non-natives.

H3. Effects of time. Responses to burning will weaken with time in annuals (with loss of germination sites and increasing competition from perennials) but will increase with time in perennials.

H4. Effects of spatial scale. Treatment effects will be more common at larger than at smaller spatial scales, consistent with the scales at which treatments enhance habitat heterogeneity.

H5. Role of pre-treatment richness. Pre- and post-treatment richness will be strongly correlated (reflecting high rates of species' survival). In addition, pre-treatment richness will mediate response to treatments, resulting in lower rates of colonization but greater rates of species loss in richer plots.

Response variables (metrics) included total post-treatment richness of shrubs or herbs; richness of annuals, perennials, natives, and non-natives; and numbers colonizing species or species lost. For each metric, a separate model was constructed at each spatial scale. *Subplot*- and *quadrat*-scale richness are the mean numbers of species per subplot or quadrat. *Plot*-scale richness is the cumulative number of species among the 10 shrub *subplots* or 20 herb *quadrats* per plot. Predictors in each model included the fixed effects of pre-treatment richness, time, (early or late), thinning intensity (SDI of cut trees), burn treatment, and interactions of treatments with time or pre-treatment richness. EU and plot were included as random effects. Data were limited to the eight EUs unaffected by wildfire. Models were developed in R (ver. 3.4.1; R Core Team 2017) using the *lme4* package (ver. 1.3-13; Bates et al. 2015).

2. Scale-dependence of overstory-understory relationships. Before examining the scale-dependence of relationships between residual overstory structure and the understory, we computed a standard set of structural metrics for each combination of plot and sampling date (n = 72 plots × 3 dates). These included density and basal area of live and dead trees, within-plot variation (CV) in density and basal area, tree growth (basal area increment), and annual and cumulative rates of mortality. For the principal tree species we also developed site-specific regression models to predict tree height from diameter. These structural summaries are not reported here due to space limitations but are available upon request.

We explored overstory-understory relationships and their scale dependence in the context of past fuel treatments and recent (2012) wildfire. We used herbaceous richness and cover data from the 8 centrally located *focal quadrats* (**Fig. 2**) in 2015, allowing maximal scaling of the overstory data. We addressed three questions in particular:

1. Do fuel treatments have long-term effects on overstory-understory relationships?
2. What is the spatial extent of overstory (grid cell to plot) for which understory metrics appear most responsive? In essence, what is the spatial scale of tree influence?
3. What is the relative importance of past fuel treatments, recent wildfire, and current overstory structure to the response of the understory?

We used generalized linear models to address these questions. For the third question, thinning (+/-) and burning (+/-) were included in all models and the relative importance of wildfire (+/-), basal area, and interactions therewith were evaluated via model selection. We tested multiple overstory metrics, but relationships with basal area were strongest and are presented here.

3. Variation associated with analytical approach. A common challenge when evaluating responses to fuel treatments—and in large-scale experiments in general—is understanding how conclusions are affected by decisions related to analytical approach. Using a common set of response data from this experiment (*plot*-scale richness in 2015), we demonstrate how these decisions can influence the significance of thinning or burning effects. We briefly assess three issues here. These and other analytical issues are examined in depth in Rossman (2017).

- *Aggregating vs. partitioning variation among sampling units*. In many fuel-reduction experiments, experimental (treatment) units are sampled with smaller plots, plot values are averaged, and treatment effects are assessed with analysis of variance (ANOVA) of experimental-unit means. We tested this approach by averaging *plot*-level responses (n = 6) for each *EU* and conducting a two-way ANOVA with main effects of thinning, burning, and their interaction. We compared these results with those of linear mixed-effects models in which *plot* values were retained (nested within *EU*s), allowing us to account for plot-level variation in treatment intensity and pre-treatment conditions.
- *Treatments as nominal vs. continuous factors*. We compared models that treated thinning as a nominal variable (+/-) with models that accounted for variation in thinning intensity (expressed as pre- to post-treatment change in SDI) within and among experimental units.
- *Accounting for pre-treatment variation.* Pre-treatment variation may mask or confound interpretation of treatment effects. We compared model outcomes using various approaches that assess, or account for, pre-treatment variation. These included testing for treatment effects prior to treatment, use of pre-treatment data as a covariate, and use of pre- to post-treatment change as the response variable.

Results & Discussion

Component 1. Review & Synthesis of the Literature

Vegetation-related management objectives of fuel treatments. Stakeholder interviews and planning documents supporting collaborative efforts at dry-forest restoration in the western U.S (CFLRP) yielded a diversity of vegetation-related management objectives of fuel treatments (**Table 2**). These provided the framework for our review of the literature.

Table 2. Vegetation-related objectives of fuel treatments in dry forests of the western U.S.

Stratum	Metric type	Objectives
Overstory	Structure / abundance	Develop and retain large/old trees
		Develop and retain snags in a variety of decay classes
		Establish heterogeneity of density/spacing/size/age at multiple spatial scales
	Composition	Favor fire-adapted species
	Physiology / growth	Limit large/old tree mortality
		Increase growth and vigor of large/old and fire-resistant tree species
	Disturbance	Increase resilience to fire, insects, and disease
Understory	Structure / abundance	Reduce density of conifer seedlings and sapling
		Promote native herb and shrub abundance
	Composition	Promote native species; limit non-native/invasive species
		Limit excessive establishment of shade-tolerant trees
		Support establishment of shade-intolerant/fire-tolerant tree species
	Physiology / growth	Favor growth and vigor of understory vegetation and/or fire-tolerant tree regeneration
	Disturbance	Increase resilience to fire, insects, disease
	Diversity	Increase species diversity at multiple spatial scales

We identified 224 papers that assessed one or more of these objectives in pine and mixed-conifer forests in western North America. The complete list of papers with details on study characteristics, response variables, and definitions is available in a data archive (Urgenson et al. 2018). Key conclusions and summaries are provided here.

Locations and forest types. Studies were concentrated geographically: 55% of studies in pine types were from Arizona; 55% of studies in mixed-conifer types were from California (**Table 3**).

Table 3. Number of studies by forest type and location (state or province; BC is British Columbia, Canada). Studies conducted in two states are tallied under each state (*n* = 7).

Forest type	AZ	BC	CA	CO	ID	MT	NM	OR	SD	WA	Total
Mixed conifer (dry or moist; *Pinus*, *Abies*, and associated species)	4	2	53	3	2	12	1	11	0	11	97
Yellow pine (*Pinus ponderosa*, *P. jeffreyi*)	60	0	21	5	1	7	4	10	3	3	110
Mixed conifer and yellow pine	4	1	3	1	0	0	1	0	0	0	9
Other (*Larix occidentalis*, *Pinus contorta*, interior *Pseudotsuga menziesii*	0	1	2	0	0	3	0	2	0	0	8
Total	68	4	79	9	3	22	6	23	3	14	224

Study duration. Nearly half (46%) of all studies were long-term (≥5 yr post-treatment) (**Table 4**). Over half were longitudinal (51% of short-term studies, 55% of long-term studies).

Table 4. Number of short- and long-term studies with different temporal approaches. A single paper may include multiple approaches. For studies of response after wildfire (*n* =18), time is time since wildfire, not fuel treatment. Three studies did not report time since treatment.

Study duration	Time (yr)	Longitudinal	Retrospective	Chronosequence	Dendroecological	Total
Short term	<5	61	12	0	4	119
Long term	5-10	34	13	1	5	62
	11-20	10	13	5	9	28
	>20	2	8	0	4	12

Vegetation strata and plant growth forms. Metrics of overstory and understory response were examined in approximately equal proportions (**Table 5**).

Table 5. Number of short- and long-term studies addressing different vegetation strata/plant growth forms. A single paper may include more than one stratum/growth form. Totals include studies that did not report time since treatment.

Vegetation stratum	Plant growth form	Short term (< 5 yr)	Long term (≥5 yr)	Total
Overstory	Live trees	86	81	170
	Dead trees (snags)	7	10	17
Understory	Herbs/shrubs	46	43	91
	Trees	30	30	60
	Seeds	7	1	8

Treatments and methods of gauging effects. Studies included individual or multiple treatments and multiple methods of gauging effects (comparisons with controls, pre-treatment data, or both) (**Table 6**). Most short- and long-term studies included controls (84% of each). However, short-term studies more often accounted for pre-treatment variation (67% vs. 41%) and almost twice as often (60 vs. 33%) included both control and pre-treatment data (i.e., employed a Before/After, Control/Impact [BACI] design). Several studies (8%) used reconstructed historical, pre-settlement forest structure (before industrial logging and fire suppression) as a basis for assessing treatment effects.

Table 6. Number of short- and long-term studies of different fuel treatments using different methods to compare effects (i.e., comparison to control [C], pre-treatment [Pre], both C and Pre [C/Pre], or historical reference [H] data). Totals include three studies that did not report time since treatment.

	Short-term studies			Long-term studies				Short-term	Long-term	
Treatment(s)	C	Pre	C/Pre	C	Pre	C/Pre	H	Total	Total	Total
Thin	15	12	9	24	5	4	4	18	28	46
Burn	26	22	18	13	7	5	3	34	17	54
Thin + Burn	12	7	7	11	8	5	1	14	14	28
Thin, Burn	1	0	0	0	0	0	0	1	0	1
Thin, Burn, Thin + Burn	30	28	28	14	10	10	3	32	14	46
Thin, Thin + Burn	12	7	6	19	8	6	2	15	23	38
Burn, Thin + Burn	4	4	3	5	4	4	5	5	6	11
Totals	100	80	71	86	42	34	18	119	102	224

Spatial scale or variation. Spatial scale or spatial variation were considered in several distinct ways in the literature: (1) comparing a metric (e.g., species richness) at multiple sampling scales (8% of studies); (2) analyzing responses among sites in different biophysical settings (e.g., soil type, productivity, forest type) (17% of studies); (3) analyzing variability in response *within* treatment units (9% of studies); and 4) characterizing spatially explicit patterns (e.g., scale of tree clumping or dispersion, overstory clump-size distributions) (12% of studies) (**Table 7**). More than one-third (37%) of studies considered at least one aspect of spatial scale. However, only 38 were long-term studies, suggesting that, in total, few studies (17%) consider both space and time in assessing the ecological effectiveness of fuel treatments.

Table 7. Number of short- and long-term studies addressing different aspects of spatial scale or spatial variation in vegetation response to fuel treatments. A single paper may include more than one stratum/growth form. Totals include studies that did not report time since treatment.

	Overstory		Understory			Study duration		
Type of measure	Trees	Snags	Herbs / shrubs	Trees	Seeds	Short-term	Long-term	Total
Multiple sampling scales	8	0	14	5	2	13	6	19
Variability within treatment units	10	0	17	4	2	8	11	21
Biophysical variation	22	1	23	7	1	14	22	37
Spatially explicit patterns	26	3	6	12	0	12	14	27

Vegetation metrics. Response metrics included aspects of overstory and understory composition, structure, diversity, and plant function that relate well to the ecological objectives of management (see '*Literature Summary Tables*'; JFSP 'Other Product Types' ID No. 8012). Three-quarters of studies (n = 171) reported *overstory*-related response metrics. In these studies, the most common metrics included tree or snag density (56% of studies), basal area (49%), and mortality (42%). About half of studies (n = 123) reported *understory*-related response metrics. In these studies, the most common metrics included aspects of species composition (abundance of individual species or groups of species; 69% of studies), total cover (52%), density (40%), and species richness (38%).

Component 2. Multi-scale Assessment of Treatment Effects

1. Variation in time and space

Total richness. Over the period of study, we recorded 151 taxa among the 48 plots (8 EUs; excluding wildfire-impacted EUs and full-plot inventories at the late sample) included in the analysis. Of these, 100 taxa were recorded before treatment, 131 in the early sample, and 138 in the late sample. Herbs were more diverse than shrubs (72-109 vs. 28-29 species), perennials were more diverse than annuals (62-88 vs. 10-21), and natives were more diverse than non-natives (67-98 vs. 5-11).

Hypothesized effects of treatments, time, and spatial scale on species richness. To facilitate comparisons, all model results are summarized in **Fig. 5**.

H1. General responses to thinning and burning. Species richness will be enhanced by thinning intensity and burning, reflecting greater colonization than loss of species. All but non-native species responded positively to burning, but the size of the effect varied markedly among

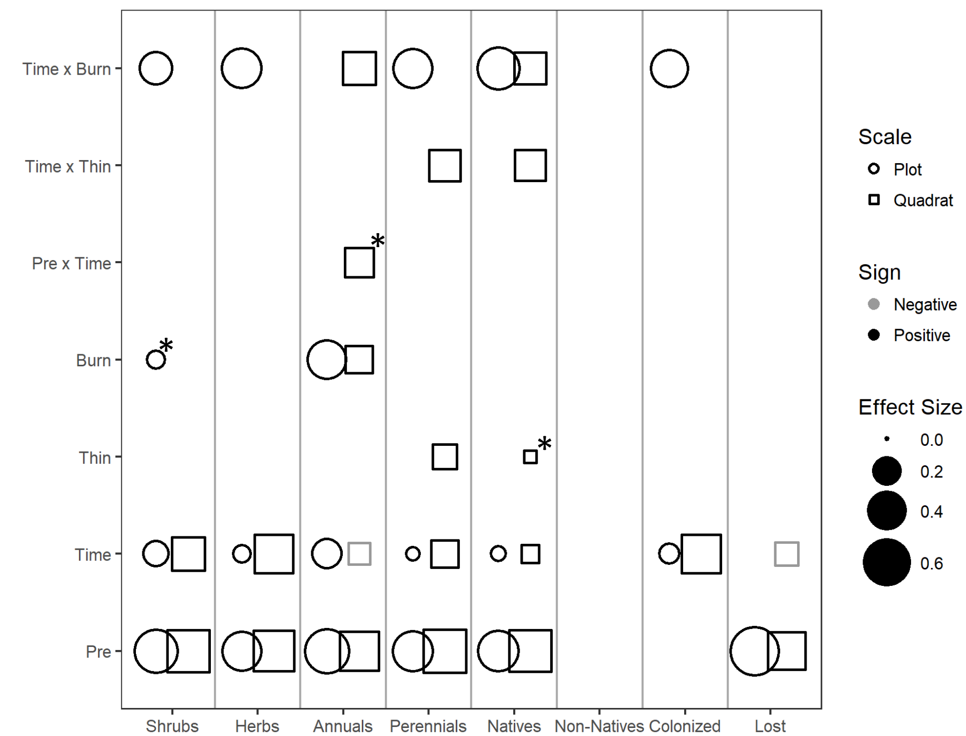


Fig. 5. Results of repeated-measures models showing standardized coefficients of significant predictors of post-treatment richness at each of two spatial scales. Plant groups are on the X axis; main effects and interactions are on the Y axis. *Pre* is pre-treatment richness; *Time* is early or late (2-3 or 10-13 yr), *Thin* is thinning intensity, *Burn* is unburned or burned. Symbol size corresponds to effect size; shading indicates the sign of relationship (negative or positive). All coefficients are highly significant ($p < 0.003$) except those with asterisks ($p < 0.1$).

groups, spatial scales, and times (**Fig. 5**). In contrast, only perennials and natives responded positively to thinning intensity.

H2. Plant life history and origin. Annuals and non-natives (groups that benefit from disturbance) will be more responsive to burning than will perennials and non-natives. Annuals responded positively to burning at both spatial scales, but perennials, only at the larger scale (**Figs. 5, 6**). Although greater numbers of perennials established, annuals were more responsive relative to the size of the annual species' pool. Non-natives were uncommon before treatment and largely unresponsive to treatment.

H3. Effects of time. Responses to burning will weaken with time in annuals (with loss of germination sites and increasing competition from perennials) but will increase with time in perennials. Burning led to an early and surprisingly persistent increase in annuals at the plot scale, but a delayed response at the quadrat scale (**Figs. 5, 6**). Perennials showed lagged responses, as expected, but at differing spatial scales in response to thinning (quadrat) and burning (plot).

H4. Effects of spatial scale. Treatment effects will be more common at larger than at smaller spatial scales, consistent with the scales at which treatments enhance habitat heterogeneity. Responses to burning were as expected. Annuals responded earlier at the plot than at the quadrat scale; shrubs, herbs, and perennials responded only at the plot scale (**Figs. 5, 6**). Responses to thinning, however, were not as expected: perennials and natives responded only at the quadrat scale.

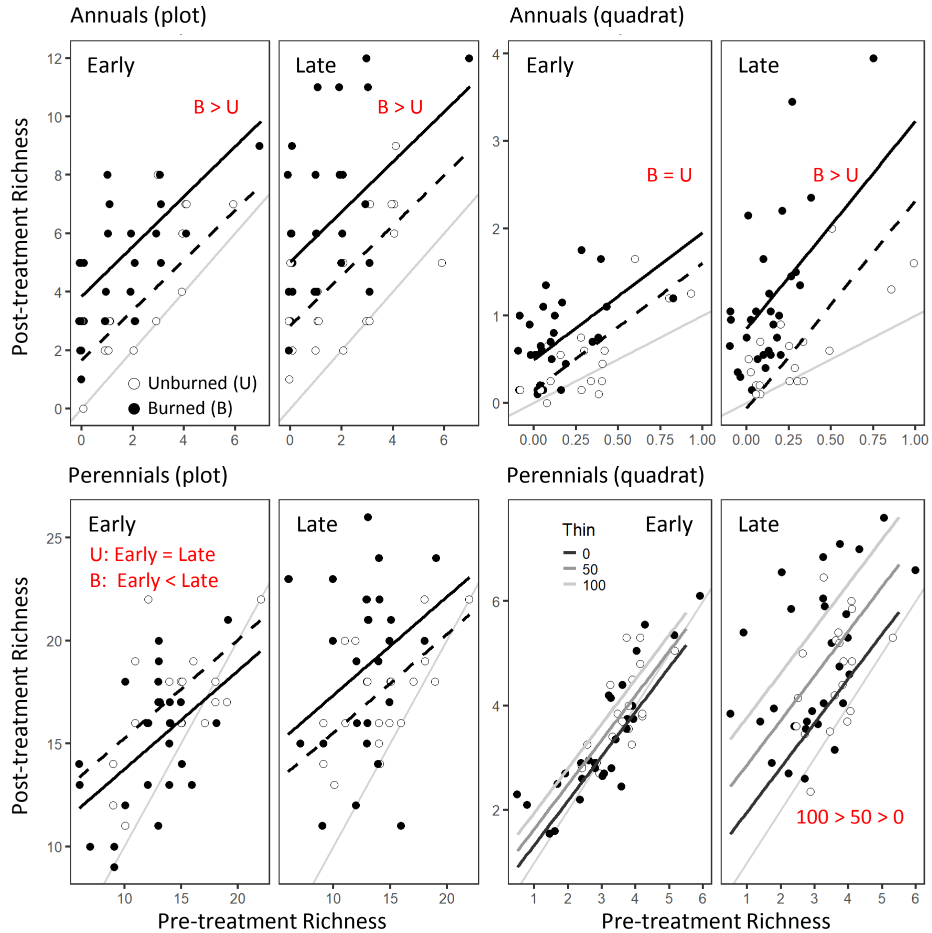


Fig. 6. Relationships of post-treatment richness to pre-treatment richness, time, and burn treatment for annuals and perennials. Separate panels for *Early* and *Late* indicate a significant time effect. Black regression lines are relationships with pre-treatment richness (B = solid, U = dashed). Results of *post-hoc* tests are in red. For perennials at the quadrat scale, regression lines are predicted richness at the specified thinning levels; wider spacing in the late sample illustrates the significant interaction with time. Thin grey lines are 1:1 relationship between pre- and post-treatment richness; points above the line indicate an increase over time.

H5. Role of pre-treatment richness. Pre- and post-treatment richness will be strongly correlated (reflecting high rates of species' survival). In addition, pre-treatment richness will mediate response to treatments, resulting in lower rates of colonization but greater rates of species loss in richer plots. Pre- and post-treatment richness were highly correlated (**Fig. 5**). However, pre-treatment richness did not mediate responses to treatments because it did not affect rates of colonization (**Figs. 5, 7**). Although species' loss correlated with pre-treatment richness, on average many fewer species were lost than colonized (**Fig. 7**).

Discussion. By modeling the 'early' and 'late' responses of multiple plant groups at two spatial scales, we were able to capture substantial variation in the effects of fuel treatments on species richness. Richness was enhanced by burning and to a lesser extent, by thinning, but at differing rates and spatial scales, reflecting variation in the pace and density of species' colonization. This variability highlights the critical value of long-term, multi-scale assessments in defining the spatial and temporal scope of fuel treatment effectiveness and in evaluating the need for further intervention.

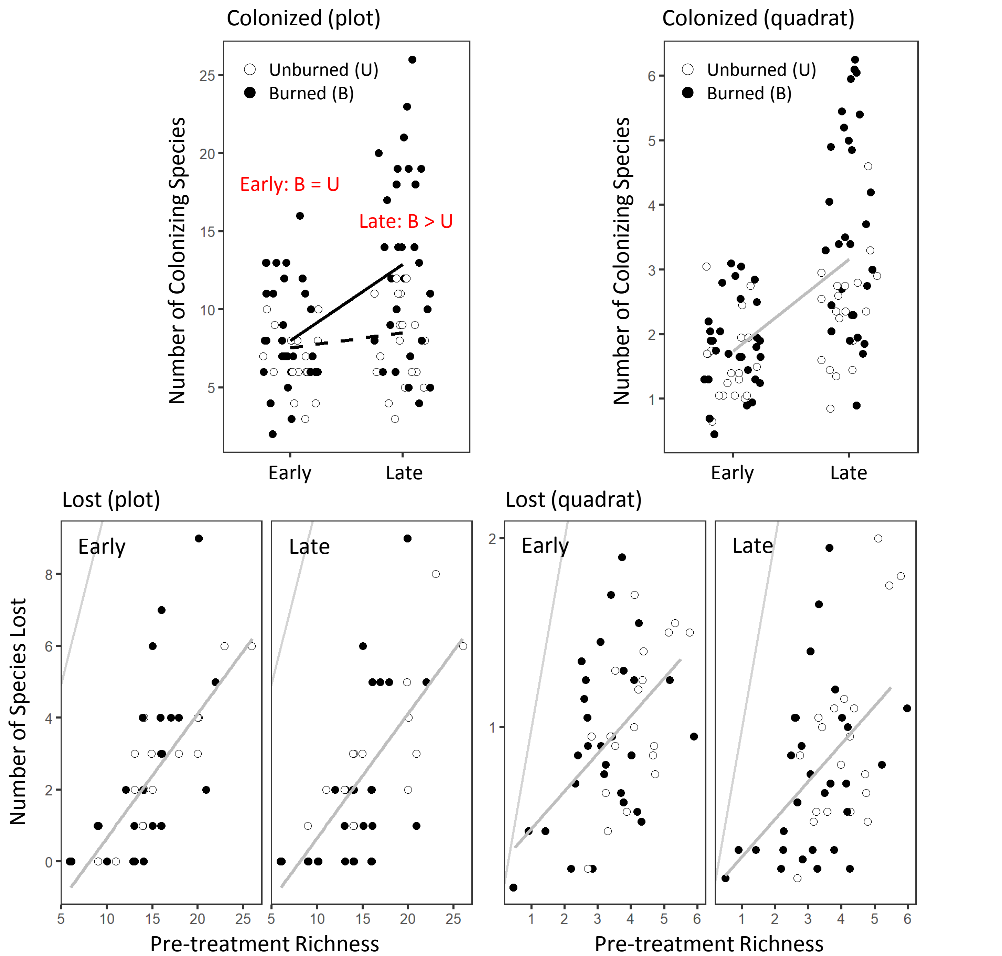


Fig. 7. Numbers of colonizing and lost species as related to pre-treatment richness, time, and burn treatment. For colonizers, there was no relationship to pre-treatment richness, but there was a significant time × burn interaction at the plot scale (*post-hoc* tests in red) and a significant time effect at the quadrat scale. For species lost, pre-treatment richness was significant at both scales, but time only at the quadrat scale (greater loss in the early sample). See Fig. 2.6 for other details.

We observed striking differences in response to the two treatments: mostly neutral effects of thinning, but positive effects of burning—well within the range of responses reported in the literature (Bartuszevige & Kennedy 2009, Abella & Springer 2015, Willms et al. 2017). However, there was also significant variation in the timing and spatial scales of response: treatment effects were rarely detected early (2-3 years), but were common later (10-13 years), most often at the plot scale. The absence of short-term effects is consistent with many reports in the literature; however, the longer-term response is more difficult to compare given the limited duration of most studies (Abella & Springer 2015).

The preponderance of 'late, plot-scale' effects on richness suggests a process of slow and sparse recruitment (**Fig. 1**, scenario 2), consistent with the patterns of herb colonization. An alternative explanation is that richness accrued slowly due to turnover, but this is not supported by the strong correlations between pre- and post-treatment richness or by patterns of species' loss (low relative to gains and unaffected by treatment). That increases in richness were relatively slow to emerge despite low cover of competing plants, suggests that any enhancement of richness by soil disturbance was weak or patchy (consistent with the post-treatment assessment of fuels; Agee & Lolley 2006). It may also reflect underlying seed limitations, e.g., depletion of the soil seed bank, low rates of dispersal, or the dependence of some plants on slower modes of vegetative spread. Others have observed similar 'insensitivity' of perennials to fuel treatments, including the inability to detect an effect of treatment 5-10 years after burning, or after multiple burns (Kerns et al. 2006, Webster & Halpern 2010). For perennial herbs, often the most diverse understory group, this insensitivity may be the result of grouping species with very different growth forms, regenerative traits, and responses to fire (McIntyre et al. 1995, Webster & Halpern 2010). Similar effects of 'species averaging' may affect the sensitivity of other broad groups of species (e.g., native herbs; Willms et al. 2017) to fuel treatments.

Annuals responded more quickly than did perennials, as expected, but they were surprisingly persistent. Their spatio-temporal dynamic suggests a process of sparse recruitment, then population expansion via local seed production (e.g., Halpern et al. 1997). Factors hypothesized to limit their persistence—suitable germination sites or competition for resources by perennials—did not appear relevant. Although competition for light may limit the temporal window for annuals in productive forests (Halpern 1989), soil resources (e.g., water) may be the primary constraint in drier forests (Riegel et al. 1992), particularly where fuel treatments reduce overstory density. If competition from perennials remains low, annuals may be able to persist.

In contrast to burning, thinning had a much narrower range of effects, despite wide variation in thinning intensity. However, the spatial scale of the thinning effect was distinctive: enhancing richness at local, but not larger scales. This pattern suggests that thinning increased resource availability but not resource diversity (**Fig. 1,** scenario 1). Although mechanical thinning can lead to patchy soil disturbance, helicopter yarding in this study likely tempered that effect (Boerner et al. 2009).

Relationships between post- and pre-treatment richness, often ignored in the literature, highlight several important characteristics of this system. First, pre-treatment variation in richness was largely maintained through disturbance, suggesting high species' survival. Second, rates of post-treatment colonization were not affected by pre-treatment richness, only by burning and time. This result has two important implications. At larger scales this suggests that the pool of potential immigrants was considerably larger than the existing pool of species. Indeed, study-wide diversity increased by 40% over the course of study (from 100 to 138 species). Some immigrants likely derived from non-forested habitats purposely avoided during plot establishment, but others were likely to have been present locally at very low densities. Although it is not possible to reconstruct pre-treatment conditions, we see evidence for this in the current distributions of species: full-plot inventories at the late sampling date showed that quadrats failed to capture ~50% of species present within the larger plot. At smaller spatial scales, e.g., the scale at which species interact, colonization patterns suggest that even where species' densities were high, communities were not fully 'saturated', thus capable of responding positively to treatment.

Considerable attention has been devoted to the effects of fuel treatments on non-natives (Keeley 2006, Dodson & Fiedler 2006, Kerns et al. 2006, Nelson et al. 2008). Although recent reviews and meta-analyses highlight the diversity of responses to treatment (Abella & Springer 2015, Willms et al. 2017), they offer little insight into the scale-dependence, timing, or longevity of response (but see Sutherland & Nelson 2010). In this experiment, non-natives remained unresponsive to treatments, irrespective of time or spatial scale. Given abundant recruitment of native annuals, we suspect that non-natives were limited by seed supply (propagule pressure; Lonsdale 1999, D'Antonio et al. 2001, Keeley 2006), not by resource availability or 'biotic resistance' (preemption by the resident community). Their paucity in this experimental setting likely reflects long-term exclusion of fire, limited grazing, absence of ground-based machinery during harvest, and long distances to potential seed sources (e.g., roadsides; Gelbard & Belnap 2003).

2. Overstory-understory relationships

1. Do fuel treatments have long-term effects on overstory-understory relationships? In 2015, 10-13 years after treatment, herb richness was negatively correlated with local overstory basal area only in unthinned plots; there was no relationship in plots that were thinned (**Fig. 8**). Burning did not have a similar mediating effect on this relationship. Thinning thus appears to have 'severed' the constraining influence of overstory structure on understory diversity.

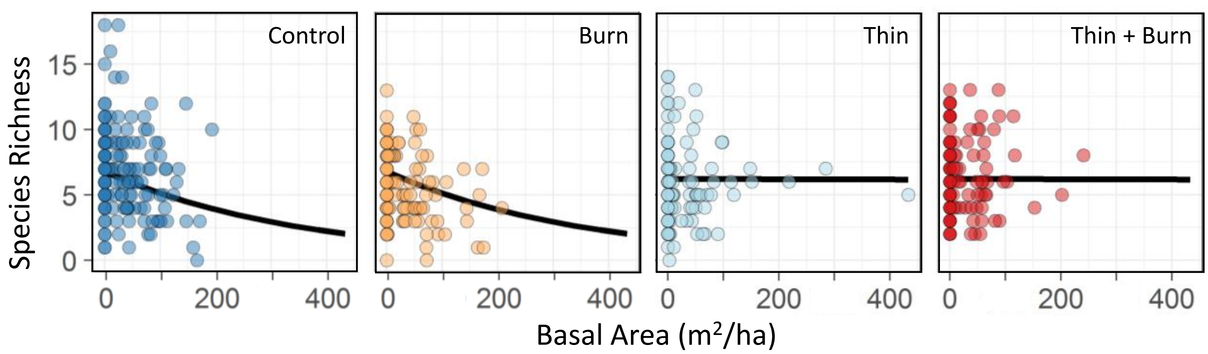


Fig. 8. Relationships between *quadrat*-scale herb richness and local basal area (BA, *grid-cell* scale) among fuels treatments. The negative relationship with BA was detected only in plots that were not thinned.

2. What is the spatial extent of overstory (grid cell to plot) for which understory metrics appear most responsive? In essence, what is the spatial scale of tree influence? In tests over a range of spatial scales (extents) in the overstory, the negative effect of basal area on *quadrat*-scale herb richness was significant only at the smallest scale (25 m^2 *grid cell*; **Fig. 9**).

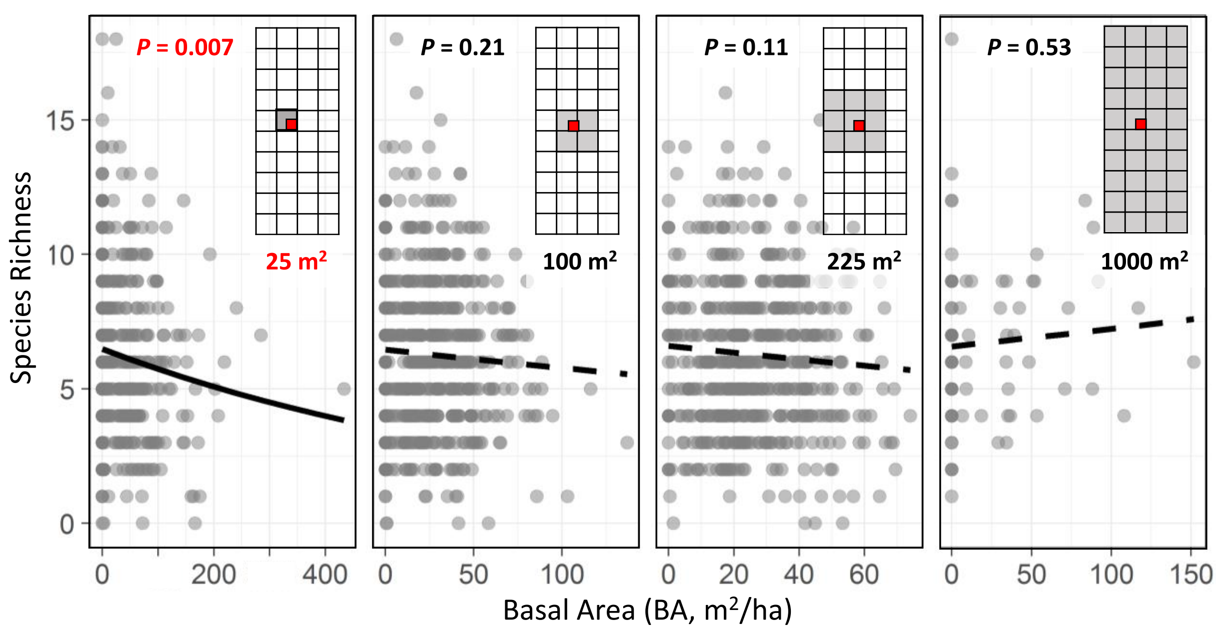
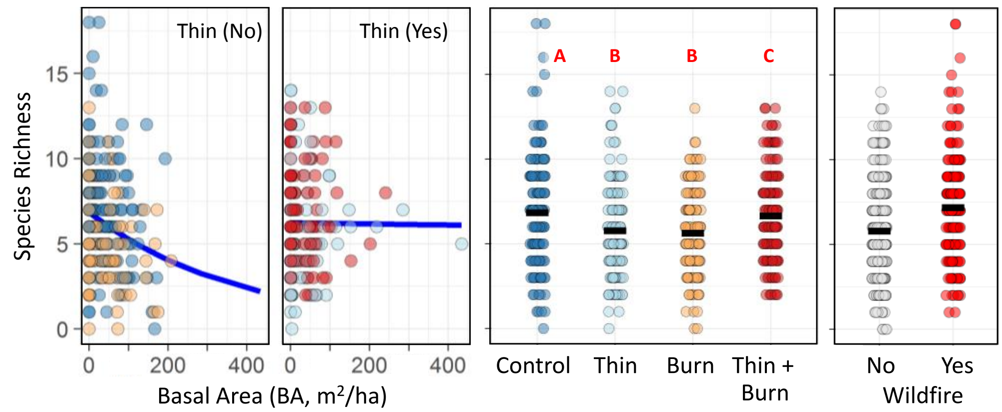
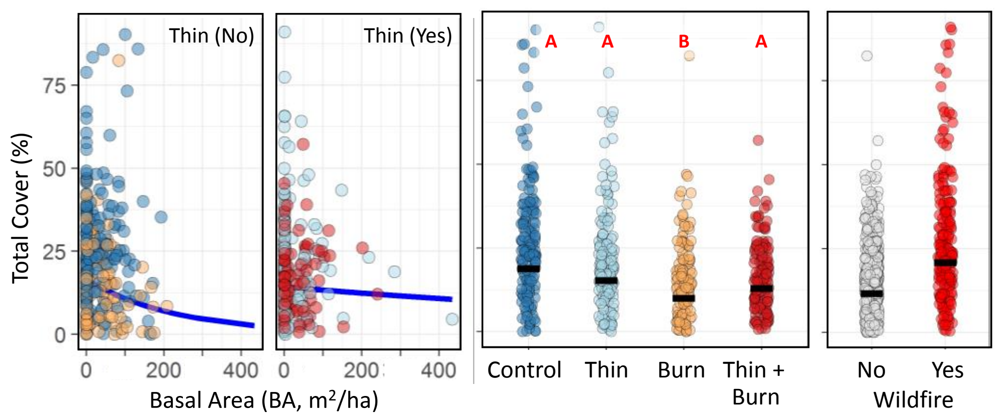


Fig. 9. Relationships between *quadrat*-scale herb richness (red square) and basal area of increasing spatial extent (numbers of grey grid cells). The only significant relationship (p = 0.007) was at the smallest spatial extent.



Term	*P*
Thin	0.667
Burn	0.463
Wildfire	**<0.001**
BA	**0.003**
Thin x Burn	**<0.001**
Thin x BA	**0.002**

Fig. 10. Individual and interactive effects of current tree basal area, past fuels treatments, and recent (2012) wildfire on *quadrat*-scale herb richness. *P* values are from a linear mixed-effects model testing main effects and interactions.



Term	*P*
Thin	0.884
Burn	**<0.001**
Wildfire	**<0.001**
BA	**0.011**
Thin x Burn	**0.010**
Burn x Wildfire	**0.046**
Thin x BA	0.060

Fig. 11. Individual and interactive effects of current tree basal area, past fuels treatments, and recent (2012) wildfire on *quadrat*-scale herb cover. *P* values are from a linear mixed-effects model testing main effects and interactions.

3. What is the relative importance of past fuel treatments, recent wildfire, and current overstory structure to understory response? Past thinning and burning had interactive effects on species richness, whereas recent wildfire increased it (**Fig. 10**). In comparison, effects of basal area were less pronounced and were restricted to units that had not been thinned. Past burning and recent wildfire also had strong, but contrasting effects on total herb cover: burning reduced cover but wildfire increased it (**Fig. 11**). The effect of basal area was significant but weaker.

Discussion. Thinning 'breaks' the overstory-understory relationship. Presumably, overstory effects will be re-exerted in thinned areas as tree density or size increase, but this will take time. In our system, characterized by little post-thinning recruitment of trees, the change in relationship between overstory and understory may persist for decades.

Effects of the overstory on understory richness and cover are strongest at relatively small spatial extents and are not evident at larger spatial scales (e.g., 1000-m^2 plots). The influence of trees thus appears to be "local", coinciding with the crown areas of larger individuals. However, the mechanism of interaction is as likely to be below ground (competition for soil resources) as it is to be above ground (competition for light) (Riegel et al. 1992).

Although the overstory affected the understory, as evident in the response to local basal area in the absence of thinning, these effects were less important than the effects of fire (past burning or recent wildfire). However, effects of past and recent fire differed: herb cover was lower in

Burn than *Control* plots, but higher in plots that experienced wildfire than in those that did not. These differing responses to fire may relate to differences in time since burning, to fire intensity or severity, or to factors unrelated to fire (e.g., spatial variation in the composition or density of the soil seed bank). The positive response to wildfire is particularly surprising as the units affected generally had greater overstory influence (3 of 4 units were not thinned) and less well-developed understories. Yet, they developed greater herb diversity and cover after fire. In sum, our results suggest potentially complex responses of the understory, in both time and space, to the individual and interactive effects of fuel treatments, residual forest structure, and recent disturbance.

3. Variation associated with analytical approach

We provide several illustrations of how conclusions about the ecological effectiveness of fuel treatments (in this instance, enhancement of herb richness) are affected by decisions regarding analytical approach. These and other issues are discussed in full in Rossman (2017).

Aggregating vs. partitioning variation among sampling units. Using post-treatment richness data aggregated for each experimental unit (means of 6 plots), we conducted a two-way ANOVA for comparison with more complex models incorporating pre- and post-treatment variation at the plot level (see below). The ANOVA yielded non-significant effects of treatment ($R^2 = 0.42$; Thin, $P = 0.51$; Burn, $P = 0.91$; and Thin × Burn, $P = 0.24$). Several factors may have contributed to the absence of significant treatment effects: low replication (8 EUs in total, so 7 df), an unbalanced design, treatment of thinning as nominal variable, and large pre-treatment variation. In subsequent analyses we used linear mixed-effects models to assess two of these factors: thinning as a nominal vs. continuous factor and pre-treatment variation among plots.

Thinning as a nominal vs. continuous factor. We compared the results of linear mixed-effects models that treated thinning as a nominal vs. continuous variable (thinning intensity, expressed as pre- to post-treatment change in stand density index, SDI). With the former, neither thinning nor burning was significant (*Model 1*, **Table 8**). With the latter, there was a significant (positive) interaction between thinning and burning: richness increased with thinning intensity to a greater degree in burned than in unburned plots (*Model 2*, **Table 8**).

Table 8. Linear mixed-model results (model R^2 and P values) comparing thinning as a nominal vs. continuous variable (thin intensity) for predicting post-treatment, plot-level richness of herbs. Thin intensity was computed as pre- to post-treatment change in stand density index (change in SDI). *EU* was included as random effect. Significance was evaluated using α = 0.1.

Model	Predictor type	R^2	1. Thin or 2. Thin intensity	Burn	1. Thin × Burn or 2. Thin intensity × Burn
1	Nominal (thin vs. no thin)	0.35	0.44	0.92	0.17
2	Continuous (thin intensity)	0.35	0.29	0.99	**0.07**

Accounting for pre-treatment variation. We illustrate how methods of accounting for pre-treatment variation can alter conclusions about thinning and burning effects (**Table 9)**. Analysis of pre-treatment richness data alone (*Pre*, *Model 1*) revealed a strong negative correlation with thinning intensity: plots with higher pre-treatment SDI (thus thinned more intensively to meet the basal area target of the thinned treatment), also had fewer species at the outset. Subsequent analysis of post-treatment richness data (*Post*, *Model 1*) yielded a significant treatment interaction; however, the strong correlation between *Pre* and thinning intensity confounds the effect of thinning intensity with initial richness. Adding *Pre* as a covariate to the model (*Model*

2) enabled subsequent interpretation of the thinning effect as just that: significant positive effects of *Pre*, thinning, and burning indicated that richness was enhanced by treatments even after accounting for pre-treatment variation. An alternative modeling approach accounts for *Pre* in the response variable (as *Change* between *Pre* and *Post*, *Model 3*); this also yielded positive effects of treatments and explained greater variation (62 vs. 49%). However, the ecological interpretations of these two models differ due to the forms of the response (post-treatment richness vs. amount of increase in richness). Finally, a model of *Change* that included *Pre* as a covariate (*Model 4*), yielded significant main effects and interaction, indicating that thinning intensity enhanced richness to a greater degree in burned than in unburned plots, irrespective of initial richness.

Table 9. Linear mixed-model results (model R^2 and P values) comparing approaches to account for pre-treatment variation (*Pre*). *Thin* is 'thinning intensity' (see **Table 8**). *Model 1* tests effects prior to treatment using *Pre* as the response. *Model 2* uses *Pre* as a covariate. *Model 3* uses change in richness as the response. *Model 4* uses change in richness as the response and *Pre* as a covariate. *EU* was included as random effect. Type I (sequential) sums of squares were used. Although tested, there were no significant interactions with '*Pre*'. Significance was evaluated using α = 0.1.

Model	Response variable	Predictors	R^2	Pre	Thin	Burn	Thin × Burn
1	*Pre*	Thin, Burn	0.56	–	**<0.001**	0.12	0.49
1	*Post*	Thin, Burn	0.35	–	0.50	0.10	**0.07**
2	*Post*	*Pre*, Thin, Burn	0.49	**0.06**	**0.05**	**0.03**	0.10
3	*Change* (*Pre* to *Post*)	Thin, Burn	0.62	–	**<0.001**	**0.02**	0.14
4	*Change* (*Pre* to *Post*)	*Pre*, Thin, Burn	0.63	**<0.001**	**0.05**	**0.03**	**0.10**

Discussion. Previous studies have reported both significant and non-significant effects of thinning and prescribed burning on understory diversity and abundance (Abella & Springer 2015, Willms et al. 2017). However, few have considered whether statistical outcomes or ecological interpretations are sensitive to methods of analysis. We found that, *for the same data*, the apparent ecological benefits of fuel treatments (expressed by the significance of treatment effects) can vary with analytical approach. Our comparative analyses illustrate the importance of several factors: data aggregation, consideration of treatments as categorical vs. continuous predictors, and whether and how analytical models account for pre-treatment variation. Incorporating these factors into the design of experiments, monitoring protocols, and analyses of responses, can yield important insights into the nature of ecological variation in space or time and how it is shaped by initial conditions, treatment characteristics, and post-treatment processes.

Science Delivery Activities & Products

We have used a diversity of approaches and venues to deliver our research findings to the science and management communities. Details are provided in **Appendix B**.

Presentations/workshops. We presented our research to a diverse set of audiences, reaching scientists, managers, and practitioners representing academia, federal and state land management agencies, Native American tribes, NGOs, industry, and the public. We presented at conferences, symposia, workshops, and other venues in each year of the grant (2014, twice in 2015, four times in 2016, and twice in 2017) (see **Appendix B**). An invited presentation is also planned for 2018.

Articles, technical reports, and theses. Several manuscripts have been published or are in review in the following journals: Environmental Management (2017), Restoration Ecology (*in press*), and Forest Ecology and Management (*in review*). Three other manuscripts are in draft form or in preparation. This project also produced one MSc. thesis comprising two research chapters, reflected in the publications noted above. In addition, data from this project will be published as part of other JFSP research products (see description of tree mortality modeling efforts described under *Compilation, Assessment, and Availability of Historical & New Data*). Finally, once key papers are accepted for publication we will work with the Northwest Fire Science Consortium (NWFSC) on two *Research Briefs* that will address key findings from this project.

Data. For Component 1, we compiled a very detailed summary of the attributes of the 224 studies identified through our systematic review. These attributes are available through the Forest Service Research Data Archive (Urgenson et al. 2018).

For Component 2, we created a comprehensive database that includes the historical (2000-2007) and new (2015) vegetation data for this study. This database is available digitally through the Forest Service Research Data Archive (Bakker et al. 2018). It includes data from the overstory, shrub, and herb layers, along with metadata and a detailed field manual (Halpern et al. 2017). The Data Archive is not set up to store electronic photographs, but repeat photographs are available on request.

Conclusions, Implications for Management, & Future Research

Component 1. Review & Synthesis of the Literature

Studies not geographically representative. Our systematic review identified 224 papers that examine vegetation-related ecological responses to thinning and prescribed fire treatments in western North America. Response metrics include aspects of overstory and understory composition, structure, diversity, and plant function that link with restoration objectives in fire-adapted forests. However, we found several gaps in published information related to spatial and temporal scales of vegetation responses to fuel treatments. First, much of this research is concentrated in Arizona pine and Californian mixed- conifer forests. Thus, there is risk of inappropriately generalizing research findings to other regions, including the Pacific Northwest and Northern Rockies, which differ in forest structure, composition, and patterns of disturbance. Additional research and monitoring are needed in these relatively understudied regions to verify whether fuel treatments are achieving management objectives. Second, only 16% of studies examined how responses to thinning and burning are influenced by biophysical conditions (e.g., soil type, site productivity, or other environmental variation). Research is needed to enhance our understanding of spatial variation in responses to fuel treatments implemented across environmentally diverse landscapes.

Spatial variability important but understudied. Interviews with CFLRP collaboratives and analysis of planning documents suggest that managers are interested in achieving spatial heterogeneity in understory and overstory vegetation using treatments designed to meet fuel-reduction and ecological-restoration objectives. In practice, this requires managing for variation in the spatial patterning of trees, including the number and sizes of clumps and openings, variation in tree sizes and ages, and retention of large/old trees that reflect historical (pre-European settlement) conditions, or conditions prior to more recent grazing, logging, and exclusion of fire. In the understory, achieving spatial heterogeneity means supporting variation in the abundance and diversity of native species at multiple spatial scales within and among treatment units. However, few of the 224 studies included in our review considered spatial variation in the understory: only 6% examined spatially explicit measures of understory distribution, 8% analyzed variability *within* treatment units, and 6% compared a metric (e.g., species richness) at multiple sampling scales. Thus, analyses of the spatial aspects of vegetation responses to fuel treatments are diverse but limited. Among studies including at least one of these measures of spatial variation ($n = 38$, 17% of studies), only half were long term (≥5 years), highlighting the dearth of studies that consider both the spatial and temporal aspects of ecological responses to fuel treatments. Research that addresses the long-term effectiveness of fuel treatments in meeting management objectives related to the spatial patterning of vegetation structure and composition remains a critical need.

BACI designs uncommon. Finally, although 46% of the papers reviewed examined long-term responses to fuel treatments, only 33% of long-term studies employed a BACI design, incorporating both control and pre-treatment data in analyses. Findings from Component 2 of this project highlight the importance of pre-treatment data in interpreting vegetation responses to fuel treatments. Where pre-treatment data are lacking it can be difficult to distinguish between responses to treatment and variation in initial conditions, and thus to quantify the nature or magnitude of vegetation response. *In sum, our work underscores the rarity and value of long-term, multi-scale assessments for interpreting ecological responses to thinning and burning in dry forests of western North America*.

Component 2. Multi-scale Assessment of Treatment Effects

Value of long-term, multi-scale assessments and pre-treatment data. Our work has a number of important implications for monitoring the ecological effectiveness of fuel treatments. First, it underscores the value of long-term multi-scale assessments, and the advantages of BACI designs more generally, for interpreting ecological responses. Pre-treatment data were critical to (1) distinguishing between thinning effects and structural influences on the understory prior to treatment, (2) quantifying the magnitude of response to thinning and burning, and (3) characterizing the broad range of vegetation states that responded positively to treatment. Analyses based on post-treatment data alone would have yielded very different conclusions about the effectiveness of treatments and the pre-treatment contexts in which they were effective.

Our results also illustrate how short-term assessments may not detect important ecological responses that are slower to emerge. Short-term assessments may lead to false conclusions about the effectiveness of fuel treatments, but could trigger further interventions that are unnecessary, costly, or counterproductive (e.g., if they introduce or promote expansion of non-natives). On the other hand, it is possible that significant effects in the late, but not early, time period in this study exaggerate what are actually shorter temporal lags in some plant groups. Clearly, more frequent sampling would have clarified the time course of the response. This uncertainty points to the value of both frequent and longer-term measurements. Nevertheless, the late sample was critical to documenting the longevity of what are often assumed to be transient effects (e.g., rapid turnover of annuals after fire).

Longevity of ecological effects. Our ability to demonstrate positive long-term responses to burning points to the effectiveness of this treatment in promoting native plant diversity, despite falling short of fuel-reduction objectives (Agee & Lolley 2006). Interestingly, this positive outcome may relate directly to the low-severity and patchy nature of the burns, enhancing the potential for surviving plants to contribute to post-treatment enrichment of the understory. The longevity of the response is on par with the 10- to 15-year timespans over which prescribed burning can reduce surface or ladder fuels and the risk of crown-fire (Battaglia et al. 2008, Stephens et al. 2012). Moreover, the diversity of species present in the full-plot inventories, but missed in the sample quadrats, suggests that further enrichment of the understory is possible, particularly at smaller spatial scales. Although fuel treatments promote tree regeneration in some systems (Schwilk et al. 2009, Webster & Halpern 2010), in this system they have had minimal effects on recruitment of conifers, suggesting that future decisions about re-entry may hinge less on the need to reduce fire hazard than on ecological objectives. Fire is costly and logistically challenging to work with, so delaying re-entry may be beneficial from both a biodiversity and economic perspective. The longevity of the thinning effect was also apparent in the analysis of overstory-understory relationships: plots that had been thinned did not exhibit local suppression of understory diversity by overstory basal area, as occurred in unthinned plots.

Importance of spatial scale. Our results highlight the critical role of spatial scale in detecting and interpreting ecological responses to treatments. For some groups, richness was enhanced only at larger or at smaller spatial scales (**Fig. 1**, scenario 2 vs. scenario 1). For other groups, richness was enhanced at both scales, albeit at differing rates (scenario 3). Similarly, the influence of residual overstory structure on understory metrics varied not only with the treatment context in which these relationships were examined (unthinned plots) but with the spatial scales at which they were sampled (significant only at the smallest scale). Nested sampling designs, as implemented in this study, are thus useful for capturing not only the spatial variability of pre- and post-treatment conditions, but also the scale-dependence of response. Whether the patterns of scale-dependence in this system can be generalized to other dry-forest ecosystems would require comparable analyses of similar designs, ideally those from the larger set of FFS sites (McIver et al. 2013). The ability to address both the spatial and temporal dimensions of this question would require investments in longer-term measurements.

Variation in the spatial scales at which richness is enhanced may have important implications for community resilience and stability. For example, in communities in which richness is enhanced at larger but not smaller spatial scales, a greater proportion of species may be susceptible to future disturbance (e.g., wildfire), climate change, or other stochastic processes, given greater likelihood of extirpation at lower population density. Conversely, in communities in which richness is enhanced at smaller but not larger spatial scales, species may be more susceptible to other stressors (species-specific herbivores or density-dependent pathogens; Comita et al. 2014). The spatial scales at which understories respond to treatment may also have implications for a broader set of ecosystem services, including food or habitat resources for insect pollinators or wildlife.

Consideration of plant traits. Our comparative analyses of plant groups revealed strong contrasts in the spatial and temporal behaviors of species with differing life histories (annuals vs. perennials) and origins (natives vs. non-natives). Much of this variation was masked by combining groups at higher levels (herbs). Unfortunately, much of the existing literature on fuel-treatment effectiveness approaches plant diversity from the perspective of these higher level groupings and the effects of this 'species averaging' likely explain some of the inconsistency in study findings (Abella & Springer 2015, Willms et al. 2017). In our study, for example, the small-scale responses of annuals to burning, and of perennials to thinning, were not evident in the broader responses of herbs as a whole. Moreover, in our system, patterns of herb diversity were largely driven by pre-treatment distributions and patterns of colonization of perennials, which accounted for >85% of herbaceous species. Yet, in relative terms, annuals were more responsive to fire. In ecosystems with a greater diversity of annuals, the herbaceous response to fire may be more rapid, stronger, or persistent. Similarly, in our study, patterns of diversity were dominated by native species (92% of the flora). Although the potential for spread of non-natives is a concern with fire or surrogate fuel treatments (Willms et al. 2017), our results suggest little short- or long-term risk where fire has long been excluded from the landscape (and with it, the exotic seed bank; Keeley et al. 2003, Keeley 2006), and where external seed inputs are low. Nevertheless, subtle increases in both treated and untreated plots argue for continued monitoring of non-natives, especially with any subsequent re-entry.

Despite decades of fuel treatment in dry forests of the western U.S., long-term, multi-scale monitoring of ecological responses remains a rarity. Moreover, there is a strong geographic bias in the distribution of fuel-reduction experiments, with many more in California and the southwest than in the inland Northwest. When designed and analyzed appropriately, long-term experiments can offer invaluable insights into ecological responses to restoration thinning and burning at spatial and temporal scales that are relevant to management. Our research highlights a number of the sources and possible causes of spatial and temporal variation that may hinder attempts to generalize about the ecological effectiveness of fuel treatments. Knowledge *that this variation exists*—and *that it may differ from system to system*—is critical to identifying and interpreting the ecological benefits of these treatments, and to timing subsequent entries to maintain or enhance these benefits.

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Rossman, A.K., Halpern, C.B., Harrod, R.J., Urgenson, L.S., Peterson, D.W., & Bakker, J.D. *In review.* Benefits of thinning and burning for understory diversity vary with spatial scale and time since treatment. For. Ecol. Manage. [JFSP ID No. 3807]

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Appendix B. List of Scientific/Technical Publications & Other Science Delivery Products

Articles in Peer-Reviewed Journals

In print

Urgenson, L.S., C.M. Ryan, C.B. Halpern, J.D. Bakker, R.T. Belote, J.F. Franklin, R.D. Haugo, C.R. Nelson, and A.E.M. Waltz. 2017. Visions of restoration in fire-adapted forest landscapes: lessons from the Collaborative Forest Landscape Restoration Program. Environmental Management 59:338-353 [JFSP ID No. 3804]

In press

Urgenson. L.S., C.R. Nelson, R.D. Haugo, C.B. Halpern, J.D. Bakker, C.M. Ryan, A.E.M. Waltz, T.R. Belote, and E. Alvarado. *In press.* Social perspectives on the use of reference conditions in restoration of fire-adapted forest landscapes. Restoration Ecology. doi: 10.1111/rec.12640 [JFSP ID No. 3803]

In review

Rossman, A.K., C.B. Halpern, R.J. Harrod, L.S. Urgenson, D.W. Peterson, and J.D. Bakker. *In review*. Benefits of thinning and burning for understory diversity vary with spatial scale and time since treatment. Forest Ecology and Management. [JFSP ID No. 3807]

In preparation

Rossman, A.K., J.D. Bakker, and C.B. Halpern. *In preparation*. Differing approaches to analyzing BACI designs lead to different interpretations: a case study of thinning and burn effects on forest understories. Target journal: Northwest Science.

Bakker, J.D., A.K. Rossman, C.B. Halpern, and L.S. Urgenson. *In preparation*. Scale dependence of overstory-understory relationships in dry, mixed-conifer forests. Target journal: Forest Ecology and Management.

Urgenson, L.S. J.D. Bakker, C.B. Halpern, and A.K. Rossman. *In preparation.* A systematic review of objectives and metrics used in assessing the ecological effectiveness of fuel-reduction treatments.

Technical Reports

Northwest Fire Science Consortium Research Briefs (*two planned; forthcoming*)

Graduate Thesis

Rossman, A.K. 2017. Responses of dry forest understory diversity to thinning intensity and burning: the importance of time, space, and analytical approach. MSc Thesis. University of Washington, Seattle. 102 p. [JFSP ID No. 364]

Conference and Symposium Abstracts

Peterson, D.W., A.K. Rossman, J.D. Bakker, C.B. Halpern, R.J. Harrod, and L.S. Urgenson. 2018. The importance of time and space when monitoring effectiveness of forest restoration treatments. Special symposium session: Lessons Learned from Long-term Fuel Treatment and Fire Monitoring Studies, The Fire Continuum Conference, Missoula, MT [invited presentation]

Bakker, J.D., A.K. Rossman, L.S. Urgenson, and C.B. Halpern. 2017. Scale dependence of overstory-understory relationships in dry, mixed-conifer forests. Natural Areas Conference, Fort Collins, CO. [invited presentation] [JFSP ID No. 8005]

Rossman, A.K., J.D. Bakker, and C.B. Halpern 2016. Understory responses to thinning and burning vary with lifeform and the spatial scale of observation. 101st Annual Meeting of the Ecological Society of America, Fort Lauderdale, FL. [JFSP ID No. 8003]

Rossman, A.K., J.D. Bakker, and C.B. Halpern 2016. Understory responses to dry forest restoration differ in the short and long term. 89th Northwest Scientific Association Conference, Bend, OR. [JFSP ID No. 8004]

Urgenson, L.S., C.B. Halpern, E. Alvarado, J.D. Bakker, J.F. Franklin, and C. Ryan. 2015. Defining desired conditions for restoration of fire-prone forest landscapes: Lessons from the Collaborative Forest Landscape Restoration Program. 9th IALE World Congress, Portland, OR. [JFSP ID No. 8000]

Urgenson, L.S., C.B. Halpern, E. Alvarado, J.D. Bakker, J.F. Franklin, and C. Ryan. 2014. Defining desired conditions for restoration of dry forest landscapes: lessons from the Collaborative Forest Landscape Restoration Program. 2014 Society for Ecological Restoration Northwest-Great Basin Regional Conference on Collaborative Restoration, Redmond, OR. [JFSP ID No. 8001]

Workshop Materials

Bakker, J.D., C.B. Halpern, L.S. Urgenson, and A.K. Rossman. 2016. Monitoring effectiveness of forest restoration treatments: the importance of time and space. Fuels Treatment Effectiveness: JFSP Workshop for Current Research, Preliminary Results and Implications: IAWF 2016 Fuels and Fire Behavior Conference, Portland, OR. [invited presentation]

Other Outreach

University of Washington presentations

Rossman, A.K. 2017. Dry forest understory responses to thinning and burning: the importance of time, space, and analytical approach. MSc. Thesis Defense, University of Washington, Seattle, WA. [JFSP ID No. 364]

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