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RAPID ASSESSMENT OF POSTFIRE PLANT INVASIONS IN CONIFEROUS FORESTS OF THE WESTERN UNITED STATES

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Abstract. Fire is a natural part of most forest ecosystems in the western United States, but its effects on nonnative plant invasion have only recently been studied. Also, forest managers are engaging in fuel reduction projects to lessen fire severity, often without considering potential negative ecological consequences such as nonnative plant species introductions. Increased availability of light, nutrients, and bare ground have all been associated with high-severity fires and fuel treatments and are known to aid in the establishment of nonnative plant species. We use vegetation and environmental data collected after wildfires at seven sites in coniferous forests in the western United States to study responses of nonnative plants to wildfire. We compared burned vs. unburned plots and plots treated with mechanical thinning and/or prescribed burning vs. untreated plots for nonnative plant species richness and cover and used correlation analyses to infer the effect of abiotic site conditions on invasibility. Wildfire was responsible for significant increases in nonnative species richness and cover, and a significant decrease in native cover. Mechanical thinning and prescribed fire fuel treatments were associated with significant changes in plant species composition at some sites. Treatment effects across sites were minimal and inconclusive due to significant site and site × treatment interaction effects caused by variation between sites including differences in treatment and fire severities and initial conditions (e.g., nonnative species sources). We used canonical correspondence analysis (CCA) to determine what combinations of environmental variables best explained patterns of nonnative plant species richness and cover. Variables related to fire severity, soil nutrients, and elevation explained most of the variation in species composition. Nonnative species were generally associated with sites with higher fire severity, elevation, percentage of bare ground, and lower soil nutrient levels and lower canopy cover. Early assessments of postfire stand conditions can guide rapid responses to nonnative plant invasions.

Key words: canonical correspondence analysis; CCA; disturbance; fire ecology; fire effects; fuel treatments; fuels reduction; invasion; nonnative species; species diversity; species–environment relationships; species richness.

Introduction

Approximately 50 000 nonnative species have been introduced to the United States (Pimentel et al. 2004). While some are considered beneficial (e.g., food crops, livestock, pest control), many have serious negative ecological, economic, and social consequences (Davis et al. 2000, Pimentel et al. 2004). Forty-two percent of all species listed as threatened or endangered under the Endangered Species Act are listed primarily as a result of nonnative species. Economic costs of nonnative species are estimated at $120 billion per year (Pimentel et al. 2004). Only land-use change ranks higher than nonnative species as a driver of species extinction (D'Antonio and Vitousek 1992). Nonnative plant invasion has been shown to alter ecosystem structure and function and poses a serious threat to native species diversity (Vitousek 1990, Stohlgren et al. 1999*b*, Mack et al. 2001). Effects include the alteration of resource availability and soil stability, promotion of erosion, accumulation of litter, salts, or other soil resources, allelopathy, and the alteration of natural fire regimes and trophic structures (Vitousek 1990, Gordon 1998, Richardson et al. 2000, Mack et al. 2001, Brooks et al. 2004, Wolfe and Klironomos 2005). Early detection and rapid response to new invasions may be effective tools for protecting habitats most at risk (Peterson and Vieglais 2001, D'Antonio et al. 2004).

Increased size and intensity of disturbance of natural communities has been shown to be positively correlated with nonnative plant invasion (Hobbs and Huenneke

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1992, D'Antonio 1993). Often these disturbances result in increased nutrient availability (e.g., after fire), which is also shown to increase ecosystem invasibility (Huenneke et al. 1990, Stohlgren et al. 1999*b*, Bashkin et al. 2003, Brooks 2003). Once established, invasive species may alter nutrient cycling, creating an environment more suitable to further invasion (Evans et al. 2001).

In vegetation types such as Ponderosa pine that are naturally characterized by frequent, low-intensity fires, suppression of fire has lead to increased loading of surface and crown fuels (Covington and Moore 1994). The current forest structure in these systems increases the potential for the occurrence of larger and more severe wildfires than those expected to occur within the historical range of variation (Covington and Moore 1994, Fule et al. 1997). These high-intensity wildfires may also increase the potential for subsequent establishment of nonnative species (Crawford et al. 2001, Keeley et al. 2003, Barclay et al. 2004, Wolfson et al. 2005, Hunter et al. 2006). Increased light availability, nutrients, and bare ground are associated with recent high-severity fires, all of which are known to aid in the establishment of nonnative species (Meekins and McCarthy 2001, Keeley et al. 2003). Fuel treatments, including mechanical thinning and prescribed fire, have the potential to mitigate the effects of severe wildfires (Fernandes and Botelho 2003, Graham et al. 2004), however, prefire fuel manipulations may also create disturbances that encourage establishment of nonnative species (Battles et al. 2001, Sieg et al. 2003). The invasion of alien plants has also been shown to affect fire regime characteristics including frequency, intensity, spatial extent, and seasonality (Brooks et al. 2004). If these changes are beneficial to fire-promoting invaders, an invasion fire-cycle may be created, causing the system to move even farther away from its pre-invasion condition. Such is the case with cheatgrass (*Bromus tectorum* L.), where more frequent fires benefit the invader at the expense of native shrub species, which lack a sufficient fire interval to regenerate (D'Antonio and Vitousek 1992, Brooks et al. 2004).

Because of the problems associated with managing heavily infested areas, it is important to determine the types of disturbance that increase the potential for invasibility. If a set of disturbance characteristics can predict the invasibility of a postfire forest stand, managers could respond quickly to invasions. Our objectives were to determine (1) to what degree wildfire and wildfire severity predict increases of nonnative plant species; (2) the influence of fuel treatments in facilitating or reducing nonnative invasion; and (3) the ability of the wildfire event and associated abiotic variables (e.g., soil nutrients, canopy closure, percent bare soil) to predict nonnative species invasion. We addressed these objectives by comparing burned vs. unburned and treated vs. untreated plots to infer the effects of fire, fuel treatments, and associated site conditions on nonnative species invasion.

FIG. 1. Map of western United States indicating study site locations.

METHODS

Study design

We positioned our study sites in coniferous forests in the western United States that experienced wildfires greater than 4000 ha (Fig. 1). Most of the sites were Ponderosa pine dominated, with natural fire regimes believed to be frequent and non-stand replacing. The fires that recently took place at these sites were likely of a higher intensity than was historically the case. Data were collected mid-summer in the first growing season following the fire, except for the High Meadow Fire, which was sampled during the second growing season. Study sites included the Aspen fire (Arizona), Davis fire (OR), Cerro Grande fire (New Mexico), Hayman fire (Colorado), High Meadow fire (Colorado), Power fire (California), and the Fischer fire (Washington). Most of the burned acreage is managed by the USDA Forest Service and comprises a range of elevations and forest types (Table 1). Land managers provided spatial data prior to site selection. These data included wildfire perimeter and progression, fuel treatment boundaries and descriptions, forest cover type, hydrology, roads and trails, topography, salvage activities, administrative boundaries, botanical surveys, and fuel inventories.

A total of 475 plots were located at the seven sites. Plots were paired, with one plot in a treated stand, and one being in an untreated stand 200 m away. This distance was used to minimize the differences in stand conditions and site characteristics as well as to reduce the potential impact of fuel treatment boundaries on fire effects. Pairs of plots were then located in such a way to capture the environmental gradient that was encompassed by the wildfire with respect to elevation, aspect,

TABLE 1. Site characteristics of named fires.

Site	Fire	Burn date	Size (ha)	No. plots	Location	Elevation (m)	Forest type
1	Aspen	June 2003	34 297	40	Coronado NF, Arizona	2043–2804	*Pinus ponderosa, P. strobiformis, Abies concolor, Quercus* spp.
2	Davis	June 2003	8572	74	Deschutes NF, Oregon	1403–1854	*Pinus ponderosa, Pinus* spp., *Abies concolor, Pseudotsuga menziesii*
3	Cerro Grande	May 2000	19 283	78	Bandelier NM, New Mexico	1972–3023	*Pinus ponderosa, P. edulis, Pseudotsuga menziesii, Juniperus* spp.
4	Hayman	June 2002	55 749	103	Pike, San Isabel NF, Colorado	1979–2699	*Pinus ponderosa, Pseudotsuga menziesii*
5	High Meadow	June 2000	4439	92	Pike, San Isabel NF, Colorado	2146–2576	*Pinus ponderosa, Pseudotsuga menziesii*
6	Fischer	August 2004	6653	30	Wenatchee NF, Washington	497–1186	*Pinus ponderosa, Pseudotsuga menziesii*
7	Power	October 2004	6799	58	El Dorado NF, California	1215–1939	*Abies concolor, Pinus* spp., *Calocedrus decurrens, Quercus* spp.

Note: Abbreviations in the "Location" column are: NF, National Forest; NM, National Monument.

and slope. Treatment units were identified from spatial data layers provided by land managers. Treatments were broadly described and encompassed a wide range of activities. These included canopy treatments such as shelterwood cuts, commercial and pre-commercial thins, and timber stand improvements, as well as surface treatments such as underburns, broadcast burns, and pile burns. We categorized treatments for sampling and analysis as canopy, surface, or combination and focused on those that were completed within ten years of the wildfire event. Specific data on treatment intensity (e.g., stems left standing/ha, fuel consumption levels, percent mortality) were not available, however we attempted to reconstruct pre-wildfire stand conditions in both treated and untreated plots with measurements of tree density (no./ha) and diameter (cm), canopy bulk density (kg/m^3, after Scott and Reinhardt 2001), and canopy base height (m, after Scott and Reinhardt 2001). For purposes of this analysis, treatment effects were treated as a categorical variable.

We used a 5×20 m nested-intensity version of the modified-Whittaker plot to collect vegetation data. This plot consists of four 1-m^2 subplots and one 10-m^2 subplot nested in the 100-m^2 plot (Barnett and Stohlgren 2003). This size plot has been shown to adequately capture trends in dominant vegetation and the environmental gradient while being small enough to allow a greater sample size as compared to the standard modified-Whittaker method (Barnett and Stohlgren 2003). We recorded foliar cover and average height for each species found in the 1-m^2 subplots as well as percent cover of litter, duff, rock, and bare ground. Species with less than 1% cover were recorded as 0.5% cover. Species cover values were averaged from the four 1-m^2 subplots and did not include tree canopy cover or dead vegetation. The presence of additional species not found in the smaller subplots was recorded at the 100-m^2 plot level. If species were unidentifiable in the field, we pressed and later identified them at the Colorado State University herbarium. We excluded unidentifiable species from the study (less than 1% of species occurrences). Nonnative invasive species were categorized as such using the Natural Resources Conservation Service PLANTS database (U.S. Department of Agriculture 2006). We were hesitant to rank species for control from our rapid assessment because current frequency and cover may not be indicative of future dominance. Some species are highly invasive at one or more sites (e.g., cheatgrass), but not at other sites. In addition, some particularly invasive species may not have become established yet. However, we generally found that high frequency, cover, and broad distributions of a nonnative species at specific sites likely indicate greater future cover and dominance (Chong et al. 2006, Crall et al. 2006). We also addressed the possibility of postfire restoration seed mixes having been contaminated with nonnative species, but this was only an issue at the Cerro Grande site (see Hunter et al. [2006] for quantitative analyses). Nonnative species that were intentionally included in the seed mixes (e.g., sterile barley and wheat) were not included in the nonnative species analyses.

We measured the forest canopy for percent scorched, scorch height, percent consumed, and char height and assigned a stand damage score for each plot (Pollet and Omi 2002). These data, as well as those pertaining to prefire forest structure, were collected from variable radius plots defined with an angle gauge (Avery and Burkhart 2002) and centered on each nested-intensity fixed plot. Damage scores were then combined into three categories: unburned (damage = 0), low severity (damage = 1; some canopy scorching, but no canopy consumption), and high severity (damage = 2; at least minor evidence of canopy consumption). We used a spherical densiometer to estimate canopy closure (Lemmon 1956) and Key and Benson's (2005) composite burn index to calculate ground char rating. Whether or not a specific plot burned or received prefire fuel treatments were treated as categorical variables. The effects of the two general types of fuel treatments (prescribed fire vs. mechanical thinning) were analyzed individually as well as combined (treated vs. untreated plots).

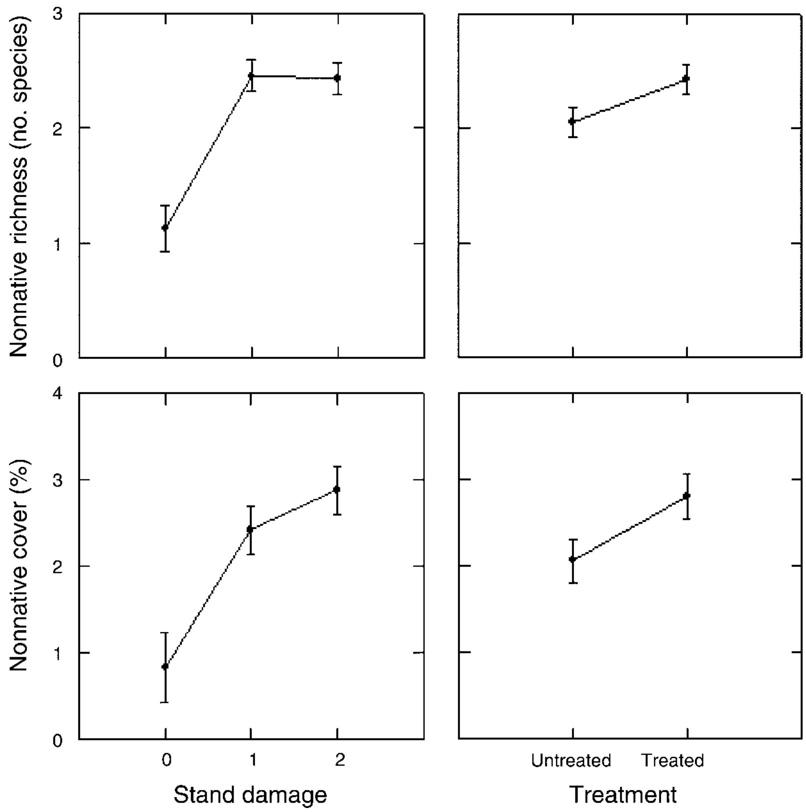

FIG. 2. Richness and cover (mean ± SE) demonstrating effects of wildfire (0, no wildfire; 1, low severity; 2, high severity) and fuel treatments on nonnative richness and cover. The models include site and site × burning and site and site × treatment effects, respectively.

We collected soil samples from the corners and center of the 100-m^2 plot to a depth of 5 cm and pooled them into one composite sample for each plot. We then air dried and sieved the samples and ground them using a standard roller mill. We analyzed the samples for percentage of total carbon and nitrogen using a LECO-1000 CHN analyzer (LECO Corporation, Saint Joseph, Missouri, USA) and measured inorganic carbon using the modified pressure-calcimeter method (Sherrod et al. 2002). We measured soil texture using an ASTM 152H-Type hydrometer (Gee and Bauder 1979). We calculated potential direct incident radiation (McCune and Keon 2002). Potential direct incident radiation (PDIR) has been shown to be a more useful variable than aspect in quantitative ecological studies because in addition to aspect, it takes into account slope and latitude.

Statistical analysis

Prior to analysis, we transformed heavily skewed environmental data using either log or square root transformations. Soil nutrient data in particular are known to have a lognormal distribution (Palmer 1993). Transformations followed the formulas developed by Beers et al. (1966) and McCune and Keon (2002).

We performed analysis of variance (ANOVA) to determine site, treatment effects (mechanical thinning vs. prescribed fire and treated vs. untreated), and wildfire effects (low vs. high severity and burned vs. unburned) on nonnative species richness and cover and we used regression tree analysis to determine which variables are important in explaining nonnative species richness and cover. We also analyzed the data using canonical correspondence analysis (PC-ORD version 4; ter Braak 1986, 1987) to relate the composition of nonnatives species to the surveyed environmental variables. CCA is an ordination method that constrains the main matrix (vegetation data) by a multiple regression on the second matrix (environmental variables [ter Braak 1987]). Palmer (1993) showed that CCA is a robust method for analyzing species–environment relationships. We analyzed the nonnative species richness and cover data set against the quantitative (total soil C and N, percent clay, percent bare ground, PDIR, canopy cover, elevation) and categorical (treated/untreated, burned/unburned, stand damage, ground char) environmental variables of interest. We reduced multicollinearity by developing a Pearson correlation matrix to identify and remove redundant variables. Unless otherwise stated, $P < 0.05$ indicated significance.

TABLE 2. ANOVA results of linear least-squares regression of site, treatment, and burning effects on nonnative richness and cover.

Source	df	F	P
Treatment effect			
Nonnative richness			
Treated	1	4.18	0.0414
Site	6	84.37	<0.0001
Treated × site	6	7.49	<0.0001
Error	461		
Nonnative cover (%)			
Treated	1	4.3	0.0387
Site	6	58.07	<0.0001
Treated × site	6	5.88	<0.0001
Error	461		
Burning effect			
Nonnative richness			
Damage	2	17.01	<0.0001
Site	6	56.12	<0.0001
Damage × site	12	7.53	<0.0001
Error	454		
Nonnative cover (%)			
Damage	2	8.89	0.0002
Site	6	35.68	<0.0001
Damage × site	12	6.83	<0.0001
Error	454		

RESULTS

Effects of burning and fuel treatments

Presence of wildfire was associated with significant increases in nonnative species richness and cover across sites (Fig. 2). These effects were magnified in high-severity plots, though not significantly so. There were significant site effects on nonnative richness and cover (Table 2), largely due to the variation in nonnative species richness and cover in the burns (Table 3). Nonnative species ranged from zero (Davis fire) to 4.3 species/plot at the Hayman and High Meadow fires. Nonnative species cover averaged higher at the High Meadow fire (7.3%) in part because it was sampled two years postfire. We detected no significant effects of individual fuel treatments (prescribed fire vs. non-fire thinning treatments) on nonnative species. As a whole, fuel treatments were correlated with an increase in nonnative richness and cover when site and site × treatment were included in the ANOVA model (Table 2). This was likely due to the increased sample size and decreased variation in the main effect compared to the analysis involving individual fuel treatment types. These results remain ambiguous and inconclusive.

Relationship between abiotic variables and plant species composition

Variables known to relate to fire severity (increased bare ground, decreased canopy cover and soil nutrients) were generally correlated with one another (Table 4). Nonnative species cover was correlated with native species cover and richness, burning, and stand damage and was inversely related to soil C and PDIR. Nonnative species richness was correlated with native species richness and cover and bare soil and inversely related to soil C and PDIR. The inverse relationships with C and PDIR could be related to reduced soil carbon in severely burned sites and higher available moisture on north-facing slopes (lower PDIR values). These relationships are further described in the regression tree analyses.

Regression tree analysis showed that nonnative species richness was best explained by native species richness (Fig. 3a). On average, sites with greater than 26 native species per plot had over five times more nonnative species than sites with fewer natives. Species rich plots with higher ground char scores had twice as many nonnative species than those experiencing less severe or no fire. Nonnative cover was best explained by potential direct incident radiation (Fig. 3b). Sites with lower PDIR (more northern and eastern aspects, steeper slopes, and higher latitudes) had five times higher nonnative cover than sites with higher PDIR. Of those plots with lower PDIR, those experiencing higher fire stand damage had four times higher nonnative cover than those experiencing little or no stand damage. Proportional reduction in error values (this measure is similar to the R^2 value for a regression model) was 0.489 for nonnative species cover and 0.545 for nonnative species richness.

Canonical correspondence analysis (CCA) results showed that the strongest predictors of nonnative richness and cover were stand damage, ground char, burned/unburned, elevation, percent soil clay, and potential direct incident radiation. Nonnative richness and cover reached their greatest levels at sites with more severe fire events. Nonnative species also increased at high elevations, low PDIR scores, and low soil clay

TABLE 3. Mean (with SE in parentheses) plant species richness and percent cover per 5 × 20 m plot.

Site (fire name)	Native richness	Nonnative richness	Native cover (%)	Nonnative cover (%)
Cerro Grande	32.7 (1.2)	3.6 (0.3)	9.8 (0.9)	5.5 (0.5)
Hayman	42.2 (1.2)	4.3 (0.2)	7.6 (0.7)	0.6 (0.2)
High Meadow	42.1 (1.1)	4.3 (0.3)	13.0 (0.9)	7.3 (0.6)
Aspen	6.3 (0.5)	0.4 (0.1)	4.1 (1.3)	0.7 (0.3)
Davis	7.5 (0.4)	0	7.3 (1.6)	0
Power	8.1 (0.7)	0.7 (0.1)	7.8 (1.8)	0.3 (0.2)
Fischer	16.8 (0.6)	1.7 (0.3)	42.2 (4.8)	1.6 (0.8)

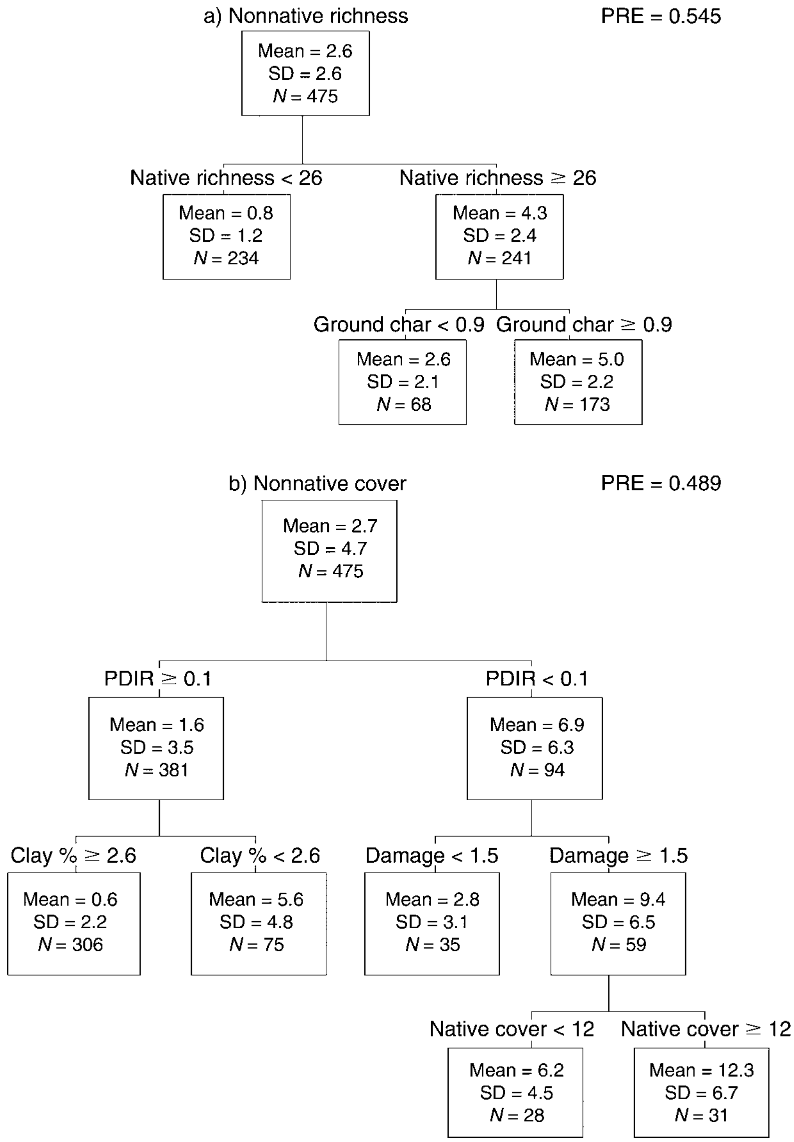

FIG. 3. Regression tree analysis for (a) nonnative richness and (b) nonnative cover. Abbreviations: PRE, proportional reduction in error; PDIR, potential direct incident radiation; *N*, sample size (number of plots). Mean and SD are (a) richness and (b) cover for the plots included in boxes.

content (Fig. 4). The first two axes explained 46% of the variation in species data (Table 5).

DISCUSSION AND MANAGEMENT IMPLICATIONS

Wildfire effects on native and nonnative plant species

Fire severity, in conjunction with PDIR and native species composition and abundance, appears to play the primary role in predicting nonnative species composition in the first postfire year in these forest systems. Increased light availability, bare ground, and decreased total soil nutrients and competition are all characteristic of the postfire environment (Table 4), and all have been shown to coincide with an increase in nonnative species (Rejmanek 1989, Crawford et al. 2001, Keeley et al. 2003). Our results suggest that while soil nutrients were not related to nonnative success as in other studies (Thomson and Leishman 2005), the other indirect effects of fire greatly increased initial establishment of nonnative species. Keeley et al. (2003) produced similar results, finding that increased canopy cover, often associated with later successional stages or increased time since fire, led to a decrease in nonnative species and an increase in the proportion of native plant species. The application of more frequent, low intensity fires, promoting conditions like those described by Keeley et al. (2003) might circumvent invasive-prone areas characteristic of high intensity, stand replacing fire such as those analyzed in this study.

TABLE 4. Cross-correlations (Pearson coefficients) among biotic and abiotic variables across all sites.

Variable	Native cover	Nonnative cover	Native richness	Nonnative richness	Soil C (%)	Soil N (%)	Soil clay (%)	Elevation	Treated
Native cover	1.00								
Nonnative cover	0.17	1.00							
Native richness	0.16	0.42	1.00						
Nonnative richness	0.13	0.64	0.76	1.00					
Soil C (%)	ns	−0.12	−0.16	−0.12	1.00				
Soil N (%)	ns	ns	ns	ns	0.64	1.00			
Soil clay (%)	0.13	ns	0.18	0.13	0.41	0.27	1.00		
Elevation	−0.37	0.25	0.51	0.42	ns	0.14	ns	1.00	
Treated	ns	ns	ns	ns	ns	ns	ns	−0.10	1.00
Burned/unburned	−0.17	0.16	ns	0.28	−0.23	−0.14	ns	ns	ns
Stand damage	−0.21	0.11	ns	0.20	−0.16	−0.13	ns	ns	ns
Ground char†	−0.25	ns	−0.23	ns	−0.12	−0.15	ns	−0.10	ns
Canopy cover	0.10	ns	ns	ns	0.17	0.10	ns	ns	ns
Bare soil (%)	−0.24	ns	0.13	0.19	−0.35	−0.22	ns	0.16	ns
PDIR‡	−0.10	−0.42	−0.44	−0.34	ns	−0.13	−0.26	−0.25	ns

Notes: Table entries of "ns" indicate that the correlation was not significant at $P < 0.05$.

† Ground char is an index of fire severity on the forest floor surface and was calculated by measuring percent char and consumption of various fuels size classes using the composite burn index (CBI) introduced by Key and Benson (2005).

‡ Potential direct incident radiation.

The "rich get richer" theory proposed by Stohlgren et al. (1999*a*, 2003) is based on the concept that native and nonnative species respond to the environment in a similar fashion, resulting in a positive correlation between the two (Gilbert and Lechowicz 2005). Our findings support this concept, finding positive correlation coefficients for all native/nonnative relationships except one. It is interesting that the only negative relationship between native and nonnative species occurred at the site experiencing the highest native species cover. Perhaps a threshold value of native cover must exist before any inhibitory effects on nonnative species become evident at the small spatial scales studied. However, our results generally suggest that focusing invasive plant control efforts on stands that were species rich prefire might decrease success of postfire invaders.

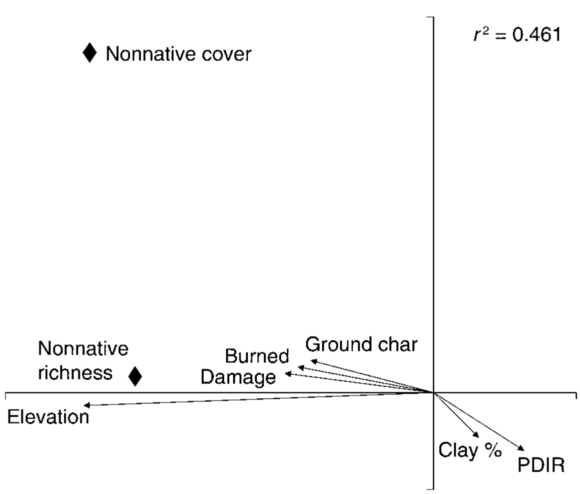

FIG. 4. Canonical correspondence analysis biplot results. The biplot shows the top three variables for predicting axis 1 and the top three variables for predicting axis 2 (see Table 4). Diamonds represent the response variables measured.

The regression tree analysis as well as the CCA explained roughly half of the variance in nonnative species occurrence. While this is encouraging, it does leave half of the variance unexplained. The low eigenvalues indicate that in the first year postfire there is very little natural variation in species composition at these sites, leading us to believe that there were important environmental variables that went unmeasured. Possible examples include precipitation, soil micronutrients, site productivity, and distance to seed source (e.g., roads, trails, fire perimeter, and method of seed dispersal of studied species). Nevertheless, the use of paired burned and unburned plots provided evidence that forests that contain nonnatives prior to the fire may contain more nonnatives after the fire, and thus might be targets for control efforts.

Fuel treatment effects on native and nonnative plant species

The role of fuel treatments in influencing nonnative species is inconclusive and seems to be less important than that of wildfire. Our results show that wildfire

TABLE 5. Summary statistics for canonical correspondence analysis, including eigenvalues, most significant variables for axes 1 and 2 (with correlation coefficients in parentheses).

Parameter	Axis 1	Axis 2
Eigenvalues	0.137	0.023
Most significant factors	elevation (−0.942), damage (−0.429), burned (−0.384)	PDIR (−0.555), soil clay % (−0.339), ground char (0.309)

Notes: The number of significant axes is three (Monte Carlo test, $P < 0.05$); r^2 for axes 1 and 2 is 0.461. PDIR is potential direct incident radiation.

TABLE 4. Extended.

Burned/ unburned	Stand damage	Ground char	Canopy cover	Bare soil (%)	PDIR
1.00					
0.74	1.00				
0.69	0.75	1.00			
−0.46	−0.58	−0.44	1.00		
0.52	0.60	0.51	−0.49	1.00	
ns	ns	0.12	−0.15	ns	1.00

consistently led to a significant reduction in native cover and an increase in nonnative richness and cover. Prescribed fire and thinning, when analyzed individually, had no effect on plant species composition. While not significant, the increase in nonnative richness and cover across fuel treatment types, likely due to the increased sample size and decreased variation in the main effect, should be of interest for future research. These ambiguous preliminary results stem from differences in severity of treatments, initial conditions, and variable responses to treatments (i.e., some fires had high local weed sources, others did not). Isolating these individual responses was not possible given the short duration of the study relative to high natural variation. However, the baseline data collected here will allow researchers to address those questions in later studies. More research is necessary to determine exactly what fuel treatment characteristics promote invasion by nonnative species. Long-term monitoring of treated stands will be required to determine whether nonnative species pose a significant, long-term threat to these postfire and post-fuel treatment stands and how they will respond to the more frequent, less intense fires if applied.

The establishment of nonnatives in the first year postfire provides an opportunity to begin control efforts before the populations grow to an unmanageable extent. Unfortunately, funding is often lacking in this area, as Burned Area Emergency Response teams usually focus on erosion control, which often includes the seeding of native as well as nonnative plant species (Robichaud et al. 2000). Preference for native seed for restoration and consideration of early nonnative control as part of wildfire response should be high priorities. However, it may be best to avoid seeding altogether in some systems where it has been shown to be ineffective as well as potentially damaging through introduction of nonnative species (Keeley et al. 2006).

While scientists and managers are aware of the negative consequences of a century of fire suppression with regard to hazardous fuel accumulation, reduced forest floor productivity, and habitat loss, its indirect effects on nonnative invasion by increasing the likelihood of high-severity wildfire has been less appreciated. In most western coniferous forests, wildland fire use (allowing unplanned lightning ignitions to burn) and prescribed fires are being increasingly used to accomplish resource objectives such as fuels reduction, habitat improvement, and increases in native species diversity, as well as reducing the threat of invasion. To reduce risks of escape, prescribed fires may sometimes be applied with lower severities than the wildfires that naturally occur in the same systems. This may raise some concerns that prescribed fires may not mimic the historic fire regime or accomplish objectives related to maintaining biodiversity. However, using low-severity prescribed fires may reduce opportunities for the establishment of nonnative species. Given the complexity of the relationships among environmental variables demonstrated by this work, land management agencies must carefully weigh the risks posed by nonnative species, fuel levels, and abiotic factors in choosing which management activities to execute for the greatest benefit to the natural resource.

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