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FUEL BREAKS AFFECT NONNATIVE SPECIES ABUNDANCE IN CALIFORNIAN PLANT COMMUNITIES

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Abstract. We evaluated the abundance of nonnative plants on fuel breaks and in adjacent untreated areas to determine if fuel treatments promote the invasion of nonnative plant species. Understanding the relationship between fuel treatments and nonnative plants is becoming increasingly important as federal and state agencies are currently implementing large fuel treatment programs throughout the United States to reduce the threat of wildland fire. Our study included 24 fuel breaks located across the State of California. We found that nonnative plant abundance was over 200% higher on fuel breaks than in adjacent wildland areas. Relative nonnative cover was greater on fuel breaks constructed by bulldozers (28%) than on fuel breaks constructed by other methods (7%). Canopy cover, litter cover, and duff depth also were significantly lower on fuel breaks constructed by bulldozers, and these fuel breaks had significantly more exposed bare ground than other types of fuel breaks. There was a significant decline in relative nonnative cover with increasing distance from the fuel break, particularly in areas that had experienced more numerous fires during the past 50 years, and in areas that had been grazed. These data suggest that fuel breaks could provide establishment sites for nonnative plants, and that nonnatives may invade surrounding areas, especially after disturbances such as fire or grazing. Fuel break construction and maintenance methods that leave some overstory canopy and minimize exposure of bare ground may be less likely to promote nonnative plants.

Key words: disturbance; disturbance corridors; fire; fire management; fuel breaks; fuel reduction treatments; fuels management; grazing; nonnative plants; invasive plants.

Introduction

Reduction of hazardous fuels has become a priority for federal, state, local, and private land managers in the United States. Population growth at the wildland–urban interface, high fuel loads resulting from fire exclusion, and large, high-severity fires have recently focused unprecedented national attention on pre-fire fuel manipulation projects. As a result, a growing number of fuel reduction programs have extended the scope of pre-fire fuel manipulations to include a wide range of vegetation types and treatment prescriptions, and the number of hectares treated to reduce fuels nationwide have increased dramatically (Rains and Hubbard 2002).

Fuel reduction treatments are generally implemented to change fire behavior, provide firefighter access, serve as an anchor point for initial attack on wildland fires, or contain prescribed fires (Agee et al. 2000). They range in size and shape from small linear features to large polygons spanning thousands of hectares. The amount of surface and ladder fuels removed can vary widely, with reduction of overstory canopy cover ranging from complete to <40% (Agee et al. 2000). Here, we will collectively refer to these treatments as *fuel breaks*, although they have been variously termed shaded fuel breaks, defensible fuel reduction zones, defensible fuel profile zones, fuel reduction projects, fuel management zones, wildfire protection zones, and community protection zones.

Fuel break construction and maintenance methods have changed over time and differ according to terrain, vegetation type, and implementing agency (Omi 1979). For example, fuel break maintenance by aerial application of herbicides and seeding with nonnative grasses was common until the 1970s (Bentley 1967, Clark 1973). More recent fuel break construction and maintenance measures include selective thinning, on-site mastication of fuels, and increased use of prescribed burning (Farsworth and Summerfelt 2002).

An unintended consequence of extensive fuel break construction and maintenance may be the establishment of nonnative plant species. Nonnative plant invasion is one of the most important issues facing land managers today because nonnative plants can permanently alter ecosystem structure and function (Vitousek 1990). Disturbance is considered one of the primary factors

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promoting nonnative invasion (Rejmanek 1989, Hobbs and Huenneke 1992), and a number of studies have documented an association of nonnative plant species with disturbed areas similar to fuel breaks, such as logging sites, roads, trails, and pipeline corridors (D'Antonio et al. 1999).

Disturbance corridors can promote invasion of surrounding wildland areas by nonnative plants (Tyser and Worley 1992, Gelbard and Belnap 2003). Areas adjacent to fuel breaks might be particularly susceptible to invasion following landscape scale disturbances such as fire (D'Antonio et al. 1999, Brooks et al. 2004). Fire has been shown to promote invasion of nonnative plants in a number of habitats (D'Antonio 2000). In many cases, nonnative species are well adapted to fire and can invade fire-prone ecosystems, particularly when natural fire regimes have been altered through fire suppression, increased human-caused ignitions, or by feedback effects with changes in plant species composition (D'Antonio and Vitousek 1992, Brooks et al. 2004).

In this study we evaluated the potential for fuel breaks to function as establishment sites for nonnative plants and for these nonnative species to invade surrounding wildland areas. We conducted this research in California, where fuel break construction began as early as 1899, and extensive fuel break systems were in place by the 1960s (Blanford 1962). We sampled fuel breaks at 24 separate locations to address the following questions: (1) Are nonnative plants more abundant on fuel breaks than in adjacent wildland areas? (2) What environmental and anthropogenic factors are correlated with the abundance of nonnatives? (3) What is the pattern of nonnative abundance adjacent to fuel breaks, and is this pattern altered by disturbances such as fire or grazing? The goals of this research were to provide fire and resource managers with information to develop fuels management strategies that both accomplish fuel hazard reduction goals and minimize the potential for nonnative plant invasion.

Methods

We investigated 24 fuel breaks, located primarily in the Sierra Nevada and coastal mountain ranges (Fig. 1; see Plate 1). These sites included coastal scrub, chaparral, oak woodland, and coniferous forest vegetation types, ranging in elevation from 200 m to 2000 m. All of our study sites were within the California floristic province, experiencing Mediterranean influenced climates, with hot, dry summers and cool, wet winters. Chaparral and coastal scrub communities were dominated by shrub species, including chamise (*Adenostema fasciculatum*), manzanita (*Arctostaphylos* spp.), scrub oak (*Quercus* spp.), California sage, (*Artemisia californica*), and California buckwheat (*Eriogonum fasciculatum*). Oak woodland and coniferous forest sites were dominated by tree species, including black oak (*Q. kelloggii*), canyon live oak (*Q. chrysolepis*), incense cedar (*Calocedrus decurrens*), white fir (*Abies concolor*), and ponderosa pine (*Pinus ponderosa*) (Fig. 2). The fuel breaks we studied varied in age from those constructed by the Civilian Conservation Corps during the 1930s to fuel reduction projects implemented as recently as 2003 (Table 1).

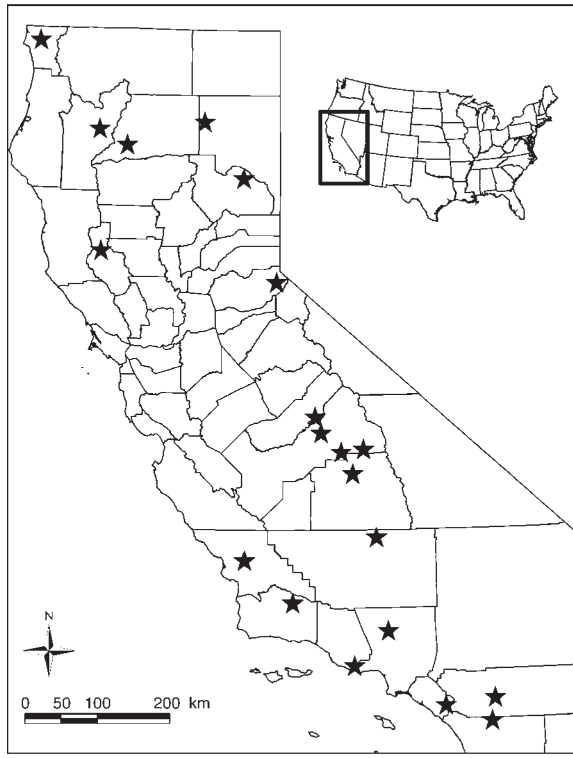

Fig. 1. Fuel break study sites (stars) across the State of California, USA.

Site selection

To select fuel breaks for this study, we obtained Geographical Information System (GIS) layers of fuel breaks, fire history, and jurisdictional boundaries of federal, state, and local land management agencies across California. Where GIS data of fuel break locations were unavailable, we used hard copy maps provided by agency staff. We sought to include at least one fuel break from each cooperating agency and to sample sites where at least a portion of the fuel break had burned within the past 10 years. In some cases, only a single fuel break within each jurisdictional boundary met this criterion. Where several fuel breaks were still under consideration, we selected those with underrepresented construction and/or maintenance regimes. We attempted to include an equal number of fuel breaks constructed by hand crews, bulldozers, and mechanical equipment within each vegetation type. We considered mechanical equipment to include logging equipment designed for selective thinning, such as rubber-tired feller bunchers and grapple skidders, and chain saws. The primary tools used to construct sites cleared by

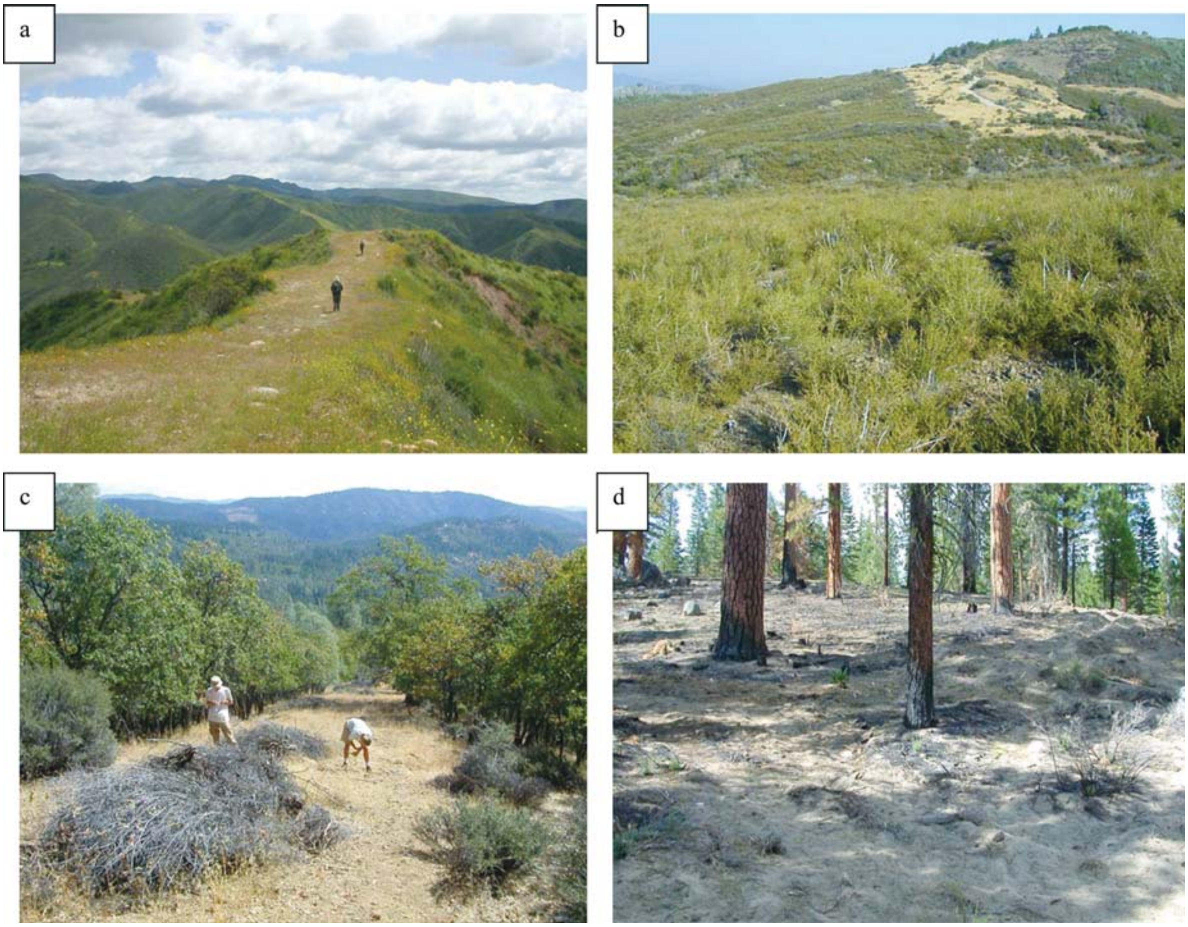

FIG. 2. Fuel breaks in different vegetation types, including (a) coastal scrub vegetation type, Casper's Wilderness Park; (b) chaparral vegetation type, Mendocino National Forest; (c) oak woodland vegetation type, Shasta Trinity National Forest; and (d) coniferous forest vegetation type, Plumas National Forest. Photo credits: K. Merriam.

hand crews were hand tools such as shovels, Pulaskis, and McCleods, although chain saws also may have been used. We collected information on current and historic land use, including activities such as grazing and logging, and evaluated these variables in our analyses. However, the land use history of each site was complex, and we could not control for many of the disturbance related factors that may have affected nonnative abundance on the fuel breaks we studied.

Sampling protocol

Data were collected during the spring and summer of 2002 and 2003. Each fuel break was sampled once. At each site, we established between 8 and 10 transects, located at intervals of between 200 m and 1500 m, depending on the total length of the fuel break. Our intent was to sample the plant community along the entire fuel break, so intervals between transects were made larger for larger fuel breaks, and smaller for smaller fuel breaks. The first transect at each site was placed at the origin of the fuel break nearest a road or wildland–urban interface area. Transects were oriented perpendicular to the fuel break. Every transect was 50 m in length, extending 10 m from the edge of the fuel break towards the center of the fuel break, and extending 40 m in the opposite direction into the surrounding vegetation (Fig. 3). Two 1-m^2 plots were located inside the fuel break, at distances of 5 m and 10 m from the fuel break edge. Four 1-m^2 plots were placed in the adjacent wildland, at distances of 5, 10, 20, and 40 m from the fuel break edge (Fig. 3). Plots were placed at these same intervals at each site to allow for comparisons across sites.

Within each plot, plant species composition data, including overstory trees and shrubs, were collected. We estimated species cover by cover class according to Daubenmire (1959), and we estimated the density of each species. All plants were identified to species according to Hickman (1993). In addition to plant species data, at each plot location overstory canopy cover was measured using a convex spherical crown densitometer (Forestry Suppliers, Jackson, Mississippi,

TABLE 1. Site characteristics of the fuel breaks included in this study.

Site name	Agency	Elevation (m)	Year constructed	No. fires since 1953	Construction method
Gasquet	USFS	202	1995	0–1	mechanical
Zuma Ridge	NPS	244	1952	3–5	bulldozer
Oso Ridge	OCPD	273	1963	2–3	bulldozer
Whiskey Creek	NPS	390	2001–2003	0	mechanical
Tower	NPS	447	1980	1–4	bulldozer
Calf Canyon	BLM/CDF	474	1965–2002	1–3	bulldozer
Shasta Divide	NPS	492	1985	0	bulldozer
Etz Meloy	NPS	652	1957	2–3	bulldozer
Oregon	USFS	922	2001	0	bulldozer
Shepard Saddle	NPS	983	1960	2–3	bulldozer
Burrough Mtn.	USFS	1109	1935	1	hand crews
Aguanga	USFS	1189	1975	0–2	hand crews
Pilot Grove	USFS	1194	1960	1–2	bulldozer
North Fork	USFS	1294	1920	2–3	hand crews
Rouse Ridge	USFS	1298	1984	1–2	bulldozer
Sierra Pelona	USFS	1302	1960	1–2	bulldozer
Lewis Creek	NPS	1461	1981	0–2	hand crews
Blacks Ridge	USFS	1533	2002–2003	0–1	mechanical
Sierra Madre	USFS	1535	1962–1966	0–2	bulldozer
Palos Ranches	BLM/USFS	1544	1977–2001	0	hand crews/bulldozer
Lookout Point	NPS	1579	1997	0	hand crews
Antelope Border	NPS	1590	2001	0	mechanical
McKenzie Ridge	USFS	1646	1960	0–2	mechanical
Fallen Leaf	USFS	2001	1995	0	mechanical

Notes: A range is shown for some variables because individual transects on the same fuel break often varied in year of construction, fire history, and construction method. Agency abbreviations are: USFS, USDA Forest Service; NPS, National Park Service; OCPD, Orange County Parks Department; CDF, California Department of Forestry and Fire Protection; and BLM, Bureau of Land Management.

USA). Duff and litter depth were measured at a single point in each 1-m^2 plot. Litter was considered to be the top layer of organic material, including freshly fallen leaves, needles, fine twigs, dead grass, and other vegetative parts that had not decomposed. Duff was considered to be the partially decomposed organic matter lying beneath the litter layer and above mineral soil, including the humus layer.

We measured slope, aspect, and elevation at the two end points of each transect. Slope, aspect, and latitude were used to generate potential direct incident radiation according to equations in McCune and Keon (2002). Plot locations were recorded with a Garmin 3+ GPS unit (Garmin, Olathe, Kansas, USA), and GIS data layers of all study plots were generated. Data on fire history was obtained from a statewide fire perimeter GIS data layer containing fires recorded since 1953 (California Department of Forestry and Fire Protection 2003). We calculated the distance of plots to roads and urban interfaces, and the density of roads within a 5 km radius (78.5 km^2), from GIS data layers using the ArcView Spatial Analyst extension (ESRI 2000). Information about fuel break age, construction and maintenance methods, and grazing history were obtained from GIS data, environmental and biological assessments, resource management plans, fire incident reports, and agency technical reports. Additional information was collected through personal communications with fuels and fire managers, botanists, range managers, and other staff familiar with each site.

Data analysis

Question 1: Are nonnative plants more abundant on fuel breaks than in adjacent wildland areas? To identify differences between fuel breaks and adjacent wildland areas, data collected from plots on each fuel break were pooled, and data collected from plots off each fuel break were pooled, providing paired measures of relative nonnative abundance, density, and species richness for each fuel break and each adjacent wildland area. We then used paired t tests to determine if relative nonnative cover, density, and species richness were significantly

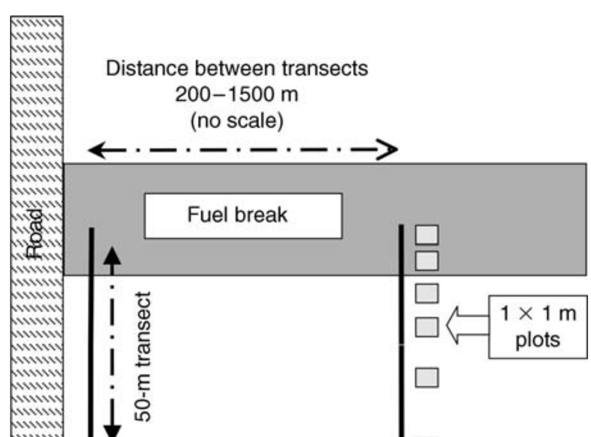

FIG. 3. Transect orientation along fuel breaks and plot locations along transects.

different on fuel breaks compared with wildland areas adjacent to fuel breaks, and evaluated significance using Bonferonni adjusted means comparisons. For all our analyses, we used relative measures, allowing us to evaluate the abundance of nonnative species as a proportion of the total plant community. Relative measures are more meaningful values when comparing across sites, which may differ greatly in absolute values.

Question 2: What environmental and anthropogenic factors are correlated with the abundance of nonnatives? Our general approach was to first use multiple stepwise regression analysis to identify the environmental and anthropogenic variables most strongly correlated with relative nonnative cover. We then used ANOVA to evaluate how significant variables identified by the multiple regression models were related to each other. For example, we used ANOVA to determine how fuel break construction method (an anthropogenic variable) was associated with canopy cover (an environmental variable).

We used logistic regression to identify environmental factors associated with the presence of nonnative species across all of our study plots. Linear regression evaluated the relationship between environmental variables and relative cover of nonnative plants in plots where they were found to occur (P for inclusion = 0.15). A P value of 0.15 is considered appropriate for inclusion of variables into multiple regression models (Zar 1999). Site and transect were included as dummy blocking variables in both analyses to evaluate any potential random effects of these factors on relative nonnative cover.

Multiple stepwise linear regression analysis was used to select anthropogenic variables with significant effects on relative nonnative abundance. This method allowed us to evaluate a number of variables in a single model, including distance to the nearest road and urban interface, fuel break construction method, maintenance method, maintenance frequency, fuel break age, use of prescribed burning, and use of precautions against nonnative invasion such as washing equipment. This analysis evaluated nonnative abundance on the fuel break, and so we used data from plots on the fuel break only. Each transect contained two plots on the fuel break; these data were pooled to generate a single measure for each of the 220 transects we established. Site was included as a dummy blocking variable in this analysis to account for the potential random effects of site differences on relative nonnative cover.

We conducted ANOVAs to determine how significant environmental variables were affected by fuel break construction method, and to evaluate if fuel break construction method and vegetation type had a significant interaction effect on relative nonnative cover. We also examined how environmental variables that were significantly correlated with nonnative presence and abundance differed in plots on fuel breaks compared with plots off fuel breaks by using paired t tests and evaluating significance using Bonferonni adjusted means comparisons. Finally, we used ANCOVA to evaluate the association between fuel break construction method (the anthropogenic variable with the strongest relationship to relative nonnative cover) and the relative cover of nonnative plants. Elevation and slope were included as covariates in this analysis to account for the potentially confounding effect of these variables.

Question 3: What is the pattern of nonnative abundance adjacent to fuel breaks, and is this pattern altered by disturbances such as fire or grazing? We examined the association between distance to the fuel break and relative nonnative cover. The interaction between distance to the fuel break and disturbance-related variables such as fire and grazing also was evaluated. We repeated the analysis of fire number and distance to the fuel break within each vegetation type; however our analysis of grazing was limited to chaparral and oak woodland plant communities, because very few sites in other vegetation types had been grazed. The interaction between distance from the fuel break and fuel break age category also was examined. The fuel breaks we sampled did not have a continuous age class distribution, but were clumped into three discrete age class categories corresponding to fuel breaks that were <10 years of age, between 10 and 30 years of age, and >30 years post construction. ANOVA was used for all analyses, and distance to the fuel break was treated as a nested factor within transects for all analyses evaluating this variable.

Data analyses were performed using SYSTAT version 10 (SPSS 2000). Residuals from each analysis were plotted to identify outliers and evaluate homogeneity of variance (Wilkinson et al. 1996). Percentage values were arcsine square-root transformed to improve normality and homogeneity of variance. Tests of the assumption of homogeneity of slopes for analysis of covariance (ANCOVA) were conducted as appropriate. Potential direct incident radiation was not included in regression models because of collinearity with other variables (Belsley et al. 1980). All other variables included in the multiple regression models did not exhibit collinearity.

TABLE 2. Ten most common nonnative plant species observed.

Scientific name	Life-form	Vegetation type	No. plots
Bromus tectorum	AG	CH, CF, OW	244
Bromus madritensis	AG	CH, CS, OW	223
Vulpia myuros	AG	CH, CF, OW	217
Bormus hordeaceus	AG	CH, CF, OW, CS	184
Bromus diandrus	AG	CH, CF, OW, CS	177
Erodium cicutarium	AF	CH, CS, OW	150
Torilis arvensis	AF	CH, CF, OW	122
Centaurea melitensis	AF	CH, CS, OW	99
Aira caryophyllea	AG	CH, CF, OW	82
Avena barbata	AG	CH, CS, OW	79

Notes: Life-form abbreviations are: AG, annual grass; AF, annual forb. Vegetation type abbreviations are: CF, coniferous forest; OW, oak woodland; CH, chaparral; and CS, coastal scrub.

TABLE 3. Complete list of nonnative species encountered sorted by frequency of occurrence.

Scientific name	Life-form	Vegetation type	No. plots
Bromus tectorum	AG	CF, OW, CH, CS	244
Bromus madritensis	AG	OW, CH, CS	223
Vulpia myuros	AG	CF, OW, CH	217
Bromus hordeaceus	AG	CF, OW, CH, CS	184
Bromus diandrus	AG	CF, OW, CH, CS	177
Erodium cicutarium	AF	OW, CH, CS	150
Torilis arvensis	AF	CF, OW, CH	122
Centaurea melitensis	AF	OW, CH, CS	99
Aira caryophyllea	AG	CF, OW, CH	83
Avena barbata	AG	OW, CH, CS	79
Hypochaeris glabra	AF	OW, CH, CS	77
Brassica nigra	AF	CH, CS	76
Filago gallica	AF	CF, OW, CH, CS	66
Centaurea solstitialis	AF	OW, CH	43
Sonchus oleraceus	AF	CH, CS	36
Medicago polymorpha	AF	OW, CH, CS	35
Avena fatua	AG	OW, CH, CS	31
Bromus arenarius	AG	OW, CH	30
Galium parisiense	AF	OW, CH	25
Erodium botrys	AF	OW, CH, CS	24
Silene gallica	AF	CH, CS	22
Vulpia bromoides	AG	CF, CH	20
Cynosurus echinatus	AG	OW, CF	19
Erodium moschatum	AF	CH, CS	19
Descurainia sophia	AF	CH	15
Elytrigia intermedia	PG	CF, CH	14
Poa bulbosa	PG	CH	14
Bromus sterilis	AG	OW, CH	12
Gastridium ventricosum	AG	OW, CH	12
Silene noctiflora	AF	OW, CH	12
Hedypnois cretica	AF	CS	11
Lactuca serriola	AF	CF, OW, CH	10
Schismus barbatus	AG	CH, CS	9
Cerastium glomeratum	AF	OW, CH	7
Phalaris aquatica	PG	CH	7
Sisymbrium altissimum	AF	CH, CS	7
Anthriscus caucalis	PF	CH	6
Cerastium fontanum	PF	OW, CH	6
Melilotus indica	AF	CS	6
Arenaria serpyllifolia	AF	OW	5
Lamarckia aurea	AG	CS	5
Anagallis arvensis	AF	CH, CS	4
Galium divaricatum	AF	OW	4
Gnaphalium luteo-album	AF	CF, CH	4
Hordeum murinum	AG	CH, CS	4
Raphanus raphanistrum	AF	CH	4
Cirsium vulgare	BF	CF	3
Cytisus scoparius	S	OW	3
Malva parviflora	AF	CH	3
Poa compressa	PG	CF	3
Taeniatherum caput-medusae	AG	OW, CH	3
Trifolium hirtum	AF	CH	3
Agrostis stolonifera	PG	CH	2
Carduus pycnocephalus	AF	OW	2
Carduus tenuiflorus	AF	CH	2
Foeniculum vulgare	PF	CH	2
Genista monspessulana	S	OW	2
Geranium pusillum	AF	OW	2
Poa palustris	PG	CF	2
Taraxacum officinale	AF	CF	2
Torilis nodosa	AF	OW	2
Briza maxima	AG	CH	1
Briza minor	AG	CH	1
Convolvulus arvensis	PF	OW	1
Geranium molle	AF	OW, CH	1
Hirschfeldia incana	BF	CH	1
Hypochaeris radicata	PF	OW	1
Lactuca saligna	AF	CH	1
Leontodon taraxacoides	AF	OW	1
Petrorhagia dubia	AF	CH	1
Plantago lanceolata	PF	CF	1
Silybum marianum	AF	CS	1
Solanum dulcamara	SS	OW	1
Sonchus asper	AF	CH	1
Spergularia rubra	AF	CF	1
Stellaria media	AF	OW	1
Trifolium dubium	AF	CH	1
Vicia hirsuta	AF	CS	1

TABLE 3. Continued.

Notes: Life-form abbreviations are: AG, annual grass; AF, annual forb; BF, biennial forb; PF, perennial forb; PG, perennial grass; S, shrub; SS, subshrub. Vegetation type abbreviations are: CF, conifer forest; OW, oak woodland; CH, chaparral; and CS, coastal scrub.

RESULTS

We identified 737 plant species in our 1-m^2 plots both on and adjacent to 24 separate fuel breaks. Approximately 85% were native, 11% were nonnative, and 4% could not be identified due to lack of fresh plant material. Nonnative plants were present in 49% of our plots. The most frequently occurring nonnative plants were cheat grass (*Bromus tectorum*) and red brome (*Bromus madritensis*). No single nonnative species emerged as dominant at all of our study sites. Cheat grass had the highest relative cover of all nonnative species at eight study sites, and red brome had the highest relative nonnative cover at three sites. At the remaining 13 sites, a different species had the highest relative cover among nonnatives. Almost all nonnative species were annual grasses and forbs (64 of 79 species). Only 15 perennial nonnative species occurred in our study, including six perennial grasses, six perennial herbs, two shrubs, and one sub-shrub. We did not encounter any nonnative trees. A list of the 10 most common nonnative species is provided in Table 2, and a complete list of nonnative species is given in Table 3.

Question 1: Are nonnative plants more abundant on fuel breaks than in adjacent wildland areas? Absolute and relative nonnative species number, cover, and density were significantly higher on fuel breaks than off fuel breaks (Fig. 4). On fuel breaks, 65% of plots contained nonnatives, while only 43% of plots off fuel breaks contained nonnatives ($N = 1543$, $F_{1,\ 1541} = 74.28$, $P < 0.001$). Of the 79 nonnative plant species identified, 21 were restricted to fuel breaks and 9 were found only in wildland areas adjacent to fuel breaks.

Question 2: What environmental and anthropogenic factors are correlated with the abundance of nonnatives on fuel breaks? Relative nonnative cover on fuel breaks varied greatly among sites, ranging from 0% to over 70%. Nonnative cover also differed significantly between vegetation types. Fuel breaks in coastal scrub habitats had the highest relative nonnative cover (68.3% ± 4.0%

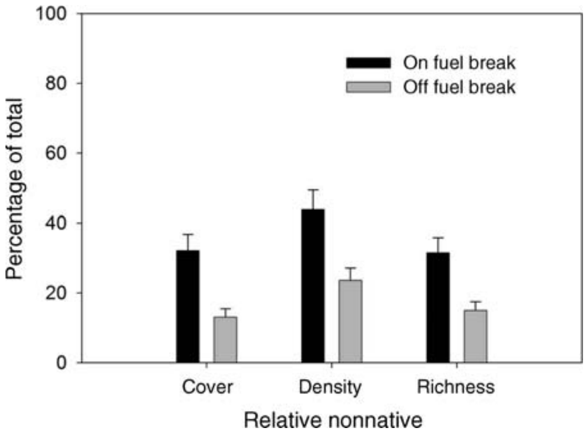

FIG. 4. Paired t tests indicate significant differences between relative nonnative cover, density, and species richness on and off fuel breaks (cover, $t = 5.423$, df = 23, $P < 0.001$; density, $t = 4.180$, df = 23, $P < 0.001$; richness, $t = 5.208$, df = 23, $P < 0.001$). Values are means + SE.

[mean ± SE]), followed by chaparral (39.0% ± 2.4%), oak woodland (25.0% ± 2.5), and coniferous forests (4.0% ± 1.1%).

Fuel break construction method, maintenance method, maintenance frequency, fuel break age, distance to roads, and the dummy blocking variable for site were significantly associated with relative nonnative cover on fuel breaks (Table 4). Of these factors, fuel break construction method had the highest standardized coefficient (–0.631). Fuel breaks constructed by bulldozers had significantly higher relative nonnative cover than fuel breaks constructed by hand crews, and fuel breaks thinned mechanically had significantly lower relative nonnative cover than fuel breaks constructed by other means ($N = 220$; effect of construction method, $F_{2,\,215} = 118.655$, $P < 0.001$; effect of covariate elevation, $F_{1,\,215} = 20.049$ $P < 0.001$; effect of covariate slope, $F_{1,\,215} = 2.905$, $P = 0.090$). The presence of nonnatives also was significantly associated with fuel break construction method ($N = 220$, $F_{2,\,217} = 7.001$, $P < 0.001$); 49% of plots contained nonnatives on fuel breaks constructed by bulldozers, compared with 20% of plots on fuel breaks constructed by hand crews, and 4% of plots on mechanically thinned fuel breaks.

TABLE 4. Multiple linear stepwise regression analysis of the association between anthropogenic variables and relative nonnative plant cover on fuel breaks.

Effect	Standard coefficient	Tolerance	t	P (two-tailed)
Constant	0.000		14.443	<0.001
Construction method	−0.631	0.698	−13.487	<0.001
Maintenance frequency	0.221	0.733	4.835	<0.001
Site	0.121	0.821	2.816	0.005
Fuel break age	0.084	0.711	1.818	0.071
Maintenance method	0.068	0.892	1.636	0.103
Distance to roads	−0.062	0.925	−1.532	0.127

Notes: Data represent plots on the fuel break only, pooled to provide one value per transect. Variables dropped from the multiple stepwise linear regression as not being significant at $P > 0.15$ included distance of the fuel break to urban interfaces, prescribed burning, and use of precautions against nonnative invasion such as washing equipment ($N = 220$, adjusted multiple $r^2 = 0.666$, standard error of estimate = 0.207).

TABLE 5. Logistic regression model of association between environmental variables and nonnative plant presence across all plots.

Parameter	Estimate	SE	t	P
Constant	3.346	0.393	8.520	<0.001
Canopy cover (%)	−1.622	0.140	−11.611	<0.001
Duff depth (cm)	−0.029	0.005	−5.778	<0.001
Litter cover (%)	−1.150	0.204	−5.631	<0.001
Elevation (m)	−0.001	0.000	−4.584	<0.001
Rock cover (%)	−1.489	0.344	−4.323	<0.001
Bare ground cover (%)	−0.767	0.227	−3.378	0.001

Notes: The blocking variable for site and the continuous variable litter depth were not significant at $P < 0.15$ and were removed from the model ($N = 1408$; total model log-likelihood, −721.854; constants-only model, −972.943; chi-square $P < 0.001$; McFadden's $Rho^2 = 0.258$).

To determine if the strong association of nonnative cover with fuel break construction method was related to vegetation type, we repeated our analysis of fuel break construction method and relative nonnative cover within each vegetation type separately. We found that fuel break construction method was significantly associated with relative nonnative cover in coniferous forest ($N = 39$, $F_{2,\,36} = 5.300$, $P = 0.010$), oak woodland ($N = 57$, $F_{2,54} = 20.432$, $P < 0.001$), and chaparral ($N = 108$, $F_{2,\,105} = 58.294$, $P < 0.001$). We had very few plots constructed by hand crews or mechanical thinning within the coastal scrub vegetation type, so we were unable to evaluate the effect of fuel break construction method in this vegetation type.

Elevation, slope, duff depth, overstory canopy, bare ground, litter cover, rock cover, and the dummy blocking variables for transect and site were significantly

TABLE 6. Multiple linear stepwise regression analysis of the relationship between environmental variables and relative nonnative plant cover across all plots where nonnatives were found.

Effect	Standard coefficient	Tolerance	t	P (two-tailed)
Constant	<0.001		29.253	<0.001
Canopy cover (%)	−0.354	0.763	−10.002	<0.001
Elevation (m)	−0.229	0.895	−7.024	<0.001
Bare ground (%)	−0.129	0.739	−3.578	<0.001
Slope (%)	−0.097	0.722	−2.656	0.008
Litter cover (%)	−0.094	0.651	−2.462	0.014
Transect	0.076	0.741	2.129	0.034
Site	0.067	0.975	2.143	0.032

Notes: Variables with $P > 0.15$ were removed from the model, including rock cover, litter depth, and duff depth ($N = 754$, adjusted multiple $r^2 = 0.281$, standard error of estimate = 0.225).

TABLE 7. Paired t tests indicated significant differences in environmental variables significantly associated with nonnatives in plots on fuel breaks compared with those off fuel breaks, except for the variables elevation and rock cover.

Dependent variable	Mean on fuel break	Mean off fuel break	t	P
Canopy cover (%)	26.1	62.2	−8.950	<0.001
Elevation (m)	1056.8	1055.8	0.875	0.391
Bare ground (%)	25.2	18.1	2.292	0.031
Slope (%)	16.7	25.9	−5.704	<0.001
Litter cover (%)	46.4	63.5	−5.449	<0.001
Duff depth (cm)	6.6	14.6	−6.668	<0.001
Rock	8.5	8.8	−0.260	0.797

Note: Significance was determined using Bonferroni method.

associated with the presence and abundance of nonnative plant species (Tables 5 and 6). Several of the variables significantly negatively associated with nonnative cover (overstory canopy cover, litter cover, duff depth, and slope) were significantly lower in plots on fuel breaks compared with plots off fuel breaks (Table 7). Other environmental variables significantly associated with nonnative cover, including overstory canopy cover, litter cover, and duff depth, were significantly lower on fuel breaks constructed by bulldozers than on fuel breaks constructed by other methods (Fig. 5). Fuel breaks constructed by bulldozers also had significantly more bare ground exposed than sites cleared mechanically.

Question 3: What is the pattern of nonnative abundance adjacent to fuel breaks, and is this pattern altered by disturbances such as fire or grazing? Relative nonnative cover decreased significantly with distance from the fuel break ($N = 1538$, $F_{4,\ 1518} = 5.635$, $P < 0.001$). There also was a significant interaction between fire number and distance from the fuel break (Fig. 6). In the absence of fire during the past 50 years, relative nonnative abundance did not change with increasing distance from the fuel break. In areas that had experienced one or two fires in the past 50 years, nonnatives were more abundant both on fuel breaks, and in plots that were within 20 m of the fuel break. Sites that had burned three or more times in the past 50 years not only had

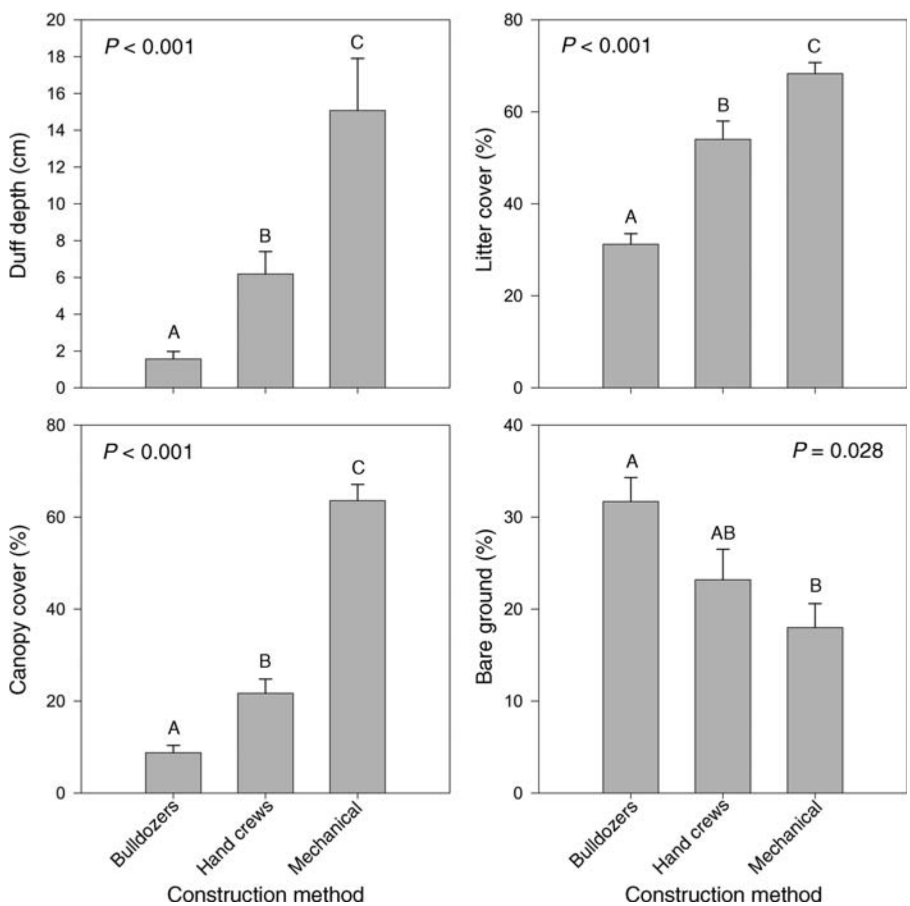

FIG. 5. MANOVA on arcsine square-root transformed percentage data found significant relationships between fuel break construction method and environmental variables significantly associated with nonnatives, including duff depth, litter cover, canopy cover, and bare ground ($N = 198$, $F_{6,\ 188} = 11.608$, $P < 0.001$). Univariate P values are indicated on graphs. Values are means + SE. Letters indicate significantly different means based on post hoc analysis conducted using Bonferroni multiple-comparison t tests.

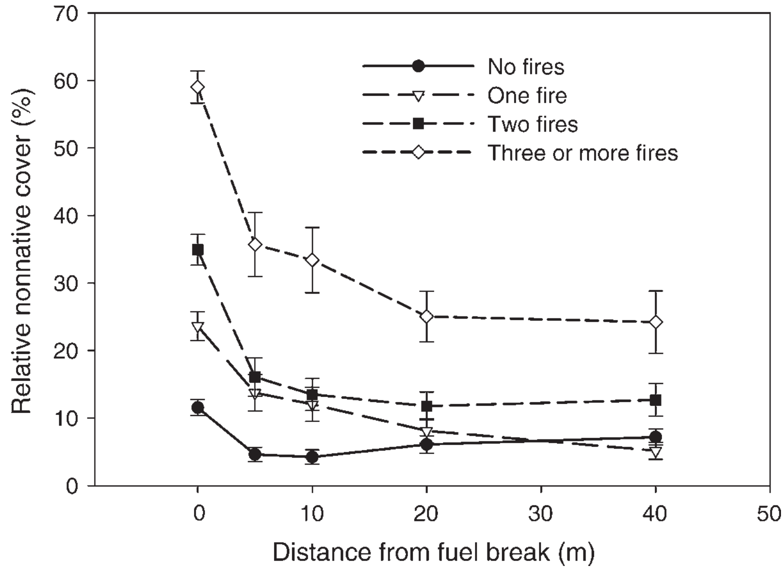

FIG. 6. Two-way ANOVA conducted on arcsine square-root transformed data found a significant interaction effect on relative nonnative cover between number of fires and distance from the fuel break ($N = 793$, $F_{12,\ 773} = 2.366$, $P < 0.001$). Values are means ± SE.

much higher nonnative cover on the fuel break, but also at distances of up to 40 m from the fuel break.

Relative nonnative cover was higher in areas that had been grazed than in ungrazed sites (Fig. 7). There was not a significant interaction between grazing and distance from the fuel break. However, there was a significant interaction between plot distance from the fuel break and fuel break age category (Fig. 8). Relative nonnative cover on fuel breaks, and in plots adjacent to fuel breaks, increased with fuel break age.

These patterns of nonnative abundance in association with fire, grazing, and distance from the fuel break were similar within most vegetation types. However, sample sizes in some vegetation types were too low to adequately test all variables. The interaction between number of fires and distance from the fuel break was significant in chaparral ($N = 720$, $F_{12,\ 700} = 13.030$, $P < 0.001$) and coniferous forest vegetation types ($N = 339$, $F_{12,\ 319} = 3.789$, $P < 0.001$). Only the main effects of number of fires and distance from the fuel break were

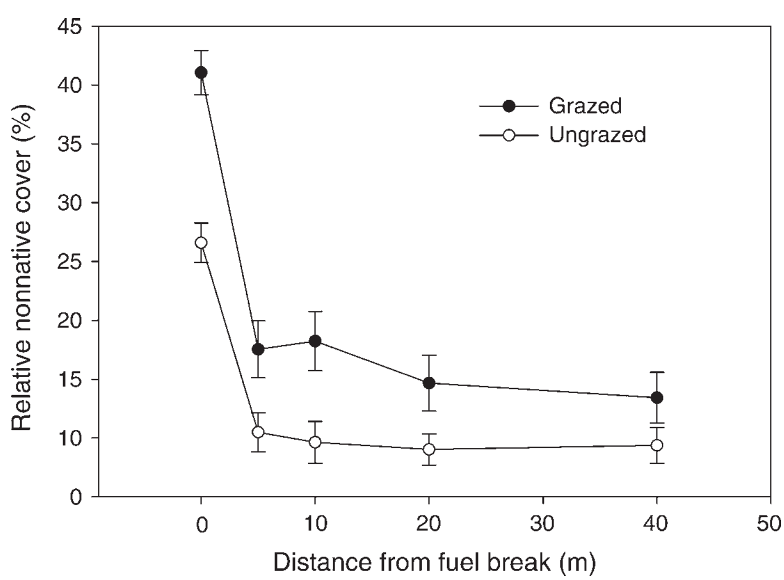

FIG. 7. Two-way ANOVA conducted on arcsine square-root transformed data found that the main effect of grazing was significantly associated with relative nonnative cover in oak woodland and chaparral vegetation types ($N = 1108$, $F_{1,1008} = 33.978$, $P < 0.001$), as was the main effect of plot distance ($N = 1108$, $F_{4,1008} = 62.459$, $P < 0.001$); however, there was not a significant interaction between these variables. Values are means ± SE.

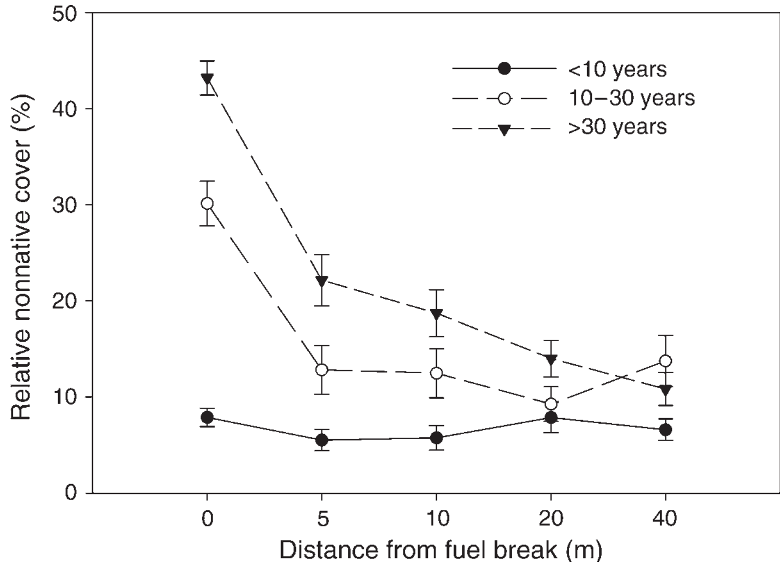

FIG. 8. Two-way ANOVA conducted on arcsine square-root transformed data found significant differences in relative nonnative abundance with distance from the fuel break and fuel break age ($N = 1543$, $F_{12,1523} = 15.377$, $P < 0.001$). Values are means ± SE.

significant in oak woodland vegetation types ($N = 385$; number of fires, $F_{3,\ 365} = 11.827$, $P < 0.001$; distance, $F_{4,\ 365} = 6.588$, $P < 0.001$); however, in coastal scrub vegetation types, where most sites had experienced multiple fires, only distance from the fuel break was significantly associated with relative nonnative cover ($N = 95$, $F_{4,75} = 5.965$, $P < 0.001$).

DISCUSSION

Our study demonstrates that fuel breaks have the potential to promote the establishment and spread of nonnative plants. We found that environmental variables significantly associated with nonnative species presence and abundance, including overstory canopy, litter cover, and duff depth, were significantly lower on fuel breaks than in adjacent wildlands. Removal of canopy cover may benefit nonnative plants by reducing competition with natives and changing light, nutrient, and water levels (McKenzie et al. 2000, Parendes and Jones 2000). Removing litter and duff and disturbing soils on fuel breaks can provide sites for nonnative plant establishment, stimulate nonnative seed germination, and change temperature, moisture, and nutrient availability in ways that benefit nonnative plants (Hobbs and Atkins 1988, Reynolds et al. 2001). These findings suggest that fuel break construction and maintenance strategies that retain some overstory canopy and ground cover may reduce the establishment and widespread invasion of nonnative plants.

Fuel break construction method was very strongly associated with relative nonnative abundance. Although we measured a number of other anthropogenic variables, fuel break construction method may have been more directly related to nonnative abundance, because it was associated with measurable differences in canopy cover, duff depth, and litter cover. We found that fuel breaks constructed by mechanical thinning had significantly lower nonnative cover than those constructed by bulldozers in all vegetation types. Mechanical thinning retains overstory canopy, which we found was associated with a decrease in nonnative abundance. Conversely, even in vegetation types with relatively low nonnative cover, such as coniferous forests, the use of bulldozers significantly increased the abundance of nonnative plants. Bulldozers have large blades specifically designed to remove surface soil layers, and may be more likely to introduce nonnative seeds into fuel breaks by disrupting soil seed banks and transporting seeds between sites.

We might have expected that fuel breaks built by hand crews would be the least likely to be invaded by nonnative plants, but instead we found that these fuel breaks had significantly lower overstory canopy cover, litter cover, and duff depth than fuel breaks constructed by mechanical equipment. This result is consistent with the emphasis of hand crews on removing surface fuels to construct effective fire lines. Fuel breaks built by hand crews had significantly higher cover of nonnatives than fuel breaks constructed by mechanical thinning.

Fuel breaks in chaparral and coastal scrub vegetation types were more likely to contain nonnative species. This pattern may be explained by a number of factors, including land use history, topographic and environmental factors, and differences in the life history characteristics of the dominant species in these vegetation types (Keeley 2001). For example, fuel breaks in coastal scrub and chaparral habitats had experienced more frequent fires during the past 50 years, occurred at lower elevations, were dominated by shrub species, had

PLATE 1. (Upper) Etz Meloy Fuel Break, Santa Monica Mountains National Recreation Area; (lower) Tower Fire Line, Whiskeytown National Recreation Area. Photo credits: K. Merriam.

relatively low canopy cover, and had more exposed bare ground. Conversely, coniferous forest and oak woodland sites had experienced fewer fires during the past 50 years, were more likely to be grazed, occurred at higher elevations, were dominated by tree species, had higher canopy cover, and had deeper duff and litter depths. Despite these differences, we found that fuel breaks were associated with increased nonnative abundance in all vegetation types. This suggests that fuel treatments in California are likely to promote nonnative plant species across a wide range of vegetation types and with varying land uses.

Nonnative species represented a larger proportion of total plant cover in plots on fuel breaks, and relative nonnative cover increased with fuel break age. These results suggest that nonnatives can displace native species on fuel breaks, and that nonnatives become increasingly dominant over time. Nonnatives may thrive on fuel breaks because they can more easily tolerate frequent disturbances caused by fuel break maintenance. Nonnative species also may reduce native species abundance by altering ecosystem processes. For example, the two most common species encountered in our study, cheat grass and red brome, have been found to change soil nutrient cycling in ways that negatively affect native plants (Evans 2001). These species can also alter fuel characteristics such that fires become less intense and more frequent (D'Antonio and Vitousek

1992, Keeley 2001, Brooks et al. 2004). Reduced fire intensity may increase the survivorship of nonnative seeds, and increased fire frequencies can kill native plants that are adapted to longer fire return intervals (D'Antonio 2000, Keeley and Fotheringham 2003, Brooks et al. 2004). We observed much higher abundance of nonnatives in coastal scrub vegetation types and chaparral where fire frequencies have increased due to anthropogenic ignitions (Keeley and Fotheringham 2003). However, even in coniferous forests, where fire return intervals have been reduced due to fire suppression, we found that a single fire significantly increased the abundance of nonnative species. This suggests that efforts to restore natural fire regimes to vegetation types where fire has been suppressed may promote the invasion of nonnative plants.

The lack of one dominant nonnative species across our sites suggests that fuel breaks may create favorable conditions for a number of different nonnative plant species. Although the habitat requirements of some of the nonnative species we observed are not well known, many of the nonnative species we found, including cheat grass and red brome, are known to colonize disturbed sites with open canopies and exposed bare ground (D'Antonio et al. 1999, Bossard et al. 2000). Invasion by a particular species may reflect which species has a nearby seed source. Most of the nonnatives we observed were annuals, and annual species are generally well adapted to colonize disturbed sites because of their short life cycles (Barbour and Billings 2000).

We found a general pattern of declining nonnative abundance with increasing distance from the fuel break. This pattern is consistent with models of species invasions that predict the spread of nonnatives from an initial point of introduction (Tyser et al. 1998). Fuel breaks may act as points of introduction for nonnatives because they receive external inputs of nonnative seeds through vehicles, equipment, or humans traveling on them (Schmidt 1989, Lonsdale and Lane 1994). Although some authors have suggested that dispersal does not limit alien plant abundance in later stages of invasion (e.g., Wiser et al. 1998), our results suggest that fuel breaks become increasingly important sources of nonnative seeds with time. We found that older fuel breaks had much higher nonnative abundance both on the fuel break and at distances of up to 20 m from the fuel break. Giessow (1997) found a similar pattern in fuel breaks 80 years of age and older in coastal scrub habitats in southern California.

Wildland areas adjacent to fuel breaks were more likely to be invaded by nonnative species when these areas had been subject to recurrent fires. Numerous studies have found that fire can promote nonnative plant invasion, even in fire adapted vegetation types (D'Antonio 2000, Brooks et al. 2004). Unburned sites did not exhibit a steep decline in nonnative abundance with distance from the fuel break, but the occurrence of a single fire in the past 50 years resulted in a pattern of declining nonnative abundance with distance from the fuel break. This pattern suggests that fuel breaks may act as seed sources for the colonization of burned sites. Studies have shown that seed availability is important for post-fire recolonization, particularly after high intensity fires where soil seed banks are destroyed (Turner et al. 1997, Keeley 2004).

Grazed sites also had more abundant nonnatives than ungrazed sites. Grazing has been found to increase the abundance of nonnatives, particularly where native plant communities did not evolve with intensive grazing (e.g., Heady et al. 1992, Mack and D'Antonio 1998). However, the decline in nonnative abundance with distance from the fuel break was similar in both grazed and ungrazed sites, suggesting that dispersal of nonnatives from fuel breaks was equally likely in grazed and ungrazed sites. Fuel breaks may not be more important nonnative seed sources in grazed sites when compared to ungrazed sites because gazing animals themselves can distribute seeds. It is also possible that differences in grazing intensity and history among our sites made it difficult for us to detect patterns of nonnative abundance associated with grazing.

This study was observational, and research using controlled, replicated experiments will be necessary to fully understand the mechanisms influencing nonnative abundance in association with fuel breaks. In this study, we have identified factors that may promote nonnative plants, and have suggested methods to reduce the probability of nonnative invasion. If these methods are strategically implemented it may be possible to both achieve fuel management goals and reduce the probability of nonnative plant invasion on fuel breaks and in surrounding wildland areas.

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