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Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California

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ABSTRACT

The Angora Fire burned 1243 ha of Jeffrey pine and mixed conifer forest in the Lake Tahoe Basin between June 24 and July 2, 2007. The Angora Fire burned at unusually high severity due to heavy fuels; strong winds; warm, dry weather; and unseasonably low fuel moistures. The fire destroyed 254 homes, and final loss and suppression cost estimates of $160,000,000 make the Angora Fire one of the ten costliest wildfires in US history. The Angora Fire burned into 194 ha of fuel treatments intended to modify fire behavior and protect private and public assets in the Angora Creek watershed. The fire thus provides a unique opportunity to quantitatively assess the effects of fuel treatments on wildfire severity in an area of wildland–urban interface. We measured fire effects on vegetation in treated and adjacent untreated areas within the Angora Fire perimeter, immediately after and one year after the fire. Our measures of fire severity included tree mortality; height of bole char, crown scorch, and crown torch; and percent crown scorch and torch. Unlike most studies of fuel treatment effectiveness, our study design included replication and implicitly controlled for variation in topography and weather. Our results show that fuel treatments generally performed as designed and substantially changed fire behavior and subsequent fire effects to forest vegetation. Exceptions include two treatment units where slope steepness led to lower levels of fuels removal due to local standards for erosion prevention. Hand-piled fuels in one of these two units had also not yet been burned. Excepting these units, bole char height and fire effects to the forest canopy (measured by crown scorching and torching) were significantly lower, and tree survival significantly higher, within sampled treatments than outside them. In most cases, crown fire behavior changed to surface fire within 50 m of encountering a fuel treatment. The Angora Fire underlines the important role that properly implemented fuel treatments can play in protecting assets, reducing fire severity and increasing forest resilience.

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1. Introduction

Although wildfire behavior is driven by fuels, weather, and topography, human influences on wildfire are largely restricted to intentional or unintentional effects on fuels. As a prime example of the law of unintended consequences, more than 70 years of fire suppression policies in the western United States have led to accumulations of forest fuels that are playing a major role in increasing wildfire size and severity in many semiarid forest types, especially where management practices such as timber harvest have increased surface fuels and homogenized forest structure (Skinner and Chang, 1996; Allen et al., 2002; Graham et al., 2004; Keeley et al., 2009; Miller et al., 2009b). Increased temperatures and changing patterns of precipitation due to climate change greatly exacerbate the problem. Recent data have shown that western fire seasons are beginning earlier and lasting longer than in the past (Brown et al., 2004; Westerling et al., 2006). Extreme fire weather is becoming more frequent, and forest fires are predicted to continue to grow larger, more severe, and more difficult to suppress (Flannigan et al., 2000; Fried et al., 2004; McKenzie et al., 2004; Miller et al., 2009b). Changing fire regimes will influence vegetation distributions in California, which in turn will further alter fire regimes (Lenihan et al., 2003; McKenzie et al., 2004).

These disquieting developments are further complicated by trends in human geography. The density of houses and other private structures in formerly "wildland" landscapes of the West is increasing rapidly (Field and Jensen, 2005). The extent of California's wildland–urban interface (WUI), that area where homes are located in or near undeveloped wildland vegetation (WUI definitions vary; see Stewart et al., 2007), grew almost 9%

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from 1990 to 2000 while the number of houses in new WUI grew by almost 700% over the same period (Hammer et al., 2007). Development in the WUI is leading both to increasing fire ignitions and to increasing losses of property and life. With 5.1 million houses in a roughly 29,000 km^2 WUI of highly fire-prone vegetation, California is the focus of much of the nation's WUI issues (Radeloff et al., 2005). Hammer et al. (2007) point out that 25 people were killed and 3533 structures were destroyed by wildfires in California in the thirty years from 1955 to 1985, while 32 people were killed and 7467 structures lost in fifteen years between 1985 and 2000. Since 2000, this pattern has continued, with 2003 and 2007 alone combining for more than 8500 destroyed structures and 30 deaths. Annual wildfire suppression costs have been averaging US$ 1 billion since 2001, with the value of threatened structures and the presence of private land playing major roles in the rising costs (Liang et al., 2008).

These alarming ecological and socioeconomic patterns have led land management agencies to embark on a large-scale effort to reduce fuel availability in many western forests by the emplacement of strategically located "fuel treatments" (USDA-USDI, 2000; WGA, 2001; USDA, 2004). In a fuel treatment, reduction of forest fuels is carried out in order to ameliorate fire behavior, with a primary focus on enabling more effective fire control, but with other secondary purposes identified depending on the project in question (Husari et al., 2006; Reinhardt et al., 2008). Theoretical considerations and modeling studies provide strong support for the efficacy of properly implemented fuel treatments in modifying wildfire behavior (e.g., Stephens, 1998; Finney, 2001; Graham et al., 2004; Stephens and Moghaddas, 2005; Schmidt et al., 2008). However, controlled empirical investigations of fuel treatment effectiveness in wildfire conditions remain rare. Martinson and Omi (2008) cited approximately two-dozen empirical tests of fuel treatment effectiveness, but aside from their own could find only four studies which combined statistical tests with adequate controls for topography and weather to be able to unambiguously discern a fuel treatment effect in a real wildfire. These studies (Pollet and Omi, 2002; Skinner et al., 2004; Raymond and Peterson, 2005; Cram et al., 2006; Martinson and Omi, 2008) plus another recent study (Strom and Fulé, 2007) all found significant reductions in fire severity in treatments which had explicitly included reduction of surface fuels (e.g., thinning followed by prescribed fire, or prescribed fire alone). In addition, two Canadian studies investigated effectiveness of fuel treatments in jack pine (*Pinus banksiana*) using experimental crown fires, but sample size in both cases was one. In one of the studies (Stocks et al., 2004) fuel treatment without surface fuel reduction had little effect on fire severity. In the other study (Schroeder, 2006), treatment of both canopy and surface fuels strongly reduced fire severity.

Although plans have been developed for networks of wildland fuel treatments across large areas of the West, most work completed to this point in California has occurred in or near the WUI (USDA, 2004, 2005). National Forest management in the Sierra Nevada is guided by the Sierra Nevada Forest Plan Amendment (SNFPA; USDA, 2004), which mandates that at least 50% of initial fuel treatment work in the Sierra Nevada should take place in the WUI until the WUI is sufficiently treated. There are several key differences between fuel treatment priorities and outcomes in the WUI versus in wildlands. WUI fuel treatments are intended primarily to protect private property and to create safe zones for direct attack tactics based on mechanized support, while wildland treatments are typically meant to slow fire spread so as to provide time for indirect efforts to succeed in creating conditions ahead of the fire that are more likely to result in its control; treatment goals may also include reducing fire severity for forest retention and other resource benefits (Husari et al., 2006; Reinhardt et al., 2008). Since WUI treatments are the last line of defense for asset protection, they are often subject to more intense levels of fuel removal. Because of this and their proximity to private property, WUI treatments are typically more expensive than wildland fuel treatments. Furthermore, fuel treatment in the WUI requires collaboration with the public and other agencies, and the ultimate success of WUI fuel treatments can depend heavily on fire preparations made by neighboring property owners (Cohen, 1999; Reinhardt et al., 2008).

Although much effort has been spent in constructing fuel treatments in the WUI, opportunities to empirically assess the effectiveness of WUI treatments have been few. Indeed, almost all statistical evidence for fuel treatment effectiveness at modifying fire behavior or severity has come from wildland settings, far from areas of human habitation. In this contribution we assess the performance of a set of WUI fuel treatments that encountered a highly severe, wind-driven wildfire in the Lake Tahoe Basin, California in June, 2007. Our focus was on treatments in the WUI-defense zone, that part of the WUI that is immediately adjacent to private property. A previous study of WUI treatment performance in the Angora Fire found that efforts at structure protection were strongly abetted by the fuel treatment network (Murphy et al., 2007). We used replicated transect and plot sampling in adjacent treated and untreated stands to assess performance of the same fuel treatment network with respect to its influence on forest fire severity and tree mortality. Although we sought principally to identify general patterns in fuel treatment performance, we were also interested in distinguishing the causes of variability in performance among treatments.

2. Study site

The study site is found within the Lake Tahoe Basin (LTB), in the northern Sierra Nevada of California and Nevada, USA (Fig. 1). The LTB is located 240 km ENE of San Francisco, and includes 83,000 ha of terrestrial habitats and urban areas and Lake Tahoe itself (49,600 ha). Elevations range from less than 1800 m along the Truckee River below Lake Tahoe to 3315 m at Freel Peak. Climate is Mediterranean-type, with warm, dry summers, and cold, wet winters. At the South Lake Tahoe, CA airport (1900 m, 3 km due east of the Angora Fire perimeter), the January mean minimum temperature is $-10.4\,^{\circ}C$, the July mean maximum is $23.5\,^{\circ}C$; extreme recorded temperatures are -25.9 and $37.3\,^{\circ}C$. Precipitation averages 784 mm per year, with 86% of precipitation falling as snow between November and April (Murphy and Knopp, 2000; WRCC, 2008). The Lake Tahoe Basin Management Unit (LTBMU) of the USDA-Forest Service (USFS) manages about 72% (59,800 ha) of the LTB. Other land managers include California and Nevada State Parks, the California Tahoe Conservancy, and county governments.

2.1. Forest fires in the Lake Tahoe Basin

Presettlement fire return intervals in the LTB probably averaged 5–20 years in Jeffrey pine-dominated forests (Stephens, 2001; Taylor and Beaty, 2005). As in much of the Sierra Nevada, active fire exclusion in the LTB has nearly completely eliminated fire as a natural ecological process. In addition, a large proportion of the Lake Tahoe Basin (including much of the Angora Fire area) was heavily logged in the late 19th and early 20th centuries. Together these factors have resulted in increases in tree density, canopy cover, and surface fuels (Murphy and Knopp, 2000; Taylor, 2004), and many areas within the LTB support very high fuel loadings (see below). Over the last two decades, there has been an annual average of 62 fire starts on National Forest System lands within the LTB, with 79% ascribed to humans and 21% to natural ignitions (Murphy et al., 2007). Fire suppression is extremely efficient in the LTB, with fire response times averaging 5–10 min (B. Brady,

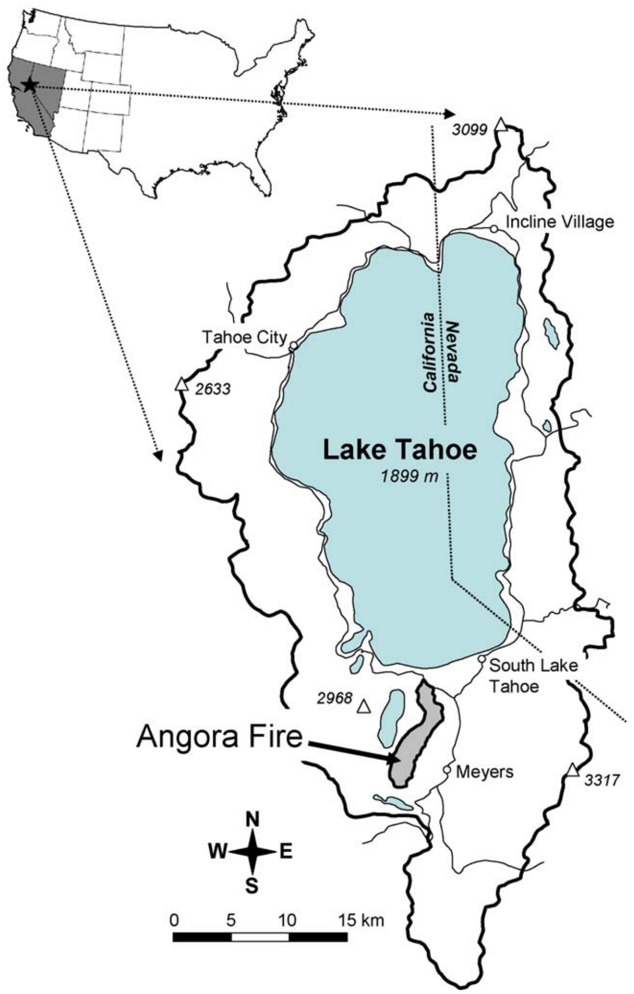

Fig. 1. Lake Tahoe Basin, California and Nevada, with the location of the Angora Fire. Outer polygon demarcates the boundary of the USDA-Forest Service Lake Tahoe Basin Management Unit (LTBMU).

personal communication), and very few fires escape initial attack. Prior to the Angora Fire, the Gondola Fire (2002; 272 ha) and the Showers Fire (also 2002; 119 ha) were the largest recorded wildland fires in the LTB.

2.2. The Angora Fire

The Angora Fire began on June 24, 2007, as the result of an illegal campfire in the upper Angora Creek drainage; the fire was declared contained on July 2 after burning 1243 ha. The Angora Fire burned exceptionally early in the fire season, and was the largest fire in the LTB since fire size records have been kept (c. 100 years). The fire area includes portions of two watersheds, the Upper Truckee River and Taylor Creek, which drain the east slope of the Sierra Nevada west of the city of South Lake Tahoe; the center of the fire was at approximately 38°53′8″N latitude and 120°2′24″W longitude (Figs. 1 and 2). Elevations in the fire area range from 2300 m on the SW boundary, to 1900 m on the northern boundary. The geologic substrate is primarily Mesozoic granitic rocks, with Paleozoic and Mesozoic metamorphic rocks found in the upper Angora Creek drainage. The geomorphic nature of the drainage was strongly influenced by Pleistocene glaciation. Soils are coarse textured and well-drained to excessively well-drained. Slopes range from 0 to 5% along the Angora Creek drainage bottom to >40% along the western and southwestern drainage boundaries. Vegetation is dominated by conifer forest with Jeffrey pine (*Pinus jeffreyi*) and white fir (*Abies concolor*) dominating lower slopes (83% of the prefire area) and red fir (*A. magnifica*) found on slopes above 2100 m (5% of the prefire area). Incense cedar (*Calocedrus decurrens*), sugar pine (*P. lambertiana*), and lodgepole pine (*P. contorta murrayana*) are associated species of the lower forests, with the latter concentrated along drainages. Quaking aspen (*Populus tremuloides*) is an important hardwood member of the Jeffrey pine-white fir forest in parts of the northern fire area and in a few places along Angora Creek. Montane chaparral (10% of the prefire area), dominated by *Quercus vaccinifolia* and species of *Ceanothus* and *Arctostaphylos*, is found on east-facing slopes along the southwestern boundary and in scattered patches elsewhere.

The Angora Fire burned at unusually high severity, caused by heavy fuels; strong winds out of the southwest (estimated at 35–50 km/h, with stronger gusts); warm, dry weather; and unseasonably low fuel moistures. Spring measurements put the 2006–2007 LTB snowpack at 29% of average, and fuel moistures were at near-record lows for the date (9% large dead fuel moisture, 73% live woody fuel moisture); the Energy Release Component (ERC) for June 24 was above the 90th percentile, a record value for the date (Murphy et al., 2007). Based on remotely sensed measures of fire severity (Relative differenced Normalized Burn Ratio [RdNBR] calibrated to canopy cover mortality; Miller and Thode, 2007; Miller et al., 2009a,b), approximately 53% of the Angora Fire burned at high severity (c. >75% canopy mortality), 21% at moderate/mixed severity (c. 25–75% mortality), and 26% at low severity (c. <25% canopy mortality) (Fig. 2). Roughly two-thirds of the fire area burned in the first day, after which winds moderated and shifted to the north. The fire destroyed 254 homes and damaged 26. Total suppression cost was approximately $12,000,000, and total property losses have been estimated at around $150,000,000, which makes the Angora Fire one of the ten costliest wildfires in US history (I.I.I., 2009).

2.3. Fuel treatments in the Angora Fire area

A total of 194 ha or 16% of the Angora Fire area had been treated for fuels in the period 1996–2006 (Fig. 2; Table 1). Other areas had been commercially thinned but had no explicit treatment of surface or ladder fuels. As these areas were not explicitly treated for fuels, we did not include them in our study. Fuel treatments were strategically located to provide protection for housing developments in the eastern and northern fire areas and to provide areas of lower fire intensity and increased safety, visibility, and operability for fire suppression efforts. Treatments were generally of the same type, beginning with a mechanical commercial harvest (removal of marked trees up to 75 cm diameter at breast height [dbh] to a target residual density; in some places this was a salvage treatment of beetle-killed stands), followed by a "precommercial thin" (so-called because tree volume removed was not sufficient to cover the cost of the operation) of trees ≤ 35 cm dbh carried out by hand, and completed with hand piling and burning of these trees and other surface and ladder fuels (Table 1). The 35 cm dbh limit for hand thinning is based on LTBMU guidelines, primarily due to unit cost issues but also to difficulties in achieving complete consumption of larger trees in fuel pile burns (S. Parsons and M. Johnson, personal communication). In most cases the three treatments were sequentially carried out over a period of three to five years (Murphy et al., 2007; Table 1). In one case, Unit 20 in the center of the fire area, the hand piles had not yet been burned when the Angora Fire occurred. Three fuels treatment units received only two treatments. The area of Unit 6 was not included in any commercial sales, and in the case of Units 16 and 20, slopes were too steep (>30%) for mechanical treatment (by Tahoe Regional Planning Agency code 71.4E; TRPA, 2004). In these three cases hand thinning was used to remove trees ≤ 35 cm dbh and then residual fuels were piled and burned.

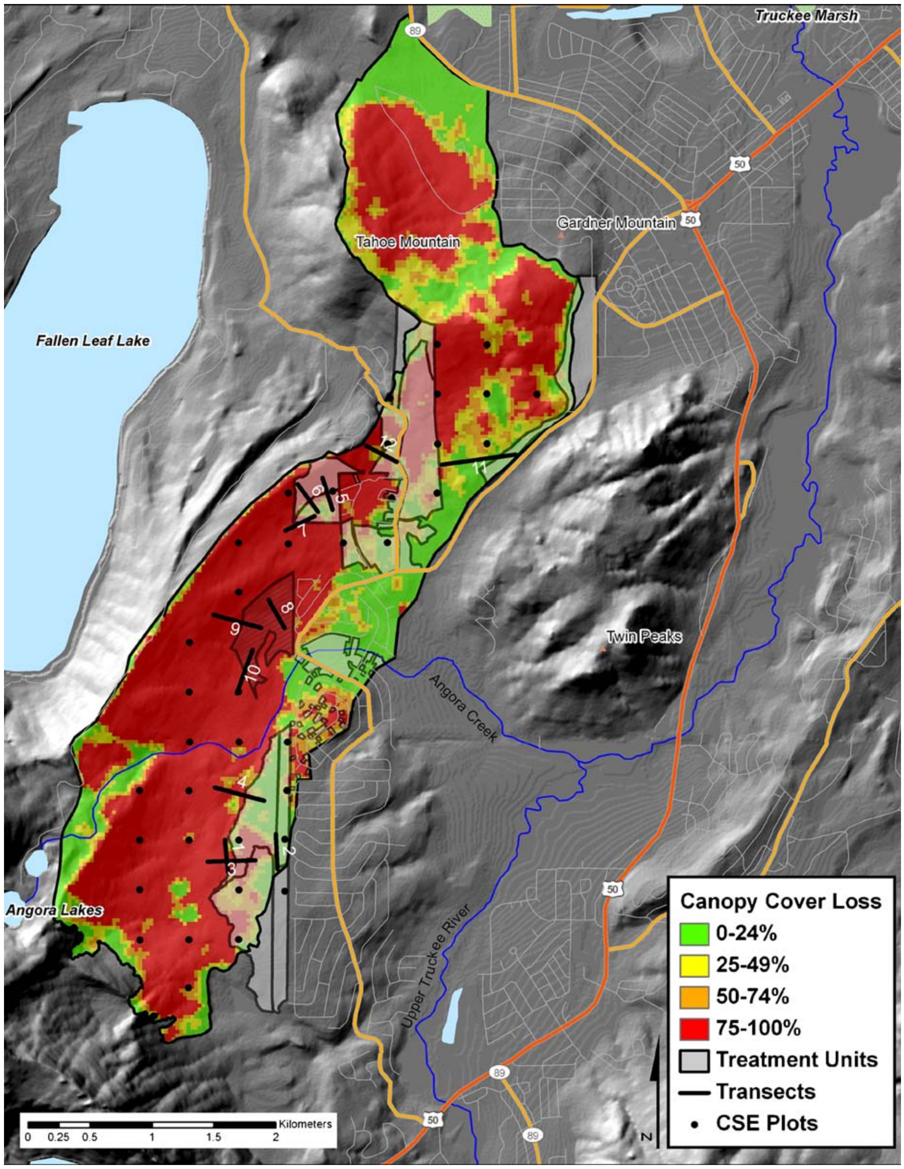

Fig. 2. Severity patterns in the Angora Fire, with locations of the transects (numbered, see Table 2) and the common stand examination (CSE) plots sampled after the fire. Treatment units which were considered "completed" at the time of the fire are shaded gray. For unit numbers, see Table 2. Unit 20, where hand-piled fuels were still on site at the time of the fire, is in the middle of the fire area (transects 8–10). We refer to the area around transects 1–4 as the "Tahoe Paradise" area in the text. Vegetation burn severity map from remotely sensed RdNBR measurements calibrated to canopy cover mortality (see text). The higher severity area in treatment Units 21 and 22 (transects 1 and 3) is partly an artifact of high shrub cover; tree mortality in this area was mostly low.

Quantitative surface fuel loading values are available for some parts of the prefire landscape from stand examination data collected by the USFS in 2006. The values were determined using photo series, which may have a tendency toward overestimation in some forest types (Sikkink and Keane, 2008). Table 1 gives prefire fuel loads (sums of all surface fuels) for fuel treatment units where available (mean = 11.8 tons/ha ± 5.3SD), and for neighboring untreated forest stands (mean = 57.9 tons/ha ± 36.7 SD). The photos in Fig. 3 show typical prefire conditions in treated and untreated stands in the Angora Fire area.

3. Methods

3.1. Field protocol—linear transects

We carried out field sampling between July and September 2007, and again between July and September 2008. We sampled sites previously treated for fuels within the fire perimeter, plus areas immediately adjacent to these sites in untreated forest. We used linear transects that varied in length from about 250 to 525 m, for the most part aligned perpendicularly to fuel treatment boundaries (Fig. 2). We only sampled fuel treatments where the treatment boundary facing the direction of fire spread was with untreated National Forest land. Transects 1 and 2 were randomly sited and used as pilots for protocol development, and transects 5 and 6 were subjectively located to enable comparison of treatment Units 16 and 17. For the remaining transects we selected locations by choosing random distances along treatment boundaries with untreated forest, beginning measurement at the northern-most vertex of the treatment polygon, with the constraint that transects were at least 200 m apart. We used maps and field visits to determine the final locations of transects, so as to avoid, among other things, roads, major riparian areas, locations where intensive fire fighting activities had occurred, and areas where there were major slope differences between treated and untreated stands (see Table 2). Transects 5, 6 and 12 were exceptions to the equal slope

Table 1
Fuel treatments completely or partially within the perimeter of the Angora Fire.

Unit ID	Project name	Treatment activity 1[a]	Treatment type 1	Year	Treatment activity 2	Treatment type 2	Year	Treatment activity 3	Treatment type 3	Year	Stand area (ha)	Final surface fuel loadings (tons/ha)[b]	Nearest untreated fuel loadings (t/ha)[b]
6	Tahoe Blvd Fuelwood Sale	Precommercial thin/ salvage	Hand	1995	Burn activity fuel piles	Hand	1996				31.8	11.2	26.4
7	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Heli	1995	Precommercial thin	Hand	2005	Burn activity fuel piles	Hand	2007	13.2		35.8
8	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Mech	1995	Precommercial thin	Hand	2005	Burn activity fuel piles	Hand	2007	36.8		29.7
11	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Mech/heli	1995	Precommercial thin	Hand	1996	Burn activity fuel piles	Hand	1997	13.4		
12	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Mech	1995	Precommercial thin	Hand	2004	Burn activity fuel piles	Hand	2006	4.7	21	
13	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Mech	1995	Precommercial thin	Hand	1996	Burn activity fuel piles	Hand	2007	3.2	8.4	
14	Tahoe Mtn Hazard Reduction	Precomm. thin–indiv.	Hand	2004	Precommercial thin	Hand	2006	Burn activity fuel piles	Hand	2007	6.7		38.5
16	Tahoe Mtn Hazard Reduction	Precomm. thin–indiv.	Hand	2004	Burn activity fuel piles	Hand	2006				11.1		67
17	Angora Hazard Reduction	Comm. thin/salvage	Mech	1997	Precommercial thin	Hand	2004	Burn activity fuel piles	Hand	2006	7.2		67
18	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Mech	1996	Precommercial thin	Hand	2004	Burn activity fuel piles	Hand	2006	4.5		
19	Tahoe Mtn Hazard Reduction	Comm. thin/salvage	Mech	1996	Precommercial thin	Hand	2004	Burn activity fuel piles	Hand	2006	10.3		
20	Angora Hazard Reduction	Precomm. thin–indiv.	Hand	2004	Pile activity fuels	Hand	2004				24.5		144.1
21	Angora Hazard Reduction	Comm. thin/salvage	Mech	1996	Precommercial thin	Hand	2004	Burn activity fuel piles	Hand	2005	35.3		40.5
22	Angora Hazard Reduction	Salvage	Mech	1996	Precommercial thin	Hand	2003	Burn activity fuel piles	Hand	2005	49.7	9.6	72.4
29	Angora Hazard Reduction	Comm. thin/salvage/ precommercial thin	Mech	1996	Precommercial thin	Hand	2004	Burn activity fuel piles	Hand	2005	10.7		
30	Angora Hazard Reduction	Comm. thin/salvage/ precommercial thin	Mech	1996	Precommercial thin	Hand	2003	Burn activity fuel piles	Hand	2005	14.2	8.6	

[a] Comm. thin = commercial thin; Precomm. thin = precommercial thin; Indiv. = individual selection cut.
[b] Surface fuel loadings = sum of 1, 10, 100, 1000, and 1000+ hour fuels in prefire stands. Untreated fuel loadings are from CSE plots from neighboring untreated stands on the windward side of the treatment, except for Unit 7, 8 and 14, where the untreated stands were on the leeward side. Fuel loadings determined using fuels photo series estimations, except for Unit 30 treated fuels, which were determined from Brown's transects.

Fig. 3. Examples of prefire conditions in treated and untreated forest stands in the Angora Fire area. (A) Treatment Unit 22, just beyond the fire perimeter. (B) Untreated forest 500 m southwest of the previous photo, 20 m from the fire perimeter. Both photos taken July 2007.

rule: transects 5 and 6 were intentionally sampled in an area of variable slope (see below); the treatment boundary in Unit 12 (sampled by transect 12) is coincident with a major slope break which could not be avoided. Transect 8 was intended to be twice its final length but it was not completed due to time constraints.

Our transect sampling protocol was designed not only to allow the measurement of linear changes in fire effects as fire passed from treated to untreated stands, but also to minimize the influence of weather variability in confounding the interpretation of those effects. Under the fire spread rates which characterized the Angora Fire (c. 2 km/h for the first 3 h, lower thereafter), each transect (except transect 11) would have been completely passed by the flaming front in a period of <10 min. Treated and untreated sampling points along transects 3–6, 8, 9, and 12 were probably burned at almost exactly the same time, and the flaming front probably passed in a period of <3 min, because orientation of these transects was perpendicular to the direction of fire spread. Transects that were parallel to the direction of fire spread (transects 1, 2, 7, 10, and 11) would have taken longer to burn, perhaps 7–10 min for the first four (they burned under the extreme conditions of the first burn period), and 30–40 min for the latter (which burned in the second burn period, when winds moderated and shifted direction).

We sampled from 10 to 21 points per transect, situated at random distances (constrained to be between 15 and 35 m, averaging about 25 m; with the caveat that points were moved if trees would have been resampled at adjacent points), with approximately the same number of points within treated and untreated areas (except along transects 1 and 2, which sampled

Table 2
Transect site information and sampling means for survival and fire severity measures, plus stem densities and basal areas for sampled stands from common stand exam (CSE) plots. Only trees > 12.7 cm diameter at breast height measured along transects; all trees > 2.5 cm dbh sampled in CSE plots. All heights and lengths in meters. "sd" = standard deviation.

Transect	Treated	Treatment unit ID	Length (m)	Mean slope (%)	Points	Trees	% live (2007)	% live (2008)	Torch height	sd	Scorch height	sd	Crown base height	sd	Bole char height[a]	sd	% Crown scorch	sd	% Crown torch	sd	Stem density (per ha)[b]	Basal area (m^2/ha)[b]
1	N	na	250	5.5	10	40	30	15	10.1	3.9	16.2	3.9	4.8	3.0	9.2	4.2	95.1	8.6	62.5	33.1	1471 (3)	49.6
2	Y	21/22	250	4	10	40	95	92.5	0.5	1.3	9.0	3.8	4.4	2.3	0.8	1.4	46.8	28.5	1.6	7.9	337 (4)	33.9
3	N	na	175	6.4	9	36	36.1	30.6	7.0	7.3	15.9	3.4	5.7	2.4	10.2	4.1	81.9	23.7	40.4	40.7	1875(4)	61.3
	Y	21/22	225	6.7	7	28	78.6	71.4	0.8	2.2	10.2	4.2	5.6	3.1	3.6	3.0	50.2	29.8	4.8	18.9	294 (4)	30.6
4	N	na	200	8.3	8	32	0	0	14.7	8.4	20.1	5.8	5.9	3.6	10.4	6.7	100.0		74.7	42.0	1531 (3)	62.4
	Y	21	200	6.4	8	32	81.3	75	0.6	2.3	11.3	3.4	5.5	2.2	3.0	1.9	60.8	26.5	1.9	9.0	390 (4)	31.5
5	Y	16	125	39	5	20	0	0	13.3	5.9	23.5	4.4	7.0	3.1	13.7	4.2	99.5	2.2	66.3	36.4	766 (1)	33.1
	Y	17	125	11.6	5	20	35	35	11.8	13.8	23.7	7.2	8.6	5.5	9.3	5.4	82.0	24.7	30.3	38.2	99(1)	16.8
6	Y	16	125	27.5	5	20	0	0	18.9	4.2	24.8	3.2	7.1	2.3	14.4	3.8	100.0		92.8	8.0	766 (1)	33.1
	Y	17	125	13.2	5	20	65	80	0.4	1.3	21.1	5.3	7.4	6.0	5.3	3.5	80.6	23.4	7.9	19.1	99(1)	16.8
7	N	na	125	5	5	20	0	0	29.2	5.0	31.6	2.3	9.2	3.9	10.4	8.3	100.0		88.9	29.1	880 (2)	79.3
	Y	17	125	5.8	5	20	85	80	7.6	9.4	18.9	5.7	10.7	4.5	5.3	6.8	56.0	26.7	6.8	8.6	216(2)	47.4
8	Y	20	250	11.2	10	40	0	0	24.8	4.8	27.7	2.8	8.5	4.3	13.3	5.8	100.0		85.7	27.2	469 (tr)	55.9
9	N	na	175	42.3	7	28	0	0	16.2	3.2	22.1	2.5	4.6	1.7	9.9	1.4	100.0		98.9	4.2	2207 (4)	62.3
	Y	20	225	35	9	36	0	0	16.7	5.8	22.7	1.8	8.1	2.1	12.3	3.0	100.0		85.7	27.2	371 (2)	71.1
10	N	na	175	17.6	7	28	10.7	3.6	14.9	7.8	26.0	2.8	8.6	3.6	12.7	5.0	98.6	5.8	63.8	38.2	2188(5)	63.4
	Y	20	200	13.8	8	32	0	0	20.2	7.9	29.1	1.6	9.7	4.6	16.5	5.7	100.0		78.3	35.5	371 (2)	71.1
11	N	na	400	11.1	14	56	89.3	89.3	0.2	0.9	10.6	11.4	6.6	4.5	2.7	2.6	41.5	32.7	0.6	2.3	321 (4)	41.5
	Y	6	200	10.3	7	28	100	100	0.1	0.7	4.5	3.3	4.3	2.0	1.1	1.3	16.4	21.8	0.4	1.9	221 (tr)	28.7
12	N	na	150	39.5	6	24	12.5	7.1	12.0	10.1	24.2	5.2	5.1	3.4	10.6	3.7	96.0	10.7	47.3	35.7	571 (1)	70
	Y	12	125	16	5	20	70	55	2.3	3.7	23.5	5.2	10.7	5.0	12.6	5.7	71.0	25.6	5.1	8.1	199.1 (3)	46.1

[a] Char heights averaged from trees where char height could be measured. Transects 7–10 experienced such severe fire effects that many trees were completely carbonized and char height merged into crown torching and thus could not be separately measured. The following transects had the following numbers of trees in this severely burned condition: transect 7 treated: 1; transect 7 untreated: 15; transect 8: 32; transect 9 treated: 10; transect 9 untreated: 21; transect 10 treated: 16; transect 10 untreated: 8. As a result of this, higher char heights reported for treated (vs. untreated) portions of transects 9 and 10 should be viewed as statistical artifacts.

[b] Prefire stem densities and basal areas from common stand exam (CSE) plots located near transects. Number of CSE plots used to generate the mean value given in parentheses in the 'Stem Density' column. In two cases no CSE plots were located in the vicinity of the transects (marked with "Tr"). In these cases we used the Cottam and Curtis (1956) formulae to calculate density basal area from the transect data, but these values should be treated as rough approximations as trees < 12.7 cm dbh were not sampled and tree spatial distributions were not random.

only untreated and treated forest, respectively; and transect 11, where we sampled 21 randomized points [7 treated, 14 untreated], at an average distance of 29 m) (Table 2). We adopted a sampling protocol derived partly from the point-center quarter method (Cottam and Curtis, 1956), taking measurements of the nearest tree $\geq$12.7 cm (5 in.) diameter at breast height (dbh) in each of the four compass quadrants radiating from our sampling point. At each point we measured the slope and took a GPS reading of the location. We measured the distance to each chosen tree using a hand-held laser rangefinder, identified the tree to species (using bark and stem characteristics if necessary) and measured the dbh, overall height and height of the live crown base (the latter two with the laser rangefinder). Crown base height was measured as the vertical distance from ground level to the lowest whorl with live branches in at least two of four quadrants around the stem (Helms, 1998); estimates of the prefire live crown base height were necessary where trees were severely burned. We also coded trees as "dead" or "alive": if green needles were seen on the tree, we pronounced it "alive", if needles were completely scorched (browned) or torched (consumed) we pronounced it "dead". All sampling was conducted many weeks after bud-break.

To gauge fire effects, in 2007 we measured a number of standard fire severity metrics for each sampled tree (see Agee, 1993). We used a laser rangefinder to measure bole char height (height of surface flame effects on the main tree trunk), scorch height, and torch (consumption) height. We also estimated percent crown scorch and percent crown torch, by making an ocular determination of the percentage of the tree canopy that had been consumed and browned (scorch percentage), or just consumed (torch percentage). Torch percentage is thus a component of scorch percentage.

Where char height, scorch height, or torch height were above the tops of trees, we used the nearest examples of measurable heights to estimate local values (where other sampled trees at the location had measurements, we used these as a guide). Where no nearby trees could be found to provide a local estimate, we added two meters to tree height for scorch height and one meter for torch height; in these cases our estimates of true scorch height and torch height are conservative.

In severely burned areas, bole char height runs up into crown torching and can be difficult or impossible to distinguish. In such cases we did not measure a char height, unless it could be estimated from a nearby tree. Many of our severely burned sampling points (i.e. where char height was very high) are therefore missing char height data (see Table 2). In our graphs, we portray char height in these instances by using torch height. These char height values were not used in our statistical analyses.

3.2. Field protocol—stand examination plots

In the summer of 2008 we established eighty-two 810 m^2 (1/5 acre) plots in and around the fire area at the vertices of a 400 m grid using the USFS common stand examination (CSE) protocol (USDA, 2008). These plots are primarily intended to provide data for long-term monitoring of vegetation regeneration, tree mortality and fuel loading. In this study we used a subset of 37 of these plots to estimate pre- and postfire stand basal area (based on a variable radius plot, using a Basal Area Factor of 20), stem density (all trees $\geq$ 2.5 cm dbh), and surface fuel loading (from four 20 m Brown's transects sampled at right angles emanating from the plot center; Brown, 1974). At each plot we measured fire severity using a scale from 0 to 5, where 0 = unburned, 3 = moderate/mixed severity, and 5 = $\pm$complete overstory mortality. The analyzed subset included 13 burned plots from treated areas (from 17 total; three were removed because they occurred in Unit 20, one occurred in a riparian area) and 24 burned plots from neighboring untreated areas found within 800 m of the treated areas (from 26 total; two plots were removed because they occurred in riparian areas). We also sampled 10 control plots outside the fire area in untreated forest. In order to augment our basal area and fuel loading data, where available we employed prefire CSE data collected in 2006 by the LTBMU vegetation management staff (see Tables 1 and 2).

3.3. Data analysis

We estimated prefire stand-level tree densities and basal areas from our CSE plot data. Except in two cases (where we did not have data from nearby CSE plots; see Table 2), we do not report stand-level densities or basal areas from the transects, as the point-center quarter method is subject to bias where tree spatial distributions are not random, and many of our transect sample sizes are relatively low for density or basal area calculations (Engeman et al., 1994). We also generated size class distributions for tree species in the fire area by pooling all trees sampled along the transects with trees sampled in the CSE plots (we omitted smaller trees from the CSE plots in this analysis in order to standardize the lower dbh cutoff at 12.7 cm).

For all data, we tested for normality using the Kolmogorov–Smirnov Test and *Q*–*Q* plots. Where possible, we used data transformations to induce normal distributions so as to allow parametric statistical tests, otherwise we used standard nonparametric tests. All statistical tests were carried out in SAS 9.1 (SAS, 2003).

For our transect-based analyses, the sampling unit was the sampling point, which consisted of the averaged measurements from four subsampled trees. We used statistical tests and graphics to compare pooled treated and untreated points as well as treated versus untreated portions of each transect. Although they were not physically contiguous, for some analyses we grouped transects 1 and 2 and used them as a treated–untreated pair. In order to compare postfire survival among transects and species, we also pooled all sampled trees and statistically compared treated and untreated populations. We used Spearman rank correlation to investigate the relationship between the fire severity measures, slope, and mature tree ($\geq$12.7 cm dbh) density, measured as the inverse of the mean distance between the sampled trees and the sample point (this analysis was conducted under the understanding that mean distance to mature trees is a [very] imperfect surrogate for measures of prefire fuels or stem density, which we did not have on our transects).

For our CSE plots, we computed means for the variables of interest (tree density, basal area, fire severity) and tested for differences between treated and untreated plots using the Wilcoxon Two-Sample Test. We used one factor ANOVA to test for differences between stem density and basal area (log transformed) in our CSE data. We also used one factor ANOVA to test for differences between treated (including and excluding transects 5 and 6) and untreated points sampled on our transects in char height (square root transformed), scorch height, and percent crown scorch (arcsin-square root transformed); means comparisons were made with Bonferroni-corrected *t*-tests. Because percent crown torch could not be normalized, for this variable we used the nonparametric Wilcoxon Two-Sample Test for pairwise comparisons between treated and untreated points. We used Spearman rank correlation to investigate the relationships between fire severity, slope (%), and prefire stem density.

We used logistic regression to determine which fire severity measures and tree size variables were the best predictors of Jeffrey pine survival. We carried out both univariate and multivariate analysis, in the latter case choosing the best model from all possible subsets. We did not carry out logistic regressions for the other tree species because of low sample sizes (in the case of white fir, too few survivors). We compared predictor variables using the Wald χ^2 statistic.

As a final note, we would like to acknowledge that there is a school of statistical thought that considers the analysis of phenomena within single disturbance events as a type of pseudoreplication (Hurlbert, 1984; Van Mantgem et al., 2001). At its strictest, this viewpoint suggests we should void the results of hundreds of valuable studies conducted in areas affected by fire, flood, hurricane, and earthquake. Although we recognize the possible existence of pseudoreplication in this study and others like it, we suggest (1) that large disturbance events that occur over many days, under changing weather conditions, and across diverse physical and biotic landscapes are fundamentally impossible to replicate, and (2) they are worthwhile research objectives whether they can be replicated or not. As always, the reader should take caution against too liberally generalizing patterns observed in a single, unreplicated natural experiment to the world at large.

4. Results

4.1. Stand structure and fuels

Overall prefire stem densities (all size classes) were more than 3 times greater in the untreated stands than in the treated stands, but overall prefire basal area was only marginally higher in the untreated stands ($t = 1.756$, $P = 0.088$; Fig. 4). Before fire, treated areas were dominated by Jeffrey pine, untreated areas by white fir (Fig. 5A); based on other plots we have sampled near the study area, the unknown category of smaller trees in Fig. 5A is likely >75% white fir. The prefire stem ratio of Jeffrey pine to white fir (by far the two most common tree species) was about 2:1 (179:94) in treated stands and about 1:2 (245:510) in untreated stands (Fig. 5A). About 75% of trees in the untreated forest were <30 cm dbh versus about 30% of trees in the fuel treatments; 17% of trees sampled in the treatments were >60 cm dbh, versus 5% in untreated stands (Fig. 5B). For mature trees (≥12.7 cm dbh), average size was higher in the treated than in the untreated areas for all species except sugar pine (Fig. 5C). Pooling all species, mean prefire dbh of mature trees was 44.4 cm in treated areas versus 38.4 cm in untreated areas, a difference of 16% ($t = 3.307$, df = 891, $P < 0.001$).

Stem densities and basal areas changed dramatically after fire in the untreated CSE plots. The mean density of living trees dropped from 882.2 to 64.8 stems/ha, and stand basal area was reduced from 51.2 to 7.6 m^2/ha (Fig. 4). The treated stands were much more resilient, losing less than 50% of their prefire stem density (286.8–157.6 stems/ha), and only 18% of their basal area (36.8–30.1 m^2/ha); neither change was statistically significant. The postfire stem ratio of living Jeffrey pine to white fir was approximately 6:1 (153 vs. 25) in treated stands, and about 0.8:1 (122 vs. 160) in untreated stands.

One-year postfire surface fuel loads (sum of 1–1000-h fuels) in the CSE plots did not differ between treated and untreated stands (7.0 tons/ha ± 6.6SD vs. 6.9 t/ha ± 7.0SD). Our unburned control plots supported an average of 26.5 t/ha (±11.5SD). If we average these data with the LTBMU prefire CSE plots from within the fire perimeter, we can estimate prefire surface fuel loading in the Angora Fire area as roughly 42 t/ha (±24.1SD). This is about 3.5 times the prefire loadings in the treated plots (11.8 t/ha ± 5.3SD).

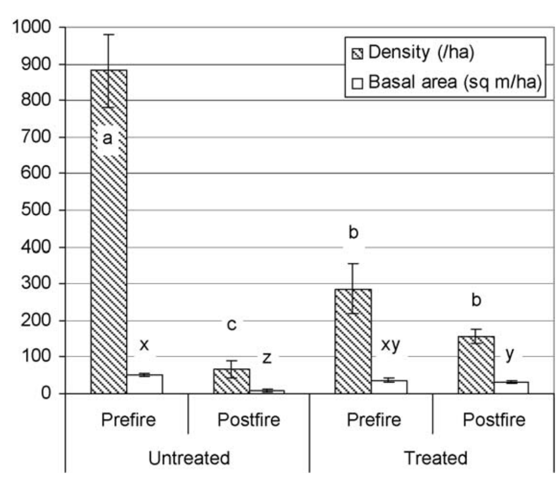

Fig. 4. Means for stem density and basal area in treated and untreated forest stands in the Angora Fire perimeter. Data from CSE plots sampled summer, 2007. Prefire data from complete stem inventory, postfire data from live stems after fire. Data with different letters are significantly different at $P \leq 0.05$ (Bonferroni-corrected t-tests; basal area log-transformed). Error bars in this and all other figures represent standard error.

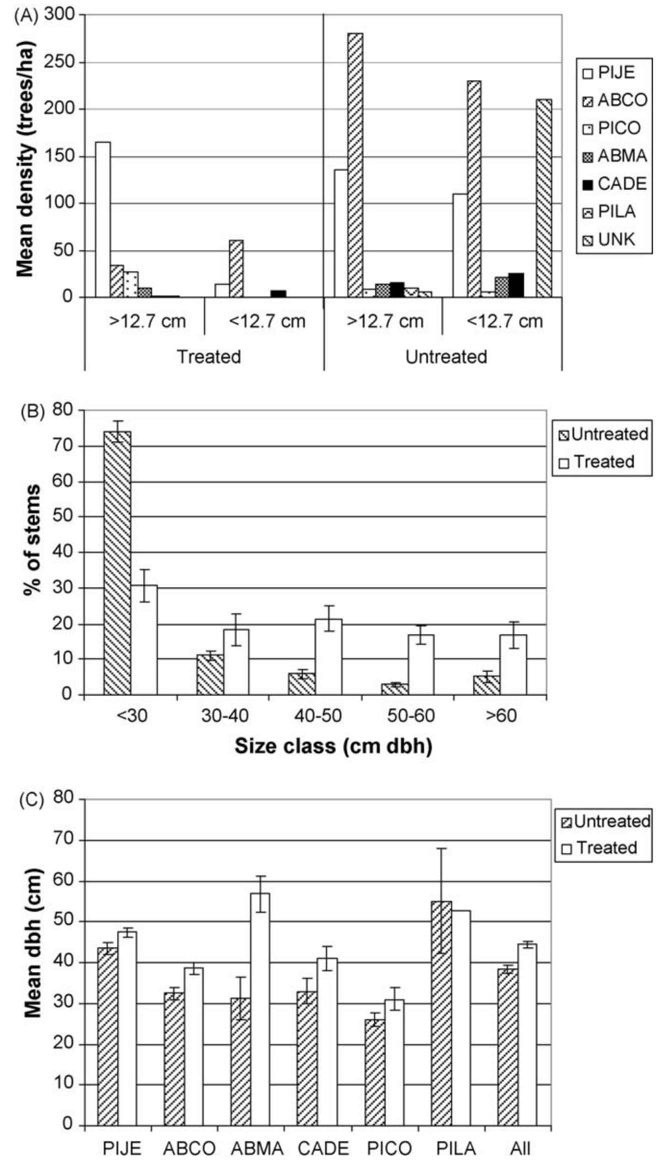

Fig. 5. Data on prefire forest structure from the CSE plots. (A) Mean density in treated versus untreated stands, blocked by young (<12.7 cm dbh) and mature (≥12.7 cm dbh) trees. PIJE = Jeffrey pine, ABCO = white fir, PICO = lodgepole pine, ABMA = red fir, CADE = incense cedar, PILA = sugar pine, UNK = unknown (probably primarily white fir). (B) Average size-class distributions of stems in treated and untreated stands. (C) Mean dbh for mature (≥12.7 cm dbh) trees in treated and untreated stands, by species.

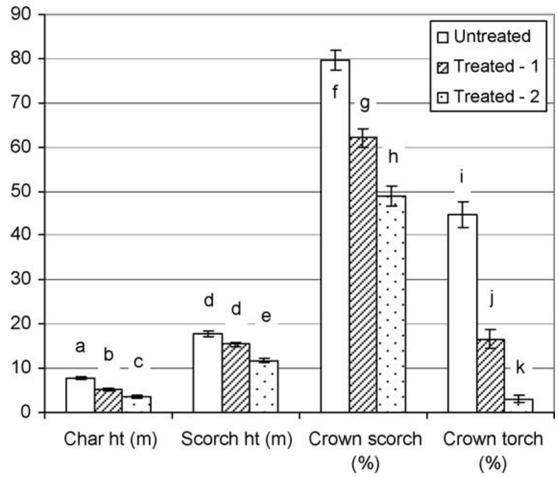

Fig. 6. Mean values for measures of fire severity in treated and untreated stands from the transects. Unit 20 (transects 8–10) excluded. Treated-1 = all treated transects; Treated-2 = transects 5 and 6 excluded. Data with different letters are significantly different at $P \leq 0.05$ (Bonferroni-corrected *t*-tests, except for crown torch, where Wilcoxon Two-Sample Test was used; bole char height square-root transformed, crown scorch and crown torch arcsin square-root transformed).

4.2. Fire severity

Fire severity was higher in untreated forest stands than in treated stands (Figs. 6 and 7). Our categorical summary estimates of overall fire severity in the CSE plots averaged about 2.5 (median 2.0; i.e. low to moderate severity) in treated forest, versus about 4.0 (median 5.0; i.e. high to very high severity) in untreated forest (Wilcoxon $Z = 2.944$, $P = 0.003$). On our transects, all of our measures of fire severity were significantly lower in treated than in untreated forest stands (Fig. 6), except for scorch height when transects 5 and 6 were included in the treated group. The largest differences between treated and untreated forest were in percent crown torch (Fig. 6) and torch height (not shown; untreated mean = 9.49 m ± 0.7SE, treatment group 1 mean = 4.34 m ± 0.5SE, treatment group 2 mean = 1.57 m ± 0.34SE; all $P < 0.01$, Wilcoxon Two-Sample Test; see the caption for Fig. 6 for definition of treatment groups 1 and 2).

In the CSE plots, our categorical measure of overall fire severity was strongly positively correlated with prefire stem density ($R = 0.665$, $P < 0.0001$), and moderately correlated with slope ($R = 0.381$, $P = 0.020$). On the transects, our measure of mature (≥12.7 cm dbh) tree density was positively correlated with all of the severity metrics (mean $R = 0.257$, all $P < 0.03$ [max = 0.292 for percent crown torch, min = 0.182 for scorch height]), as was slope (mean $R = 0.387$, all $P < 0.001$ [max = 0.457 for percent crown scorch, min = 0.317 for torch height]). However, when we blocked the analysis by treated and untreated stands, we found that in the untreated stands only mature tree density was significantly correlated with the severity metrics (mean $R = 0.308$, all $P < 0.04$), and in the treated stands only slope was significantly correlated with severity (mean $R = 0.618$, all $P < 0.0001$).

Fig. 7. (A) Untreated forest stand immediately after fire, just outside treatment Unit 21; mortality in this area was 100%. (B) Treated forest stand inside Unit 21, 250 m east of the previous photo, immediately after fire; mortality in this area was about 10%. Both photos taken July 2007.

4.3. Tree mortality

One-year postfire survival of trees ≥ 12.7 cm dbh in the CSE plots was 85.3% (±0.16SE) in treated stands versus 22.1% (±0.36 SE) in untreated stands. When all size classes are included, the CSE plot survival rates drop to 73.2 and 18.2%, respectively. In both cases the differences between treated and untreated stands were highly significant (Wilcoxon $Z = 4.143$ and 3.952, respectively, $P < 0.0001$). Trees < 12.7 cm dbh suffered high mortality in both treated (23.6% survival) and untreated stands (11.1% survival), but due to high variability between plots, differences were not statistically significant.

Along the transects, tree mortality was generally very different between adjacent treated and untreated stands (Fig. 8), with the exception of fuels treatment Unit 20 (transects 8–10; Fig. 2; Table 2), where fuel piles were not burned before the fire occurred. No trees survived in the untreated stands sampled on transects 4, 7 or 9, or in the treated areas sampled on transects 9 or 10 (Fig. 8A). Mortality was nearly 100% in the area of Unit 20 (transects 9 and 10), whether the area had been treated or not: only one sampled tree was still alive in this area in 2008. Tree mortality differences between treated and untreated stands were less pronounced along transect 11, which sampled a stand that burned under less severe fire weather conditions than the other transects (Fig. 8A).

For those transects which sampled adjacent treated and untreated stands (i.e. averaging the values in Fig. 8A but excluding transects 9 and 10), 2008 survival in treated stands was 79% versus 23.6% in untreated stands (and 74.8% vs. 10.5% if only the transects burned under severe fire weather are included, i.e. excluding transect 11). Except for transect 11 (and those transects which had 100% mortality to begin with), all sampled stands showed additional mortality between 2007 and 2008 (Fig. 8A). During the year following the fire, overall survival rates decreased by similar rates in treated (2007: 85%; 2008: 79%) and untreated (2007: 28%; 2008: 23.6%) areas. A total of eleven sampled trees (1.8% of the total sample) coded in 2007 as "dead" were "alive" in 2008 (i.e. they had 100% scorch but experienced some needle flush in the ensuing year). Five of these were Jeffrey pine, four were incense cedar; the other two were white fir and lodgepole pine. Aside from the lodgepole pine individual, all of these trees were

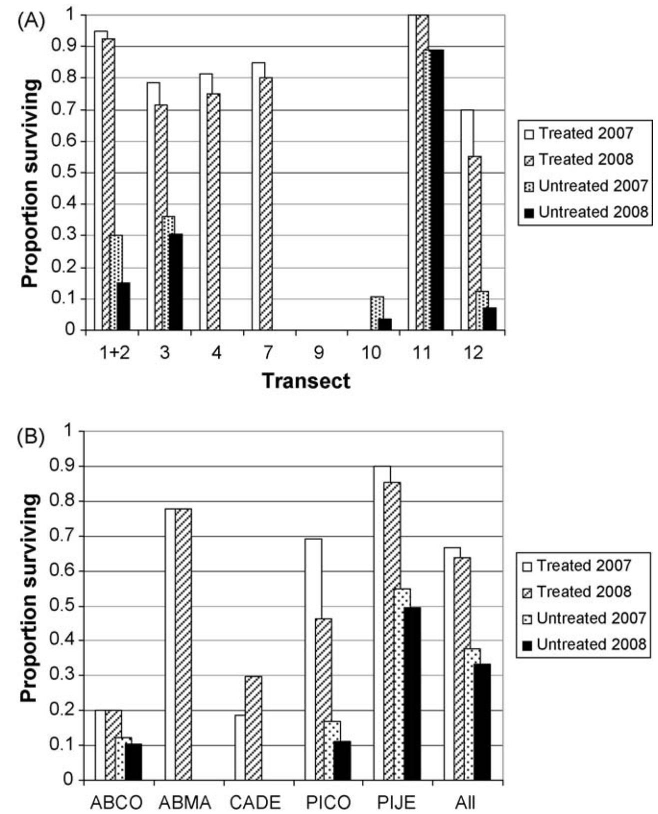

Fig. 8. (A) Proportion of sampled trees surviving immediately after fire (2007) and one year after fire (2008) along transects which sampled both treated and untreated stands (i.e. excluding transects 5, 6, and 8). (B) Proportion of sampled trees surviving immediately after fire (2007) and one year after fire (2008) in treated and untreated stands, by species. These data include transects 5 and 6 but exclude transects in Unit 20. Species codes as in Fig. 5.

larger than average (mean dbh = 52.8 cm ± 11.2SD), and seven of the eleven trees were in treated stands.

Mortality rates along transects were different between tree species, but all species survived at much higher rates in the treated areas. Fig. 8B gives species survival rates in treated versus untreated stands, excluding the treated areas in Unit 20. Transects in Unit 20 are also excluded from the following results. Overall, Jeffrey pine survived at the highest rates, in both treated and untreated stands—85% survived in treated areas in 2008 (dropping from 90% in 2007), about 50% in untreated stands (55% in 2007) (Fig. 8B). Few white fir survived fire, whether in treated (20%) or untreated (10%) stands (2007 values were 20% and 12%). Red fir survival was 78% in treated areas, but sample size was very small (12 total trees). In treated areas, 70% of sampled lodgepole pine maintained some green foliage immediately after the fire, but 34% of these had died by the summer of 2008 (Fig. 8B). Survival of lodgepole pine dropped from 17% (2007) to 11% (2008) in untreated areas. Of 27 incense-cedar sampled outside of Unit 20, only 8 were alive in 2008, and all of these were in treated stands; 3 of the 8 appeared dead in 2007 but had produced live foliage by the next year. In the CSE plots, one-year postfire survival of Jeffrey pine ≥ 12.7 cm dbh averaged 91% in treated stands versus 28.3% in untreated stands (Wilcoxon $Z = 4.052$, $P < 0.0001$); the values for white fir were 54.5% versus 8.7% ($Z = 2.415$, $P = 0.008$). With respect to trees < 12.7 cm dbh, one-year postfire survival of Jeffrey pine was higher than white fir (31.6% vs. 8.6%) but differences between treatments in percent survival were not significant.

The three best univariate predictors of Jeffrey pine survival one-year after fire were percent crown scorch, scorch height, and torch height (Wald $\chi^2 = 90.7$, 87.3 and 85.6, respectively, all $P < 0.0001$).

Table 3
Best model, logistic regression for mortality of *P. jeffreyi* in 2008. Whole model AIC = 136.9, % cases correctly predicted = 97.3.

Parameter	df	Estimate	Standard error	WALD chi-square	P
Intercept	1	−6.403	1.276	25.197	<0.0001
% crown scorch	1	0.078	0.012	40.273	<0.0001
Torch height	1	0.198	0.040	24.740	<0.0001
dbh	1	−0.047	0.017	7.373	0.007
Crown base height	1	0.155	0.065	5.764	0.016

The best-fit multivariate model for Jeffrey pine survival is given in Table 3. As expected, larger trees (measured by dbh) were more likely to survive fire, but crown base height showed a (weakly significant) inverse relationship with the probability of survival. This relationship was just as pronounced in the treated stands as in the untreated, so possible bias in overestimating crown base height due to higher fire severity in the latter does not appear to explain this result.

4.4. Variation in fire effects between treatment units

Transects 1–4 sampled fuels treatment Units 21, 22, 29 and 30 in the Tahoe Paradise area (Table 1 and Fig. 2). The ground in this area slopes very gently toward the northwest (Table 2). Average bole char height in the Tahoe Paradise area dropped from ±10 to <4 m within about 40 horizontal meters of the treatment boundary (Fig. 9A); overall mean char heights were <2.3 m in the treated stands. Fire effects to the forest canopy also changed dramatically as the treated areas were encountered (Fig. 9B). Overall, percent crown scorch averaged 92% in the untreated stands, versus 52% in the treated stands, and mean percent crown torch dropped from 59% to <3%. As with the fire severity metrics, mortality showed a strong effect of treatment. Total tree mortality in the Tahoe Paradise area in 2008 was 84% in the untreated stands and 19% in the treated stands, and spatial patterns of mortality showed a strong effect of "fire inertia", where survival increased as a function of linear distance from the treatment boundary (Fig. 9C). Note that the area of "high severity" fire mapped in the central and southwestern portions of the Tahoe Paradise area treatments (Fig. 2) is largely an artifact of shrub cover between the trees (Fig. 3) and does not correctly represent tree mortality, which is mostly low in this area.

Transects 5–7 sampled fuels treatment Units 16 and 17. Transects 5 and 6 provide insight into differences in fire behavior and fire severity between adjacent treated stands of markedly different slope steepness (Table 2). Unit 16 has average slopes of over 30%, which by LTBMU management guidelines prohibits the use of mechanized equipment to treat fuels. This means that trees and other fuel must be removed by hand, and hence density and basal area are higher in Unit 16 than in Unit 17 (Table 2), because hand treatment is restricted to trees <35 cm dbh due to issues of safety and logistics. Fig. 10A and B show how fire behavior and severity changed as slope and fuel loadings increased in Unit 16, upslope of Unit 17 (see Fig. 2; Unit 16 is northern of the two units). Ground slope decreases gradually from left to right in Fig. 10A and B. Char height in Units 16 and 17 was strongly influenced by slope (Fig. 10A; char height versus slope: $R = 0.619$, $P = 0.004$). Slope was also an important predictor of most of the other severity metrics in these treatment units (R ranging from 0.573 to 0.851, all $P < 0.01$; correlation with scorch height NS). At the same time, lower fuel loadings and the more open canopy in Unit 17 also influenced fire severity. This is evidenced by relatively abrupt changes in crown fire effects at the treatment boundary (Fig. 10B) and a strong positive correlation between percent crown scorch and mature tree density ($R = 0.605$, $P = 0.005$). All sampled trees died in Unit 16, while 54% of trees in Unit 17 were still alive in 2008 (Table 2).

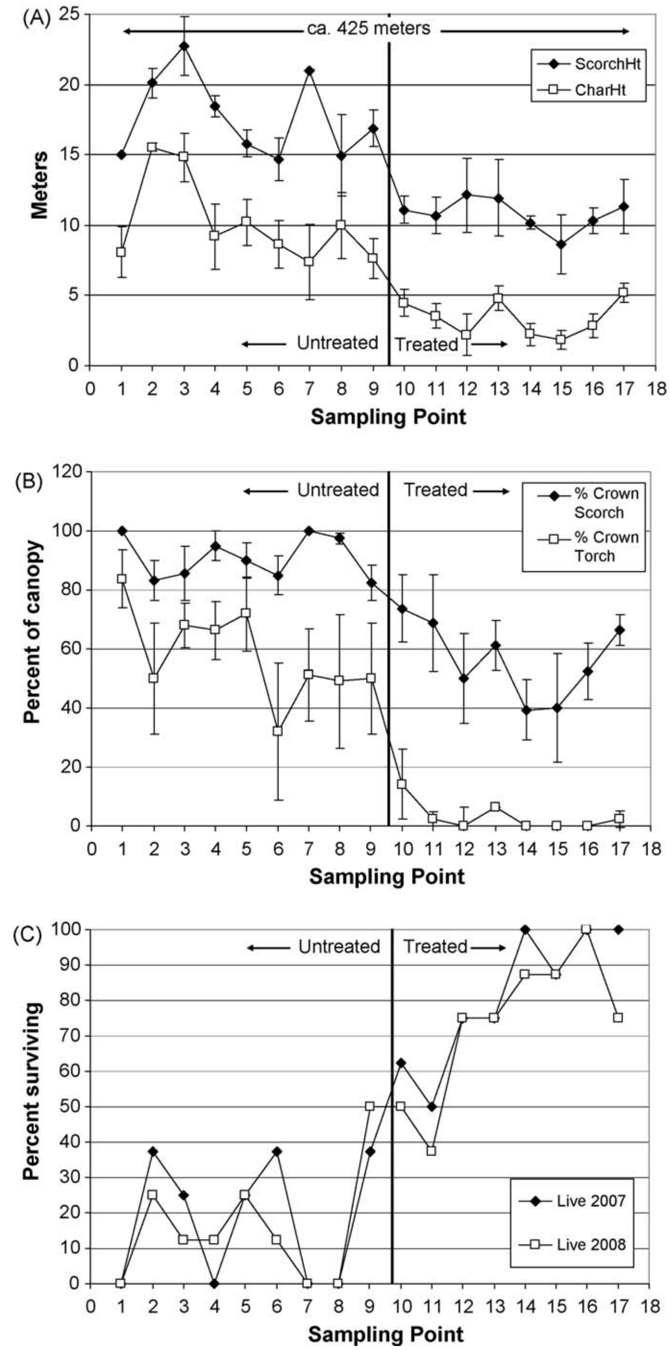

Fig. 9. Composite of fire severity measures and tree mortality at points sampled along transects 3 and 4 in the Tahoe Paradise Area. Points left of the vertical bar were untreated, points right of the bar were treated; average distance between points = 25 m. (A) Mean scorch height and bole char height. (B) Mean percent crown scorch and torch. (C) Percent of total trees sampled at each point that were alive in 2007 and 2008.

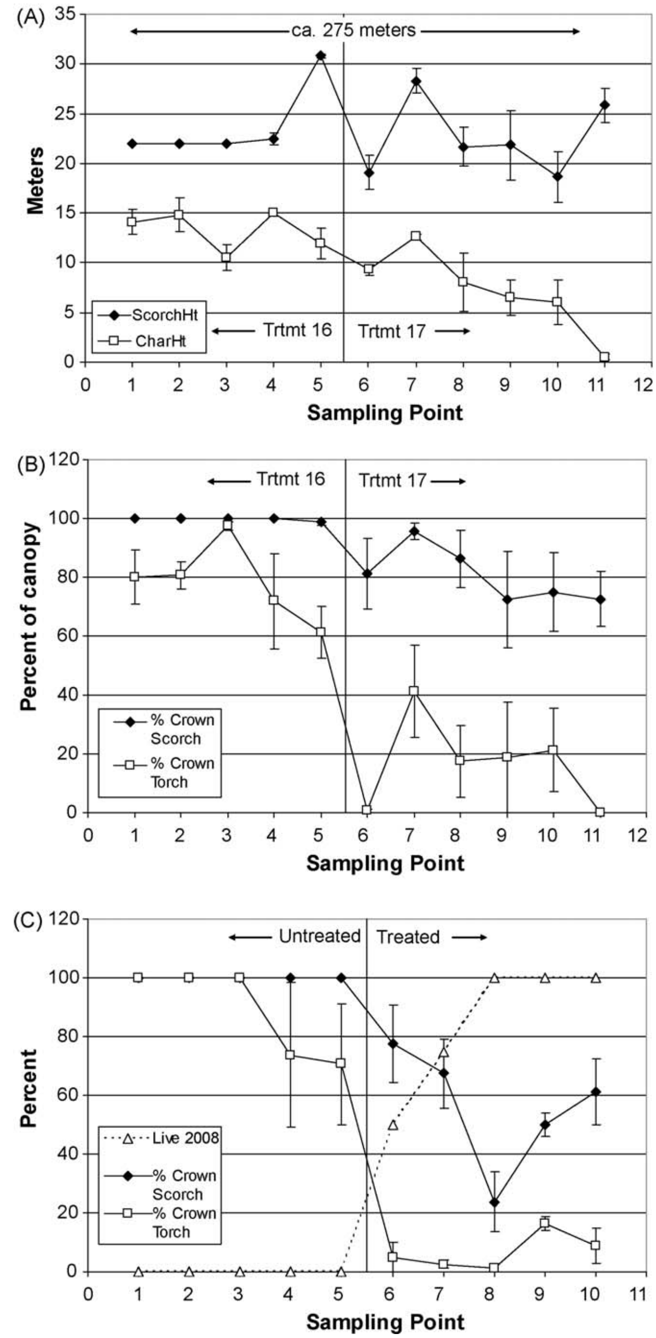

Fig. 10. The first two figures (A and B) are composites of fire severity measures sampled along transects 5 and 6. Points left of the vertical bar were in treatment Unit 16, points right of the bar in Unit 17; average distance between points = 25 m. Ground slope decreases gradually from left to right (mean = 35% at point 1, 28% at point 4, 12% at point 8, 10% at point 11). (A) Mean scorch height and bole char height; true scorch height at points 1–3 is probably much higher, as sampled trees were all < 21 m tall (see Section 3). (B) Mean percent crown scorch and torch. (C) Transect 7 (which sampled Unit 17 and neighboring untreated forest): mean percent crown scorch and torch and percent of total trees sampled at each point that were alive in 2008.

Transect 7 runs from Unit 17 into untreated stands southwest of the unit (i.e. counter to the direction of fire spread). Here, as in the Tahoe Paradise area, there is a very strong effect of the fuel treatment on fire severity, with severity and mortality decreasing with distance from the treatment boundary. Scorch heights drop from 30 to 35 m in the untreated stand to 15–17 m within 40 horizontal meters of the unit boundary; char heights drop from the tree tops to an average of about 5 m in the same distance (not shown). Percent crown scorch and torch also changed dramatically as fire entered the Unit 17 fuels treatment (Fig. 10C). High levels of crown scorching and torching outside of Unit 17 resulted in the deaths of every tree we measured, but most trees sampled within the treated area survived the fire (Fig. 10C).

The Unit 20 fuels treatment is found in the middle of the fire perimeter, in the area of highest fire severity. Like Unit 16, slopes in Unit 20 were too steep for mechanical treatment. The treatment in Unit 20 was designed to protect homes immediately to its east, but unlike the other treated stands in the area, burning of activity fuels piles had not yet been accomplished. Our measures of fire severity

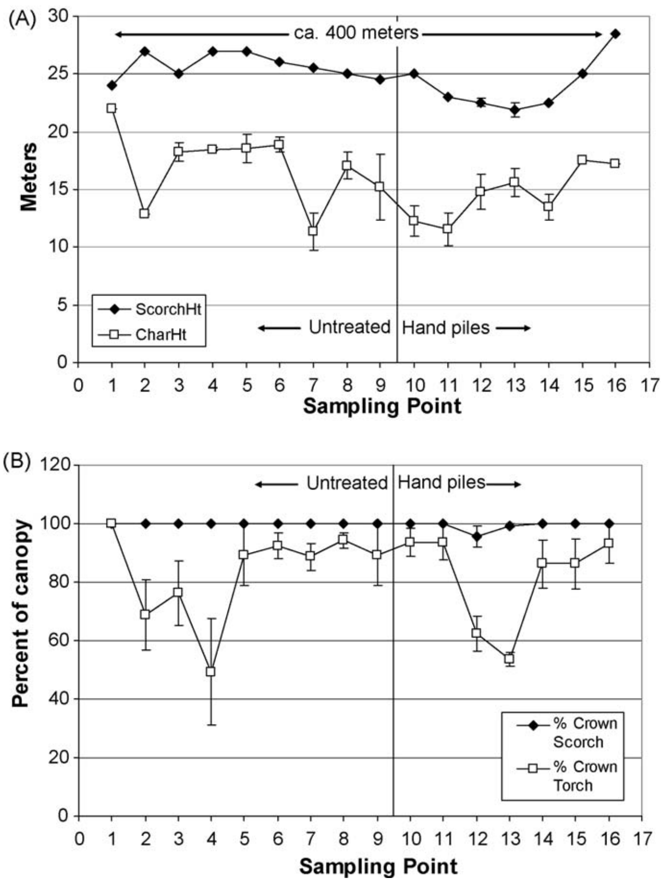

Fig. 11. Composite of fire severity measures at points sampled along transects 9 and 10 in the Unit 20 area. Points left of the vertical bar were untreated, points right of the bar were partially treated, with hand-piled fuels still on site; average distance between points = 25 m. (A) Mean scorch height and bole char height. (B) Mean percent crown scorch and torch.

do not reflect a treatment effect (Fig. 11). Char height and scorch height along transects 9 and 10 are given in Fig. 11A, percent crown scorch and torch in Fig. 11B. Crown scorching was essentially 100% along both transects, whether outside or within the treated stand. Of the 124 trees we sampled in this area, only one survived in 2008.

Transect 11 sampled an area that burned after winds had shifted direction and dropped markedly in velocity. Fuel treatment Unit 6 did not include a commercial thin (Table 1), but trees in this area are relatively low density and a number of wet swales cross the area. All of these factors led to much lower fire severity in general (Fig. 12A). Transect 11 was the only transect where we found live individuals from any species besides Jeffrey pine in an untreated stand. Points 8–10, 14–15, and 19–20 all occur in ephemeral creek bottoms, and the effects of the moist micro-environment can be seen in lower scorch heights (Fig. 12A). There was very high survival of trees along Transect 11, and there was no additional mortality between 2007 and 2008 (Table 2; Fig. 8).

Transect 12 sampled a southeast-facing slope about 1 km east of transect 5. Like transects 5 and 6, there is a change in slope at the boundary of the treated area, however there was no fuel treatment carried out above the slope break here. The treated area along transect 12 (fuels treatment Unit 12) burned more severely than any other area sampled outside of Unit 20: 45% of the trees sampled were dead by 2008, and scorch and char heights were not statistically different between the untreated and treated stands (Table 2). However, fire effects to the canopy were much less pronounced in the treated area (Fig. 12B). Prefire surface fuel loads were higher in this area than in any of the other Units where we were able to obtain data (Table 1).

5. Discussion

We quantitatively assessed the effects of fuel treatments on wildfire severity in an area of wildland–urban interface (WUI). Our results show that, in general, fuel treatments within and around the perimeter of the Angora Fire substantially changed fire behavior and subsequent fire effects to forest vegetation. Two exceptions were Units 16 and 20, where steep slopes led to a reduction in the amount of fuel removed from the treated stand, and – in Unit 20 – where fuel piles had not yet been burned when the fire occurred. Excepting these two units, bole char heights and fire effects to the forest canopy (measured by crown scorching and torching) were much lower, and tree survival much higher, within sampled treatments than outside them. The amelioration of fire behavior by these fuels treatments led to the ability of fire control personnel to safely engage in fire fighting efforts in the Tahoe Paradise area and to the east of Unit 17. Many homes were saved in these areas. It is worth noting that many (if not most) homes lost to fire in these and adjacent areas were not actually reached by the flaming front, but were ignited by falling embers cast ahead of the fire by strong winds. The lack of wildfire preparedness among homeowners – few people had reduced fuels on their property, and wooden decks, large woodpiles, and shake roofs were widespread in the burned neighborhoods – was a major factor in home loss (Murphy et al., 2007). Similar patterns in home loss and lack of preparedness were noted for the 2007 Grass Valley and Slide Fires in southern California, where wind-driven conifer fire destroyed hundreds of homes in spite of extensive forest fuel treatments on neighboring federal land (Rogers et al., 2008).

The Angora Fire was extraordinarily severe. Over 50% of the fire area burned at intensities high enough to kill all or most canopy trees, and another 21% burned at moderate severity, which averages about 50% canopy mortality. Thus, approximately three-fifths of the fire area lost most of its forest canopy. There is abundant evidence that forest fires in the Sierra Nevada are increasing in severity, and fires like the Angora Fire are no longer anomalies. Miller et al. (2009b) recently documented a strong increase in average forest fire severity across the Sierra dating back to at least the mid-1980's, when their dataset began. 2007 was an especially bad year, with about 60% of total wildfire area in the Sierra Nevada burning at high (stand-replacing) severity. According to Miller et al. (2009b), 2007 was the most severe fire year in the Sierra Nevada since the advent of Landsat satellite imagery in 1984. Losses of homes and lives to wildfire have been climbing across California since at least the 1950s (Hammer et al., 2007), but until recently the problem was squarely centered in the chaparral belt of southern California. In 2007 about 750 homes were lost to conifer wildfires in California, and many hundreds more in 2008 along with the lives of a number of civilians and firefighters. As climates continue to warm, as forest fuels continue to accumulate, and as housing developments continue to expand in conifer landscapes in California, these patterns seem unlikely to abate.

With respect to the effectiveness of fuel treatments in ameliorating fire behavior, the results of fire in Unit 20 corroborate numerous other empirical and modeling studies in finding that thinning the forest canopy without strongly reducing surface fuels does not increase tree survival, although it may decrease some measures of fire severity (e.g., Stephens, 1998; Martinson et al., 2003; Stephens and Moghaddas, 2005; Ritchie et al., 2007; Schmidt et al., 2008). In the case of Unit 20, the surface fuels were to be pile-burned within the year and the occurrence of a fire in June 2007 was unfortunate. In the case of Unit 12 (and Unit 8, which we did not sample), higher levels of surface fuels appear to have resulted in higher than average fire severity and mortality. On the other hand, the exceptional performance of the other treatments we studied (excepting Unit 16; see below) seems to justify the

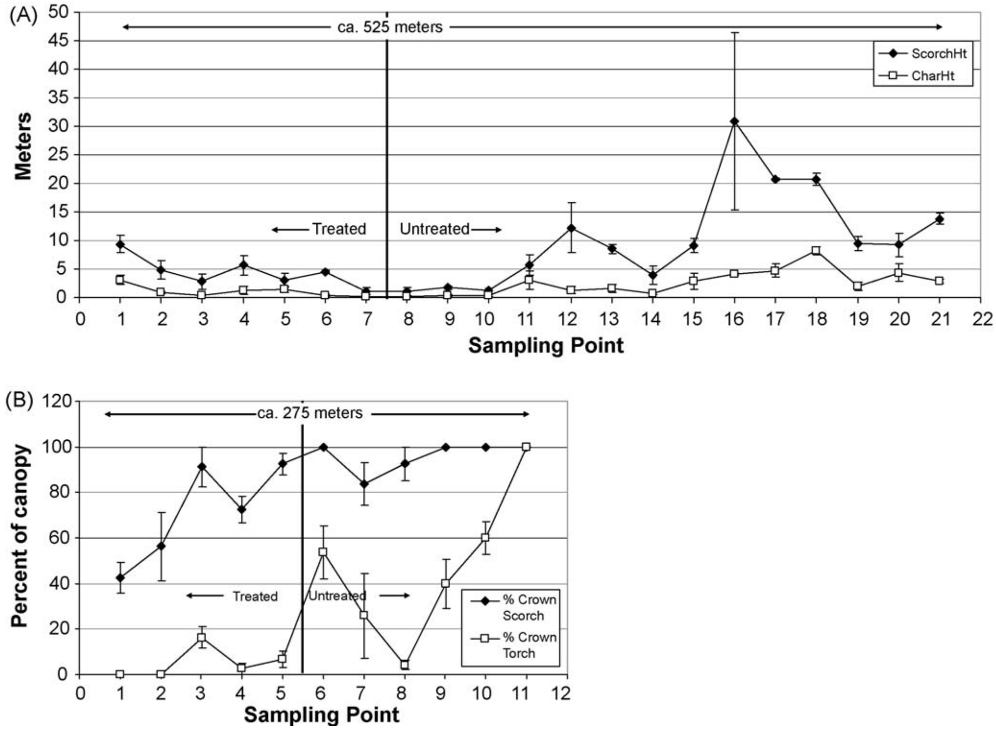

Fig. 12. Fire severity measures from points sampled along transects 11 and 12. Points left of the vertical bars were untreated, points right of the bar were treated. (A) Mean scorch height and bole char height from transect 11, which sampled treatment Unit 6 and neighboring untreated forest; average distance between points = 29 m. (B) Mean percent crown scorch and torch from transect 12, which sampled treatment Unit 12 and neighboring untreated forest; average distance between points = 25 m.

tremendous effort and expense of completing three separate entries over multiple years in one of the most strictly regulated watersheds in the United States. It should be reiterated that the Angora Fire fuel treatment network not only saved many homes, but it greatly increased forest resilience to wildfire as well. Other ecological benefits of reduced fire severity in the sampled treated areas included higher postfire soil litter cover, higher herbaceous plant cover and diversity, and lower levels of red turpentine beetle (*Dendroctonus valens*) attack. We report on these patterns in depth in a separate paper (Safford et al., in preparation).

Differences in fire severity between fuel treatment in Units 16 (>30% slope) and 17 (<30% slope) underline the importance of slope to fire behavior, but they also raise the question of how and to what extent fuels should be treated in areas of steep slopes. Steep, windward slopes cause wind acceleration (Rothermel, 1983), and facilitate preheating of fuels due to convection and, in the case of a south-facing slope, more direct insolation (Agee, 1993). Thus, all other things being equal, fire behavior on a south-facing slope will be more extreme than on adjacent flat ground. Based on this relationship, reduction of fire severity to a common level will require more fuel removal from a slope than from flat ground. Lake Tahoe land management is driven largely by water quality and clarity standards, and current code prohibits mechanical treatment of fuels on >30% slopes (TRPA, 2004). Under current practice, fuel reduction on sloping ground is thus necessarily of a lesser order than on neighboring flat ground. Our data indicate that fire behavior differences between Units 16 and 17 were influenced not only by slope, but also by canopy density differences due to fuel treatment differences in the two units. Burns et al. (2008) used fire modeling software to show that stand densities in Unit 16 at the time of the fire were sufficiently low to prevent movement of a surface fire into the forest canopy, but not sufficiently low to reduce a crown fire to a surface fire. The Angora Fire entered Unit 16 as a wind-driven crown fire and continued as a crown fire through the Unit, resulting in high fire severity and complete stand mortality. At exactly the same time, the crown fire was reduced to a surface fire in the adjacent Unit 17, which – unlike Unit 16 – had been commercially thinned. The results of the Angora Fire should stimulate discussion in the Lake Tahoe Basin and other places like it, where water quality issues severely restrict the ability of land managers to reduce fuels on steep slopes. The development and deployment of novel practices or technologies may be necessary to adequately moderate fire behavior in areas requiring fuel treatment on steep slopes. Given that soil stability and coverage are important on steep slopes in sensitive watersheds, it may also be necessary to strongly regulate or prohibit home construction atop such slopes, or to make it clear to homeowners and their insurance providers that they are inhabiting extremely hazardous terrain.

Patterns in our data suggest that fuel loadings in the Angora Fire were generally more important than topography in driving fire severity. Correlations between prefire stem densities (i.e. live fuels) and severity in our CSE plot data were much stronger than between severity and slope. In addition, on our transects, mature tree density was correlated with severity in untreated stands but slope was not, while the reverse was the case in treated stands. Mean slope and slope variability were not different between treated and untreated stands (14.6% $\pm$ 11.3SD vs. 15.4% $\pm$ 13.8SD). Taken together, we believe these patterns suggest that (1) fuel levels in the untreated stands were high enough in many places to swamp slope effects, and (2) the importance of slope in explaining severity in the treated stands is largely the result of high levels of prefire fuel reduction.

In order to decisively moderate fire behavior, fuels treatments must not only be of sufficient intensity, they must also be of sufficient size (Weatherspoon and Skinner, 1996; Graham et al., 2004; Agee and Skinner, 2005). Our data show that fire behavior in the Angora Fire was usually substantially moderated within 25–40 m of encountering a treatment boundary. Along transects 3, 4, 7 and 12, canopy fire became surface fire within this distance, and tree mortality dropped to nearly zero. In addition, major decreases in crown torching and tree mortality occurred within perhaps 50 m of the Unit 16–17 boundary. Under the weather and fuel conditions which characterized the Angora Fire, it might thus be generalized that 50 m is sufficient space to definitively reduce a crown fire to a surface fire, as long as surface fuels have been explicitly reduced. SNFPA guidelines call for the WUI-defense zone to have a minimum width of 400 m (1/4 mile) where it is demarcated (USDA, 2004). Under the most severe weather conditions, forest fires have been measured to move at up to 3 km/h, not including long-distance spotting. Given a 10-min emergency response time, a fire starting near the WUI-defense zone (a highly likely scenario and precisely what happened in the Angora Fire) could theoretically move 500 m into a treatment by the time engines arrived. With issues of access and egress, fire fighter safety (Butler and Cohen, 2004), visibility needs, space requirements for movement of machinery and fire crews, and other general requisites, 400–500 m is probably an absolute minimum for fuel treatment width in the WUI-defense zone (see also van Wagtendonk, 1996; Weatherspoon and Skinner, 1996). In places with extenuating topographic or road-system circumstances (e.g., canyons with funneling winds, locations with only one access road), widths may have to be much greater.

The SNFPA sets both broad goals and specific standards for WUI fuel treatments. WUI-defense zone treatments should be "of sufficient extent ... (to) reduce wildland fire spread and intensity sufficiently for suppression forces to succeed in protecting human life and property" (USDA, 2004, p. 130). More specifically, the SNFPA mandates that forest stands in the defense zone should be "fairly open" and dominated by larger, fire tolerant trees, typified by surface and ladder fuel conditions that lead to very low probabilities of crown fire ignition, and characterized by open and discontinuous canopy fuels (both horizontally and vertically) that result in a very low probability of sustained crown fire (USDA, 2004). The SNFPA also contains a number of specific standards and guidelines that apply to all fuel treatments in the Sierra Nevada (USDA, 2004):

1. Live conifers over 30 in. (75 cm) dbh should be retained.
2. Shade intolerant pines and hardwoods should be promoted.
3. Under 90th percentile fire weather conditions,
   (a) flame lengths should average no more than 4 ft (1.2 m);
   (b) fire-caused mortality of dominant and codominant trees should be $\leq$20%;
   (c) probability of crown fire initiation should be $\leq$20%.

Aside from Units 16 and 20, the fuel treatments we evaluated generally met these criteria. Standards 1 and 2 were met before the fire by significant removals of smaller, primarily shade tolerant conifer species (especially white fir). With respect to Standard 3, we could not directly measure flame lengths, but firefighter eyewitness reports and photos suggest that flame lengths in most of the completed fuel treatments averaged 1–1.5 m (Murphy et al., 2007; S. Burns and B. Brady, personal communication). The SNFPA standard does not make clear how long after fire mortality should be measured, but immediately after fire we estimated mortality at approximately 14% averaged across the completed treatments (excluding Units 16 and 20). Mortality one year after fire ranged from 15 to 20%, depending on the dataset (CSE vs. transect). Obviously there was some variability among the transects (Table 2; Fig. 7A). For example, transect 12 in treatment Unit 12 showed markedly higher mortality than the other completed treatments. Prefire surface fuel loads in this unit appear to have been higher than in the other completed treatments. Concerning the final standard, we know of very few instances where crown fire was reinitiated from surface fire within the completed treatments, and certainly much fewer than 20% of the trees suffered major amounts of crown torching in the completed treatments.

6. Conclusions

In summary:

1. Unlike most previous studies of fuel treatment effectiveness, our study included replication and sampled immediately adjacent treated and untreated stands in order to control for variation in topography and weather; in addition, transect sampling allowed measurement of linear changes in the effects of fire as it left untreated forest and entered fuel treatments.
2. With a few exceptions, fuel treatments substantially moderated fire severity and reduced tree mortality during the Angora Fire, meeting SNFPA guidelines for desired fire effects under severe conditions.
3. Exceptions to the above were primarily on steep slopes, where fuel treatments were of lower intensity due to soil retention guidelines, and in treatment units where surface fuels had not been sufficiently reduced.
4. Steep (especially south- and west-facing) slopes require more fuel removal than flat ground to realize the same benefit in reduced fire severity; an informed debate should be had in the Lake Tahoe Basin (and other fire-prone places like it) regarding the short- and long-term costs and benefits of restricting fuel treatment intensity on steep ground.
5. In most cases, crown fire was reduced to surface fire within 50 m of the fuel treatment boundary; when combined with other considerations, we conclude that 400–500 m appear to be a reasonable minimum width for most WUI fuel treatments.
6. Many homes burned in the Angora Fire in spite of the fuel treatment network; government efforts to reduce fuels around urban areas and private lands do not absolve the public of the responsibility to reduce the flammability of their own property.

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