Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA

Susan J. Prichard, David L. Peterson, and Kyle Jacobson

Abstract: To address hazardous fuel accumulations, many fuel treatments are being implemented in dry forests, but there have been few opportunities to evaluate treatment efficacy in wildfires. We documented the effectiveness of thinning and prescribed burning in the 2006 Tripod Complex fires. Recent fuel treatments burned in the wildfires and offered an opportunity to evaluate if two treatments (thin only and thin and prescribed burn) mitigated fire severity. Fire severity was markedly different between the two treatments. Over 57% of trees survived in thin and prescribed burn (thinRx) units versus 19% in thin only (thin) and 14% in control units. Considering only large-diameter trees (>20 cm diameter at breast height), 73% survived in thinRx units versus 36% and 29% in thin and control units, respectively. Logistic regression modeling demonstrates significant reductions in the log-odds probability of tree death under both treatments with a much greater reduction in thinRx units. Other severity measures, including percent crown scorch and burn severity index, are significantly lower in thinRx units than in thin and control units. This study provides strong quantitative evidence that thinning alone does not reduce wildfire severity but that thinning followed by prescribed burning is effective at mitigating wildfire severity in dry western forests.

Résumé : Pour s'attaquer au danger que représente l'accumulation des combustibles, plusieurs traitements des combustibles ont été appliqués dans les forêts sèches, mais il y a eu peu d'occasions d'évaluer l'efficacité de ces traitements lors d'incendies de forêt. Nous avons documenté l'efficacité de l'éclaircie et du brûlage dirigé dans le cas des incendies du Tripod Complex de 2006. Les aires où les combustibles avaient été traités récemment ont brûlé lors de ces incendies, ce qui a fournit l'occasion d'évaluer si deux traitements (une éclaircie seule ou combinée à un brûlage dirigé) ont diminué la sévérité du feu. La sévérité du feu a été très différente selon le traitement. Plus de 57 % des arbres ont survécu dans les aires traitées par une éclaircie suivie d'un brûlage dirigé (ECLBRUL) comparativement à 19 % dans les aires qui avaient seulement été éclaircies (ECL) et 14 % dans les aires témoins. En ne considérant que les arbres de gros diamètre (>20 cm de diamètre à hauteur de poitrine), 73 % des arbres ont survécu dans les aires ECLBRUL comparativement à respectivement 36 % et 29 % dans les aires ECL et témoins. Un modèle de régression logistique a mis en évidence une réduction significative de la probabilité de mortalité des arbres dans le cas des deux traitements, mais la réduction était beaucoup plus forte dans les aires ECLBRUL. D'autres mesures de sévérité du feu, dont le pourcentage de roussissement des cimes et l'indice de sévérité du feu, avaient des valeurs significativement plus faibles dans les aires ECLBRUL que dans les aires ECL et témoins. Cette étude démontre clairement de façon quantitative que l'éclaircie appliquée seule ne réduit pas la sévérité des incendies de forêt, mais qu'une éclaircie suivie d'un brûlage dirigé est une mesure efficace pour diminuer la sévérité d'un incendie de forêt dans les forêts sèches de l'Ouest américain.

[Traduit par la Rédaction]

Introduction

With a legacy of fire suppression and exclusion, millions of hectares of dry forests in western North America have fuel accumulations that are considerably higher than prior to the 20th century (Covington 2003; Hessburg et al. 2005). Wildfire frequency and area burned have increased over the past 50 years, and this trend is expected to continue under global warming scenarios (Gillett et al. 2004; McKenzie et al. 2004; Westerling et al. 2006). A variety of fuel treatments are being applied to dry forests throughout the interior West (see Agee and Skinner 2005 and Peterson et al. 2005 for reviews). Because regular prescribed burning generally reduces surface fuels, it is one of the more promising approaches to fire hazard reduction (Agee and Skinner 2005; Finney et al. 2005; Johnson et al. 2007). However, prescribed burn windows generally are short due to potential smoke impacts and fire hazard (Riebau and Fox 2001; Stephens and Ruth 2005). In most western forests, the area treated with fire remains low compared with the millions of hectares that might benefit from treatment (Stephens and Ruth 2005). Surrogate treatments involving forest thinning

Received 8 January 2010. Accepted 5 May 2010. Published on the NRC Research Press Web site at cjfr.nrc.ca on 24 July 2010.

S.J. Prichard.[1] College of Forest Resources, University of Washington, Box 352100, Seattle, WA, 98195, USA.
D.L. Peterson. US Forest Service, Pacific Northwest Research Station, 400 N. 34th Street, Suite 201, Seattle, WA 98103, USA.
K. Jacobson. US Forest Service, Lake Tahoe Basin Management Unit, 35 College Drive, South Lake Tahoe, CA 96150, USA.

[1]Corresponding author (e-mail: sprich@u.washington.edu).

and biomass removal are being implemented in many dry forests (Graham et al. 1999; Peterson et al. 2005).

A central principle underlying most fuel reduction programs is that they will mitigate the occurrence of high-severity fire events in areas with historic high-frequency, low- and mixed-severity fire regimes (Agee and Skinner 2005). Although many fuel treatment programs are being implemented, there have been few opportunities to quantitatively evaluate treatment efficacy in wildfires. Existing studies generally agree that mechanical thinning followed by prescribed burning is the most effective at mitigating wildfire severity (Finney et al. 2005; Ritchie et al. 2007). The effectiveness of fuel reduction programs, particularly that of prescribed burning, is also supported by fire behavior and effects modeling (Stephens and Moghaddas 2005; Johnson et al. 2007). Better representation of forest types and climatic regimes is needed to assist managers in planning and prioritizing fuel treatments. More definitive evidence and guidelines on the relative effectiveness of different types of fuel treatments are also needed to provide the scientific basis for fuel treatment planning in the West.

We conducted an opportunistic study to determine the relative success of recent fuel treatments in mitigating wildland fire severity, as represented by tree mortality and damage (i.e., bole char and crown scorch). The 2006 Tripod complex fires burned over 70 000 ha of mixed conifer forests and involved numerous fuel treatments, including units that had been thinned and prescribed burned within 10 years prior to the wildfire event. Our main objective was to evaluate differences in wildfire severity in stands with thin treatments (thin), thin and prescribed burning treatments (thinRx), and no treatment (control) within the Tripod Complex fires.

Methods

Study area

Treatment units are located within the southwestern section of the Tripod Complex fires approximately 10 km north of Winthrop, Washington (Fig. 1). The study area is located in the Methow Valley Ranger District of the Okanogan–Wenatchee National Forest. Climate is characterized by cold winters and warm dry summers with a prolonged summer drought. Mean annual temperature is 15.1 °C, ranging from –11.6 °C (January annual average minimum) to 30.1 °C (July annual average maximum) (Western Regional Climate Center, Winthrop, Washington, www.wrcc.dri.edu). Mean annual precipitation is 3600 mm with 70% of precipitation falling between October and March, predominantly as snow. Topography is highly dissected with steep slopes and numerous subdrainages (Barksdale 1975). Soils are generally coarse-textured Andisols with high gravel content (Natural Resources Conservation Service 2008).

Study units are located in low- to midelevation forests (Table 1). These forests are primarily composed of multi-aged stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), ponderosa pine (*Pinus ponderosa* P.&C. Lawson), and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.). Western larch (*Larix occidentalis* Nutt.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.)) are occasional stand associates. Understory plant assemblages are sparse in these dry forests. Common shrubs include antelope bitterbrush (*Purshia tridentata* (Pursh) DC) and snowbrush (*Ceanothus velutinus* Dougl. ex Hook.). Common herbaceous species include beardless bluebunch wheatgrass (*Agropyron spicatum* var. *inerme* (Scribn. & J.G. Sm.) Heller), pinegrass (*Calamagrostis rubescens* Buckl.), Idaho fescue (*Festuca idahoensis* Elmer), and raceme pussytoes (*Antennaria racemosa* Hook.) (Ohlson 1996).

Fires were historically common, with an estimated 2- to 18-year fire return interval between 1700 and 1900 from fire scar records at low elevations (Ohlson 1996). Over the past 50–100 years, fire intervals have lengthened due to fire exclusion, and forest assemblages have shifted from ponderosa pine dominance to higher densities of Douglas-fir (Lehmkuhl et al. 1993). Prior to the Tripod Complex fires, wildfires had not occurred throughout much of the study area in over 80 years.

The 2006 Tripod Complex fire was one of the largest fire events for Washington State in the past 50 years. It was preceded by hot dry weather and an ongoing mountain pine beetle (*Dendroctonus ponderosae* Hopkins, 1902) outbreak in mid- to high-elevation lodgepole pine forests. The fires initiated as two lightning strikes and converged under extreme fire weather conditions, spreading as a mixture of crown fires and variable-intensity surface fires. The fires initiated on 3 July and 23 July and were finally extinguished in early November from snow and rainfall events. Over 60% of the area burned was classified as moderate to high severity (US Forest Service 2008).

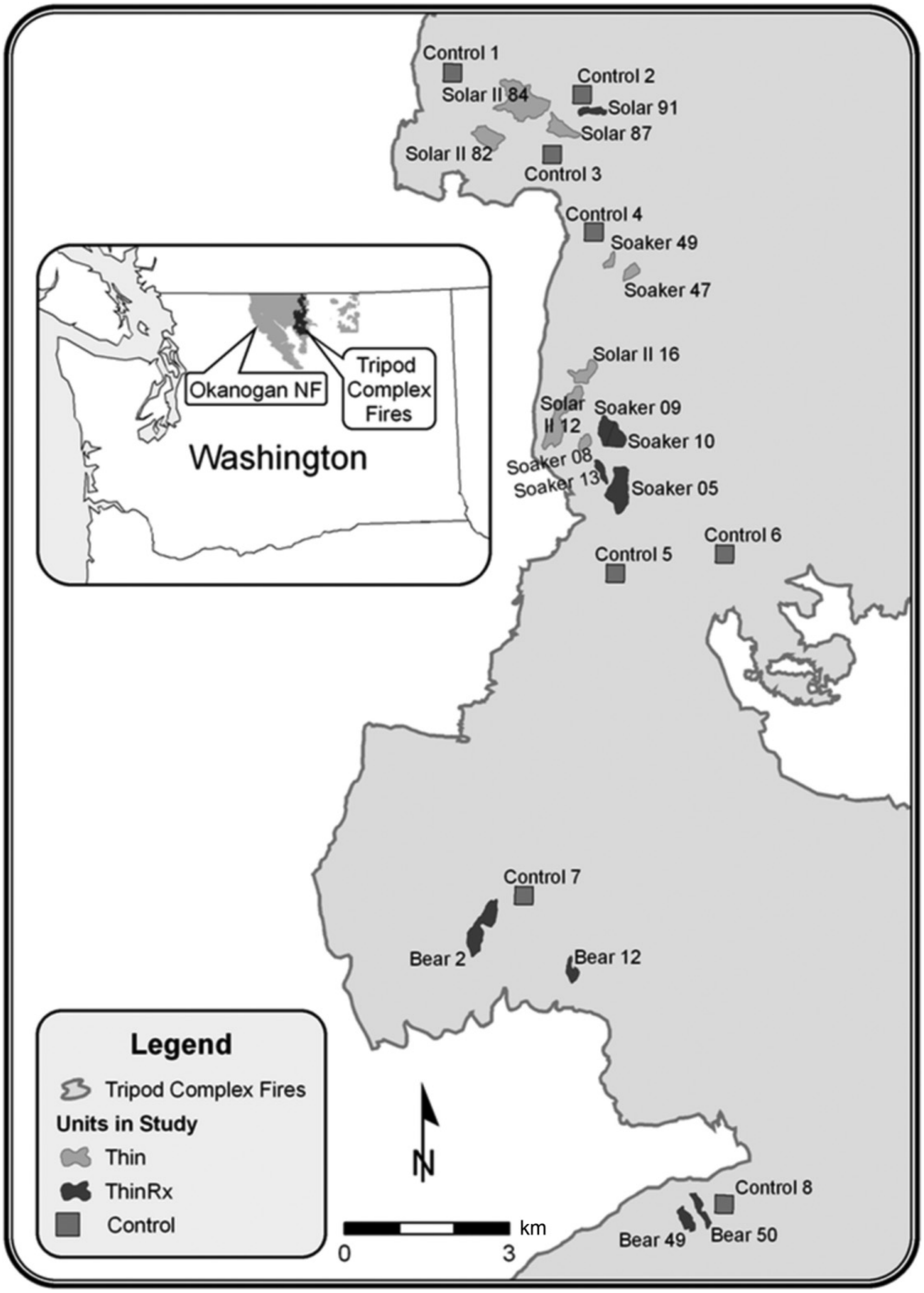
Sampling design and treatment description

Of the treatment units available for this study, several were excluded because they were located along the wildfire perimeter or were surrounded by unburned forest. We also limited treatment units to those that had been harvested or prescribed burned within the past 15 years. Units adjacent to known burnout operations were also excluded from the study, but with increasing distance from where burnouts initiated, it was unclear whether units burned as a result of the wildfire or fires ignited in burnout operations. For a balanced study design, sample size was constrained by the availability of thinRx units that met selection requirements. Eight thinned units and eight thinRx units were selected for this study (Table 1).

Eight control units with no record of harvesting or burning were randomly selected within the matrix of treatment units. Control unit selection was buffered 0.4 km from the Tripod perimeter and within 0.8 km of road access. A standard area of 8 ha was delineated for each control unit. A 2006 Burned Area Reflectance Classification image (Forest Service Remote Sensing Applications Center) was used to confirm that selected controls were not surrounded by unburned forest and were burned by the wildfire.

Mechanical thinning prescriptions included both thin-from-below harvests that targeted small-diameter and understory trees and shelterwood harvests that removed both understory and overstory trees. All timber harvests were completed 8–15 years prior to the wildfire event and were mostly whole-tree harvested by tractor. The four Solar II thin units were helicopter logged, and tree crowns were left

Fig. 1. Study area. Thin, recently thinned units; thinRx, recently thinned followed by prescribed burn units; control, unmanaged areas randomly selected throughout the burned area.



on site (Table 1). Recent (2006) burn plans are available for all Solar II units and estimated fuel loads include 9–13 Mg·ha^{-1} of fine fuels (<7.6 cm diameter), 9–22.4 Mg·ha^{-1} of large woody fuels (>7.6 cm diameter), 0.7–2 Mg·ha^{-1} of litter, and 9–13 Mg·ha^{-1} of duff. Burn plans (2005) also are available for three of the tractor-logged thin units (excluding Soaker 8) and include the following estimated fuel loads: 11–24 Mg·ha^{-1} of fine woody fuels, 22–54 Mg·ha^{-1} of large woody fuels, 5–7 Mg·ha^{-1} of litter, and 6–11 Mg·ha^{-1} of duff.

Prescribed burns were conducted on thinRx units between 0 and 6 years prior to the wildfire event. Hand lines were constructed around each unit, and units were hand- or helicopter-ignited. Burning took place either in the spring or in the fall, and all burns were recorded as successful, with full coverage and accomplishing fuel reduction objectives of reducing fine fuels by 90%–100% and large fuels by up to 70%.

An additional paired sampling design was used to evaluate differences in fire severity between treated units and adjacent untreated control stands that had similar topography and likely experienced similar fire weather at the time of the wildfire. Adjacent areas were excluded if they were upslope of the treated unit, across a major road or perennial

Table 1. Treatment unit names, area, estimated burn date(s), coordinates, aspect, slope gradient, and elevation.

Treatment	Unit(s)	Area (ha)	Estimated burn date(s)	UTM_E	UTM_N	Aspect (°)	Slope (%)	Elevation (m)
Control	C1	8.2	20 Aug.	712257	5397643	260	44	855
	C2	8.2	15 and 16 Aug.	714629	5397311	313	52	1409
	C3	8.2	18 and 19 Aug.	714114	5396203	323	45	1303
	C4	8.2	10 Aug.	714915	5394812	228	30	1731
	C5	8.2	20 Aug.	715484	5388596	157	31	1150
	C6	8.2	17 and 18 Aug.	717466	5389005	53	54	1266
	C7	8.2	10 Aug.	713983	5382667	97	21	1422
	C8	8.2	29 and 31 July	717795	5377142	236	36	1499
Thin	Soaker 8	4.9	16 Aug.	714860	5390967	177	46	1437
	Soaker 47	11.4	10 Aug.	715619	5394106	228	36	1747
	Soaker 49	3.3	10 Aug.	715227	5394285	162	27	1787
	Solar 87	12.2	18 Aug.	714260	5396683	210	31	1362
	Solar II 12	28.5	16 Aug.	714420	5391410	222	44	1399
	Solar II 16	11.0	14 Aug.	714821	5392234	257	31	1603
	Solar II 82	14.7	18 and 19 Aug.	712940	5396481	237	28	1165
	Solar II 84	41.9	16 and 17 Aug.	713540	5397157	237	23	1294
ThinRx	Bear 2	22.4	20 Aug.	713227	5382066	117	30	1430
	Bear 12	5.7	18 and 19 Aug.	714898	5381307	86	21	1495
	Bear 49	7.3	10 Aug.	717113	5376841	329	52	1450
	Bear 50	6.5	1 and 10 Aug.	717370	5377041	286	47	1437
	Soaker 5	8.1	16 Aug.	715509	5390125	134	27	1390
	Soaker 9 and 10	19.1	15 and 16 Aug.	715330	5391140	107	18	1432
	Soaker 13	4.5	16 Aug.	715175	5390460	226	26	1346
	Solar 91	5.3	16 Aug.	714816	5397017	211	26	1523
C_thin	Soaker 8 C	—	16 Aug.	714900	5390712	178	46	1394
	Soaker 47 C	—	10 Aug.	715546	5394260	219	33	1754
	Soaker 49 C	—	10 Aug.	715205	5394210	162	22	1768
	Solar 87 C	—	18 and 19 Aug.	714088	5396708	179	33	1313
	Solar II 82 C	—	18 and 19 Aug.	712844	5396575	239	35	1098
	Solar II 84 C	—	16 and 17 Aug.	713451	5431010	237	33	1247
C_thinRx	Bear 2 C	—	20 Aug.	713468	5381954	81	42	1377
	Bear 12 C	—	19 and 20 Aug.	714807	5381261	154	19	1501
	Bear 49 C	—	10 Aug.	717435	5377162	332	45	1428
	Bear 50 C	—	31 July, 1 Aug.	716919	5376747	296	52	1484
	Soaker 9 and 10 C	—	15 Aug.	715534	5391189	80	35	1385
	Soaker 13 C	—	16 Aug.	715115	5390397	234	46	1308

Note: Sampling area was not determined for adjacent controls. Control, control unit; Thin, thin units; ThinRx, thinned followed by prescribed burn units; C_thin, adjacent control to thin units; C_ThinRx, adjacent control to thin and prescribed burn units.

stream from the treatment, and (or) had distinctly different topography (i.e., >30% slope gradient and (or) >90° difference in aspect). Not all thin and thinRx units had suitable adjacent controls. A total of six thin and six thinRx units were paired with adjacent controls (Table 1).

Due to the geographic span of treatment units, sample plots burned over a range of days in late July and August. Approximate burn dates were estimated from a fire progression map and are listed in Table 1. Fire behavior between 29 July and 1 August was recorded as low with some localized fire spread and crown fire activity. Predicted maximum temperatures were 17–27 °C and minimum relative humidities were 20%–50% with midflame windspeeds of 3–6 $km \cdot h^{-1}$. Fire activity increased substantially on 10 August with extreme fire behavior noted in many areas. Predicted maximum temperatures were 18–23 °C and minimum relative humidity was 45%–55% with strong winds between 16 and 24 $km \cdot h^{-1}$ with gusts up to 40 $km \cdot h^{-1}$. Most of our study units burned between 15 and 20 August, and extreme fire behavior was noted during this period, including active crowning and rapid fire spread. Predicted maximum temperatures were 21–29 °C and minimum relative humidity was 14%–27%. Predicted midflame windspeeds were between 14 and 27 $km \cdot h^{-1}$. Fire danger ratings reached a 10-year high between 17 and 20 August.

Field sampling methods

Units were sampled with circular plots along systematic grids. We used a nested plot sampling design to accommodate variable tree densities. Treated units (e.g., thin and thinRx) were sampled using 0.2 ha plots. Control units were sampled using 0.08 ha plots to account for generally much higher tree densities in all size classes. In stands with tree densities <30 trees per plot irrespective of size class, all trees were tallied within the largest radius plot. In denser stands, smaller tree size classes were sampled in subplots: trees between 10 and 20 cm diameter at breast height (DBH) were sampled in 25.4 m radius subplots and trees <10 cm DBH were sampled in 5.1 m radius subplots. Trees with heights <1.4 m were not sampled. A minimum of 10% of each unit was surveyed.

Plots were marked with a permanent center stake and numbered metal tag. At each plot, we collected general plot information including site description, aspect, slope gradient, slope position (i.e., lower slope, midslope, upper slope, ridgetop), and site severity for the entire plot (US Department of the Interior National Park Service 2003). The following measurements were collected for each sampled tree: DBH (centimetres), crown base height (metres), height to live crown (metres), tree height (metres), maximum height of crown scorch (metres), minimum and maximum bole char (metres), percentage of the crown volume that was scorched, and tree severity index (US Department of the Interior National Park Service 2003). Tree burn severity classes were defined as follows: 1 = unburned, 2 = scorched foliage, 3 = lightly burned (some foliage and small twigs burned), 4 = moderately burned (foliage and small stems consumed), and 5 = severely burned (only charred stems remain). Recent downed trees that fell after the wildfire (e.g., logs with uncharred wood at severed stems) were tallied as trees. For consistency in observations, field personnel regularly compared and calibrated estimates of percent crown scorch, site severity index, and tree severity index.

Live trees were tagged at tree bases facing plot center for sampling of tree status in subsequent years. During the summers of 2008 and 2009, plots that had live trees in 2007 were revisited to record subsequent tree mortality. Plots with 100% mortality were marked in the center but were not revisited in subsequent years.

Data analysis

Individual stand variables and fire severity measures were summarized by unit (Table 2). To test for differences in tree mortality following wildfire between thin, thinRx, and controls, we conducted a one-factor ANOVA on measures of tree fire severity for thin units, thinRx units, and controls (Sall et al. 2007). Where ANOVA indicated statistical differences between treatments (including treatments and adjacent controls), pairwise comparisons were made using Tukey honestly significant differences tests. In cases where data were not normally distributed, equivalent nonparametric tests were used.

Because tree mortality data are binary (i.e., either live or dead), we used binomial generalized linear modeling to evaluate effectiveness of treatments on tree mortality (R programming language). A logistic model was constructed to predict the proportion of dead trees by treatment type ($p < 0.05$).

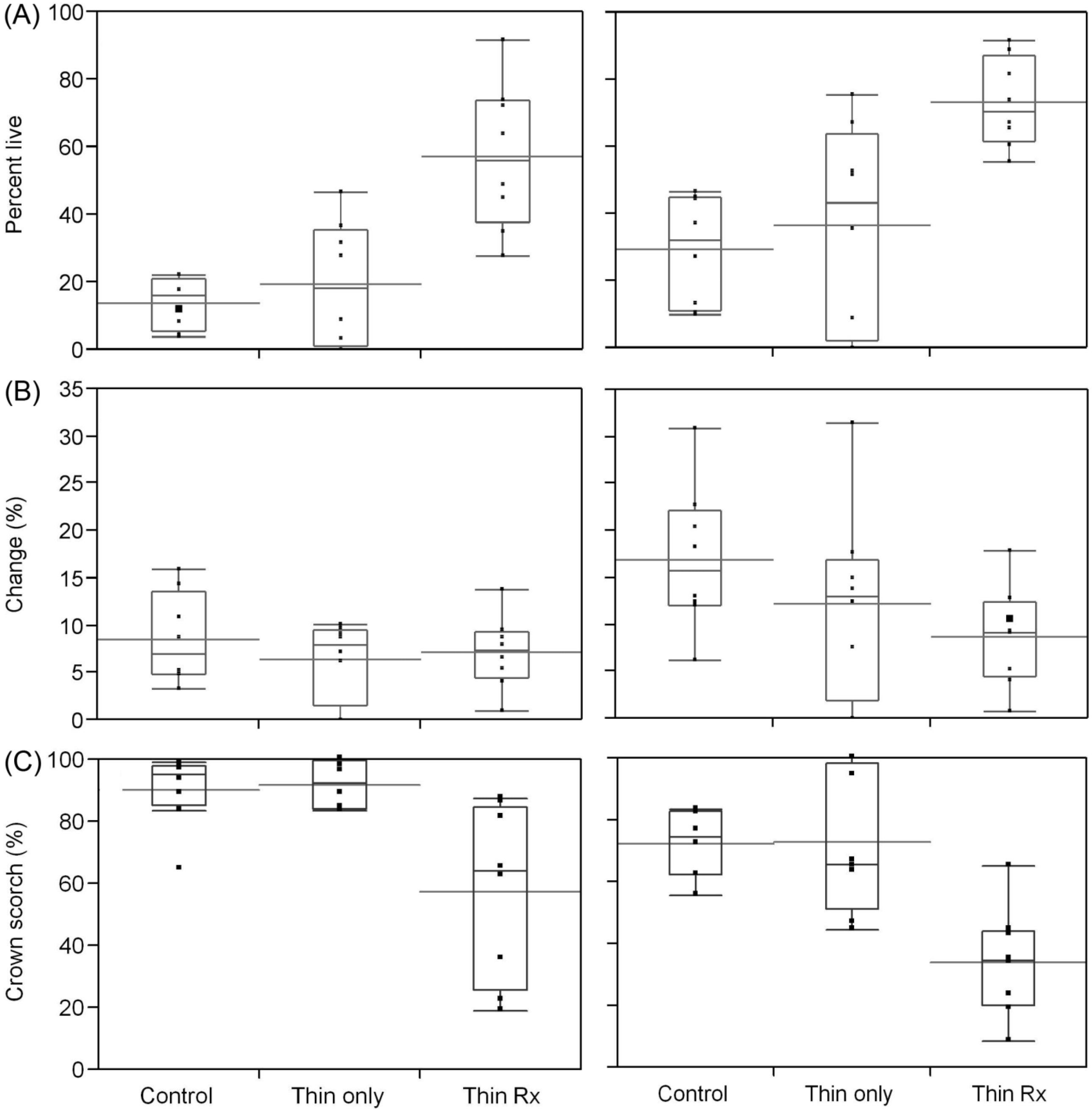
With greater crown heights and thicker bark, large-diameter trees have a better likelihood of survival than small trees (Agee 1993). Small trees were more numerous in thin and control units than in thinRx units. To remove this potential bias, we performed an additional set of analyses on trees >20 cm DBH.

Table 2. Mean and SD (in parentheses) of stand variables and fire severity measures.

	Stand variables					Fire severity measures				
	Diameter (cm)	Density (trees·ha^{-1})	Crown base height (m)	Height (m)	Height to live crown (m)	Crown scorch maximum height (m)	Minimum bole char (m)	Maximum bole char (m)	% crown scorch	Burn severity index (1–5)
All trees										
Control	11.8 (2.7)a	**1403 (463)a**	3.2 (1.1)	9.0 (1.8)	8.8 (2.4)a	8.4 (1.5)	2.2 (1.5)	3.7 (1.6)	90.1 (11.6)a	2.7 (0.3)a
Thin	16.7 (7.1)a	475 (360)b	3.3 (0.9)	10.6 (3.1)	8.1 (2.4)a	9.8 (3.2)	2.5 (2.1)	5.3 (3.2)	91.8 (7.4)a	2.8 (0.2)a
ThinRx	**22.1 (8.3)b**	172 (131)b	3.3 (1.5)	12.4 (4.0)	**5.9 (1.3)b**	7.3 (1.6)	0.9 (1.1)	2.4 (1.2)	**57.3 (28.0)b**	**2.3 (0.5)b**
Large-diameter trees (>20 cm DBH)										
Control	35.1 (5.9)	**166 (58a**	6.0 (1.5)	20.1 (2.3)	**10.3 (1.8)a**	17.3 (2.2)a	4.7 (2.9)a	8.0 (2.3)a	72.3 (10.9)a	2.4 (0.3)a
Thin	38.0 (4.4)	78 (18)b	5.4 (0.9)	18.6 (1.4)	7.4 (4.7)b	16.0 (2.5)a	4.1 (3.6)a	7.9 (3.9)a	72.6 (22.7)a	2.5 (0.4)a
ThinRx	37.3 (3.1)	53 (30)b	5.4 (2.5)	19.5 (2.0)	7.4 (1.7)b	**11.2 (3.2)b**	**0.7 (0.3)b**	**3.2 (1.1)b**	**34.0 (17.5)b**	**1.9 (0.3)b**

Note: Significant differences ($p < 0.05$, bold text) between control units, thin units, and thinned and prescribed burn units are indicated by different letters.

Fig. 2. (*a*) Percent live trees by treatment for all trees and large-diameter trees (>20 cm DBH), (*b*) percent change in mortality 1 and 2 years postfire, and (*c*) percent crown scorch by treatment for all trees and large-diameter trees. Box plots represent minimum, 25% quantile, median, 75% quantile, and maximum values from lower to upper. Horizontal lines represent the statistical mean of all units within each treatment.



Results

Stand characteristics vary by treatment type (Table 2). As expected, tree density is significantly lower in thinRx and thin units than in control units. Thin units tend to be denser than thinRx units, but this difference is not significant. Tree diameter is significantly higher in thinRx units than in thin and control units. There are no significant differences in tree height or height to crown base between treatments.

Most fire severity measures in thinRx units significantly differ from those in thin and control units. As of 2009, over 57% of all trees survived in thinRx units versus 19% in thin and 14% in control units (Fig. 2). Other tree severity measures, including percent crown scorch and burn severity index, are significantly lower in thinRx units than in thin and control units (Table 2). Mean percent crown scorch is over 90% in thin and control units compared with 57% in thinRx units. In contrast, there are no significant differences in fire severity measures between thin and control units.

Differences in tree severity are more evident when only large-diameter trees (>20 cm DBH) are considered. Over 73% of large-diameter trees survived in thinRx units versus 36% in thin and 29% in control units (Fig. 2). All measures of large-diameter tree severity in thinRx units are significantly different from those in thin and control units (Table 2). Maximum bole char is over 7.9 m in thin and control units versus 3.2 m in thinRx units. Percent crown scorch is 72% in thin and control units versus 34% in thinRx units. Considering only large trees, there still are no significant differences in fire severity measures between thin and control units.

The paired analysis of treated units versus adjacent controls resulted in similar findings (Table 3). Compared with adjacent controls, tree diameter is significantly higher in thinRx units. Tree density is significantly lower in both thin and thinRx units compared with adjacent controls. Considering all tree diameters, tree mortality and other measures of fire severity (i.e., minimum/maximum bole char, percent crown scorch, and burn severity) are significantly lower in thinRx units than in adjacent controls. There are no significant differences in fire severity measures between thin units and adjacent controls. When only large-diameter (>20 cm DBH) trees are considered, results are again very similar. Mean height and diameter of large trees are significantly higher in both thin and thinRx units than in adjacent controls. Although differences in fire severity measures are highly significant between thinRx and adjacent controls, there are no significant differences between thin units and adjacent controls.

Logistic regression models reveal significant reductions of the log-odds probability of tree death under both thin and thinRx treatments (Table 4). Both thin and thinRx treatments reduced the log-odds probably of tree mortality relative to adjacent controls, but thinRx treatments had much greater reductions than thin treatments (Table 4). Results are similar when only large-diameter trees are considered.

Tree mortality was surveyed for 3 years following the wildfire event. Following the initial survey in 2007, an additional 18% of trees died in 2008 and 7% of trees subsequently died in 2009. Percent change in tree mortality between 2007 and 2009 does not significantly differ by treatment (Fig. 2). Tree mortality markedly differs by species (Fig. 3) with the lowest mortality for western larch (21%) and ponderosa pine (39%) and highest mortality for lodgepole pine (91%) and Engelmann spruce (88%). Overall mortality for Douglas-fir is 66%.

Discussion

This study provides strong quantitative evidence that without treatment of surface fuels, thinning does not reduce tree mortality during a large wildfire. With lower tree densities and fewer understory trees than unmanaged controls, thin units likely were effective at reducing crown fire potential but not tree mortality. We did not observe evidence of crown fire in thin stands; in the first 2 years following the wildfire, red needles were retained on most dead trees (Fig. 4). In contrast, control units comprise a mixture of scorched patches of trees and areas where needle and branchwood in tree crowns were consumed by fire. High tree mortality in thin units likely was associated with cambial heating and crown scorch from intense surface fires. Maximum bole char and crown scorch height both were highest in thin units, suggesting long flame lengths and particularly high-intensity surface fires in those units.

Table 3. Mean differences and SE of the mean difference (in parentheses) between adjacent controls and treated units.

	Stand variables					Fire severity measures				
	Diameter (cm)	Density (trees·ha^{-1})	Crown base height (m)	Height (m)	Height to live crown (m)	Crown scorch maximum height (m)	Minimum bole char (m)	Maximum bole char (m)	% crown scorch	Burn severity index (1–5)
All trees										
Thin vs. control	4.496 (3.291)	**−430 (191)**	−0.031 (0.709)	2.024 (1.457)	0.917 (2.318)	1.776 (1.618)	−1.968 (2.051)	0.175 (2.078)	0.658 (6.126)	−0.142 (0.189)
ThinRx vs. control	8.755 (4.877)	**−774 (208)**	0.688 (1.111)	3.996 (2.419)	−2.083 (1.167)	−1.696 (1.779)	**−1.975 (0.579)**	**−2.004 (0.746)**	**−37.610 (12.241)**	**−0.462 (0.194)**
Large-diameter trees (>20 cm DBH)										
Thin vs. control	**5.166 (2.050)**	**−71.7 (12.8)**	0.295 (0.685)	0.894 (0.724)	1.044 (2.692)	0.454 (1.468)	−4.092 (3.092)	−2.524 (2.844)	−6.170 (12.505)	−0.205 (0.225)
ThinRx vs. control	**6.028 (1.844)**	**−115.6 (29.0)**	0.9296 (1.2858)	**2.814 (1.199)**	−1.4228 (0.9590)	**−4.5809 (1.9237)**	**−4.1761 (1.5230)**	**−4.2645 (1.4823)**	**−42.610 (7.785)**	**−0.5233 (0.1294)**

Note: Positive differences indicate that treated values are greater than controls. Significant differences ($p < 0.05$) are indicated by bold text.

Table 4. Mean percentage of live trees and SE and binary generalized linear regression models of tree mortality in 2009.

Treatment	Mean % live (SE)	Equation coefficient (SE)
Standard control, all trees		
Null variance reduction 30%		
Control (β_0)	13.91 (2.63)	1.8283 (0.0125)
Thin (β_1)	19.43 (6.52)	–0.5002 (0.0222)
ThinRx (β_2)	57.39 (7.70)	–1.7037 (0.0303)
Standard control, large trees		
Null variance reduction 41%		
Control (β_0)	29.24 (5.70)	0.9382 (0.0278)
Thin (β_1)	36.47 (10.68)	–0.6664 (0.0476)
ThinRx (β_2)	73.11 (4.69)	–1.8721 (0.0593)
Adjacent thin control, all trees		
Null variance reduction 3%		
Adjacent control (β_0)	17.08 (7.85)	1.6229 (0.0169)
Thin (β_1)	25.90 (6.76)	–0.4251 (0.0252)
Adjacent thin control, large trees		
Null variance reduction 13%		
Adjacent control (β_0)	27.63 (11.80)	0.9494 (0.0343)
Thin (β_1)	48.63 (9.73)	–0.9514 (0.0535)
Adjacent thinRx control, all trees		
Null variance reduction 20%		
Adjacent control (β_0)	29.44 (6.50)	1.2810 (0.0173)
ThinRx (β_2)	63.13 (9.10)	–1.4534 (0.0407)
Adjacent thinRx control, large trees		
Null variance reduction 56%		
Adjacent control (β_0)	40.02 (6.95)	0.5754 (0.0365)
ThinRx (β_2)	77.34 (5.01)	–1.7349 (0.0731)

Note: Regression models reflect the change in log odds of mortality relative to control units. The equation form is log-odds(mortality) = $\log[p/(1-p)] = \beta_0 + \beta_1 X_{11} + \beta_2 X_{12}$, where p is the probability of mortality, β is each equation coefficient, $X_{11} = 0$ for control and thinRx units and 1 for thin units, and $X_{12} = 0$ for control and thin units and 1 for thinRx units. The equation intercept is the log odds of mortality for control units. Negative coefficient values indicate a reduction in log odds of mortality in treated units relative to the control. All equation coefficients are significant at $p < 0.05$.

Dispersed logging slash combined with extreme fire weather likely contributed to intense surface fire behavior and high tree mortality in thin units. Piled and burning of logging slash might have mitigated wildfire severity (Strom and Fulé 2007) but was not conducted on any thin units. Because this was an opportunistic study, we have limited information about prefire surface fuel conditions. In all thin units, logging slash was characterized by forest managers as light using fuel model 11 with <12 Mg·ha^{-1} of fine woody fuels <20.3 cm in diameter (Anderson 1982). Litter accumulations were low, with depths <2 cm. Prefire shrub cover was not recorded, but shrub cover is low in these dry forests and probably did not contribute substantially to surface fire behavior. Prewildfire surface fuel data are not available on thinRx units, but prescribed burns were reported as successful in all units, with a reduction of >90% of fine surface fuels. Treatment of fine, downed woody debris and litter accumulations likely reduced surface fire intensity, flame lengths, and convective and radiative heating in thinRx units and contributed to lower postfire severity measures as compared with thin and control units.

Although tree density is not significantly different between thin and thinRx units, thin units generally have higher tree densities associated with a higher proportion of small-diameter trees and saplings than thinRx units. When considering only large-diameter trees, overall tree mortality is still much higher in thin than in thinRx units and is not significantly different from that in control units. Differences in fire severity measures between treatments (i.e., maximum height of crown scorch, minimum/maximum bole char, percent crown scorch, and tree burn severity index) were all higher in our analysis of large-diameter trees. In both thin and thinRx units, large-diameter trees are almost exclusively Douglas-fir, ponderosa pine, and western larch, all species that are resistant to fire at larger diameters and therefore have a better chance of survival (Agee 1993). Two thin units (Solar II 82 and 84) are exceptions, with mortality comparable with that in thinRx units. Both units were helicopter-logged and recorded fine woody fuel accumulations similar to those in other thinned units. Adjacent controls sustained high tree mortality, indicating that the units had severe wildfire around them. However, large-diameter ponderosa pines

Fig. 3. Percent live trees by major tree species in 2007, 2008, and 2009.

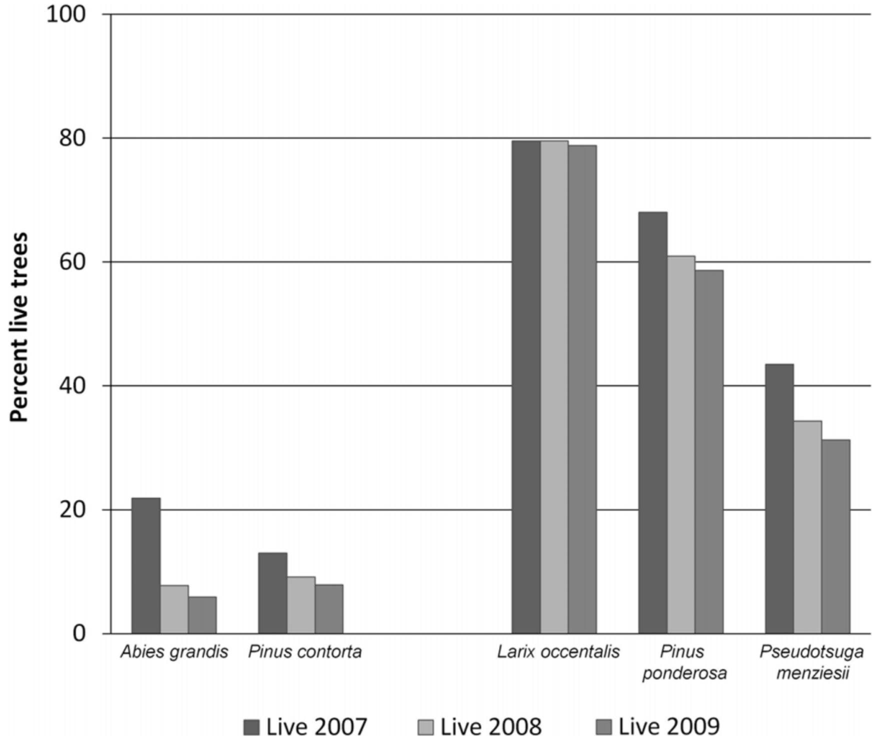
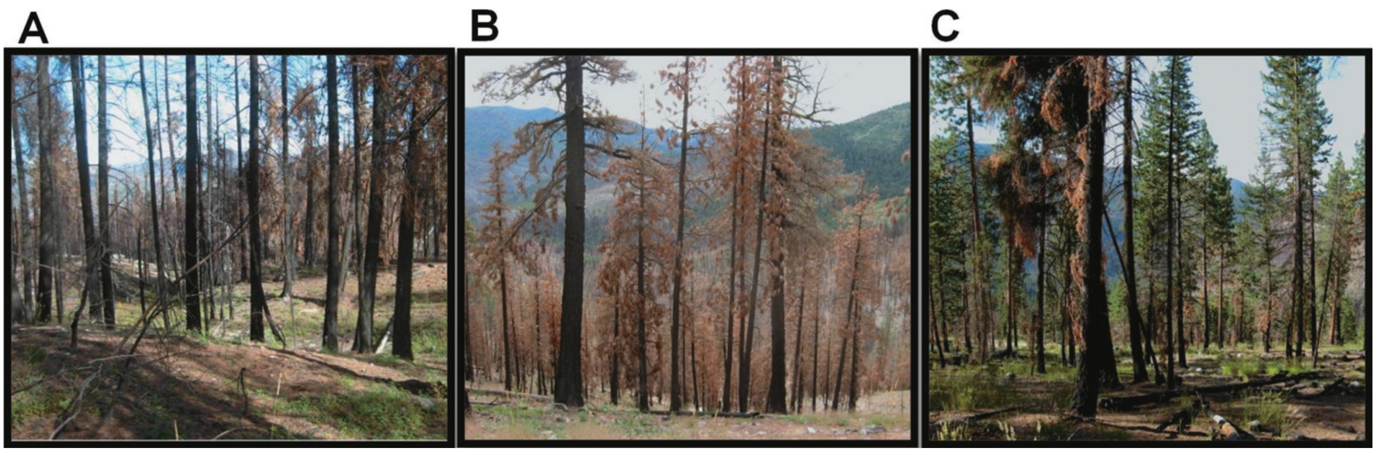


Fig. 4. Representative photographs of (*a*) control unit, (*b*) thin unit, and (*c*) thin and prescribed burn unit.



were common in both stands and may have contributed to lower mortality on these units. Our results strongly suggest that thinning alone does not mitigate wildfire severity, even when considering large-diameter trees.

When all tree sizes are considered, two thinRx units (Soaker 5 and Bear 50) have relatively high mortality. Both units were mechanically thinned, but clusters of small-diameter trees were retained. Mortality of these small-diameter trees may have been associated with the prescribed burn of the units and preceded the wildfire event.

Unit size does not appear to be a factor in treatment effectiveness. Even small thinRx units (4–5 ha in size) had low fire severity, indicating that size may not be as important as treatment type in predicting fire severity. Our results suggest that small units with low tree density and low surface fuels can alter fire behavior and reduce fire severity within a larger matrix of high-intensity wildfire (Agee et al. 2000). Small units may not affect landscape fire spread (Finney et al. 2005) but could provide protection buffers of local resources such as structures, municipal water sources, and rare species habitat (Johnson 2008).

Location-specific records of burnout operations are not available for the Tripod Complex fires. However, based on known ignition points, it is likely that some thin and thinRx units (specifically Soaker 5, 8, and 13 and Solar II 12) were impacted by burnout operations rather than the actual wildfire. At lower elevations, burnouts tended to be of higher intensity than the actual wildfire (Rick Lind, Tonasket Ranger Station, personal communication). The two thinRx units (Soaker 5 and 13) effectively mitigated fire severity, whereas the two thin units (Soaker 8 and Solar II 12) had high mortality. However, it is possible that fire severity may have been lower in these thin units had they not been involved in burnout operations.

Wildfires can be extremely variable in fire spread and intensity due to changeable environmental conditions such as fire weather and topography. When we designed this study, we added an additional analysis of adjacent controls to test for differences between treatments in areas that presumably experienced similar fire weather and behavior as the wildfire burned into the control and treated units. Our analysis of adjacent controls demonstrated very similar results to those of our balanced ANOVA design and corroborates our findings.

Management implications

Results from this study closely agree with published field research and fire behavior and effects modeling. In a field-based, retrospective study of five wildfires in the interior West, Omi et al. (2006) found that thinning followed by slash treatment was the most effective at reducing fire severity, whereas thin treatments failed to reduce fire severity and in some cases increased it. Finney et al. (2005) evaluated the efficacy of prescribed burning in the 2002 Rodeo-Chediski fire in Arizona and reported significant relationships between the age, size, and frequency of past prescribed burns and lower fire severity. Strom and Fulé (2007) studied thinned stands where slash had been piled and burned in the Rodeo-Chediski fire and found significant reductions in fire severity compared with untreated stands. Safford et al. (2009) also reported significant differences in tree mortality in thinned units where slash had been piled and burned relative to untreated areas in the Angora fire, California. In a study of fire severity following a wildfire in northern California, Ritchie et al. (2007) reported the highest tree survivorship in units that were thinned and prescribed burned. The effectiveness of fuel reduction programs, prescribed burning in particular, is also supported by fire behavior and effects modeling (Raymond and Peterson 2005; Stephens and Moghaddas 2005; Johnson et al. 2007). The national Fire and Fire Surrogates study also demonstrated that prescribed burns treatments were more effective than mechanical treatments at reducing surface fuels (Schwilk et al. 2009).

Given the similar findings to other studies, our results should be applicable to many dry forests with low- to mixed-severity fire regimes in the western United States. However, they may *not* apply to forests with flammable shrub and (or) grassland understories. Both thinning and prescribed burning can increase shrub dominance by creating gaps in the forest canopy (Bailey and Tappeiner 1998). For forest types in which flammable understory shrubs could be released by fuel treatments, the efficacy and longevity of treatments could be reduced compared with the dry forests of our study area. For example, in a landscape analysis of fire severity in the 2002 Biscuit fire in southwestern Oregon, Thompson and Spies (2009) reported that shrub cover was one of the most important predictors of fire severity. Plantations and other clearings involved in the Biscuit fire experienced the highest incidence of fire severity and were associated with a flammable shrub stratum.

Although individual fuel treatments may be effective at reducing fire severity, they may do little to alter fire spread across landscapes unless they are strategically placed (Agee et al. 2000; Agee and Skinner 2005; Finney et al. 2005). Strategic placement of fuel treatments can be difficult to implement under complex terrain and management units (e.g., wildlife reserves, riparian corridors) (Peterson and Johnson 2007) but may be necessary to suppress and or alter the course of fire spread (Finney 2007). Our study concentrated on fuel treatment effectiveness within specific treatment units and not on landscape patterns of fire spread. However, landscape fire spread did appear to be influenced by previous wildfires and fuel treatments. The most striking example of this was the approximately 1000 ha 1974 Forks fire located in the center of the Tripod perimeter. The Tripod Complex fires originated to the south and north of the old fire and wrapped around either side of the young lodgepole pine forest, burning only the edges of the regenerating trees. Similarly, a network of fuel treatments is located along the southwestern fire perimeter and was used as defensible space for back-burning to prevent fire spread toward nearby communities.

Conclusions

From fire behavior and effects modeling and available field-based studies, it appears that fuel treatments that reduce surface fuels *can* reduce fire severity. However, little is known about the effectiveness of fuel treatments in steep terrain and under extreme fire weather (Peterson et al. 2005). Although fuel treatments in this study appear to have had an impact even under extreme fire weather and steep terrain, weather and topography may supersede the importance of fuel treatments in other situations (Bessie and Johnson 1995; Cary et al. 2009). Validation of the effects of silvicultural and fuels management techniques for additional wildfires using real-time fire weather and behavior records would increase confidence in using these treatments more broadly to reduce fire hazard in fire-prone landscapes.

Increasing evidence shows that mechanical thinning followed by surface fuel removal is the most effective management approach to mitigate wildfire severity in dry forests. However, fire and fuel managers face numerous challenges in developing strategies for fuel reduction treatments. Prescribed fire is less expensive than mechanical or manual fuel removal but is often difficult to implement due to smoke management concerns and narrow windows of safe burning conditions. Targeting critical areas such as wildland–urban interfaces and appropriate forest types (e.g., those that historically supported high-frequency, low-intensity fire regimes) may help optimize resources (Agee et al. 2000; Agee and Skinner 2005; Peterson et al. 2007). Strategic placement of these fuel treatments may also be effective at limiting fire spread across critical landscapes (Finney 2007).

Acknowledgments

This study was funded by the Joint Fire Sciences Program and the USDA Forest Service Pacific Northwest Research Station. We thank Cameron Balog, Jon Dvorak, Travis Freed, Amy Jirka, Phil Monsanto, Joe Restaino, Shawn Smith, and Aarin Sengsirirak for conducting fieldwork. We thank John Daily, Gary Reed, Tom Ketchum, Meg Trebon, and Rick Lind for information on the Tripod Complex fires and logistical support. We thank Bob Vihnanek for field crew supervision, Paige Eagle for database analysis, Robert Norheim and Travis Freed for GIS analysis, and Maureen Kennedy for statistical assistance. We also thank Donald McKenzie, Clint Wright, Maureen Kennedy, Roger Ottmar, and three anonymous reviewers for invaluable comments on the manuscript.

References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Agee, J.K., and Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manag. **211**(1–2): 83–96. doi:10.1016/j.foreco.2005.01.034.

Agee, J.K., Bahro, B., Finney, M.A., Omi, P.N., Sapsis, D.B., Skinner, C.N., van Wagtendonk, J.W., and Weatherspoon, C.P. 2000. The use of shaded fuelbreaks in landscape fire management. For. Ecol. Manag. **127**(1–3): 55–66. doi:10.1016/S0378-1127(99)00116-4.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. U.S. For. Serv. Gen. Tech. Rep. INT-GTR-122.

Bailey, J.D., and Tappeiner, J.C. 1998. Effects of thinning on structural development in 40- to 100-year-old Douglas-fir stands in western Oregon. For. Ecol. Manag. **108**(1–2): 99–113. doi:10.1016/S0378-1127(98)00216-3.

Barksdale, J.D. 1975. Geology of the Methow Valley. Bull. 68. Washington State Division of Geology and Earth Resources, Seattle, Wash.

Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology, **76**(3): 747–762. doi:10.2307/1939341.

Cary, G.J., Flannigan, M.D., Keane, R.D., Bradstock, R.A., Davies, I.D., Lenihan, J.M., Li, C., Logan, K.A., and Parsons, R.A. 2009. Relative importance of fuel management, ignition management and weather for area burned: evidence from five landscape-fire-succession models. Int. J. Wildland Fire, **18**(2): 147–156. doi:10.1071/WF07085.

Covington, W.W. 2003. Restoring ecosystem health in frequent-fire forests of the American West. Ecol. Res. **21**(1): 7–11. doi:10.3368/er.21.1.7.

Finney, M.A. 2007. A computational method for optimizing fuel treatment locations. Int. J. Wildland Fire, **16**(6): 702–711. doi:10.1071/WF06063.

Finney, M.A., McHugh, C.W., and Grenfell, I.C. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Can. J. For. Res. **35**(7): 1714–1722. doi:10.1139/x05-090.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. Geophys. Res. Lett. **31**(L18211): 1–4. doi:10.1029/2004GL020876.

Graham, R.T., Harvey, A., Jain, T., and Tonn, J.R. 1999. The effects of thinning and similar stand treatments on fire behavior in western forests. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-463.

Hessburg, P.F., Agee, J.K., and Franklin, J.F. 2005. Dry forests and wildland fires of the inland Northwest USA: contrasting the landscape ecology of pre-settlement and modern eras. For. Ecol. Manag. **211**(1–2): 117–139. doi:10.1016/j.foreco.2005.02.016.

Johnson, M.C. 2008. Analyzing fuel treatments and fire hazard in the Pacific Northwest. Ph.D. thesis, College of Forest Resources, University of Washington, Seattle, Wash.

Johnson, M.C., Peterson, D.L., and Raymond, C.L. 2007. Guide to fuel treatments in dry forests of the western United States: assessing forest structure and fire hazard. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-686.

Lehmkuhl, J.F., Hessburg, P.F., Ottmar, R.D., Everett, R.L., Alvarado, E., and Vihnanek, R.H. 1993. Historic and current vegetation pattern and associated changes in insect and disease hazard, and fire and smoke conditions in eastern Oregon and Washington. *In* Eastside forest ecosystem health assessment. Vol. III. *Edited by* Paul F. Hessburg. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. pp. 589–718.

McKenzie, D., Gedalof, Z., Peterson, D.L., and Mote, P. 2004. Climatic change, wildfire, and conservation. Conserv. Biol. **18**(4): 890–902. doi:10.1111/j.1523-1739.2004.00492.x.

Natural Resources Conservation Service. 2008. Soil survey geographic (SSURGO) database for Okanogan – Methow Highlands Area, WA. WA 749. USDA Natural Resources Conservation Service, Fort Worth, Tex.

Ohlson, T.H. 1996. Fire regimes of the ponderosa pine – Douglas-fir/beardless bluebunch wheatgrass plant association in the Methow Valley of North Central Washington. M.S. thesis, Washington State University, Pullman,Wash.

Omi, P.N., Martinson, E.J., and Chong, G.W. 2006. Effectiveness of pre-fire fuel treatments. Joint Fire Sciences Program. Final Rep. 03-2-1-07. Joint Fire Sciences Program, Boise, Idaho.

Peterson, D.L., and Johnson, M.C. 2007. Science-based strategic planning for hazardous fuel treatment. Fire Manag. Today, **67**: 13–18.

Peterson, D.L., Johnson, M.C., Agee, J.K., Jain, T.B., McKenzie, D., and Reinhardt, E.R. 2005. Forest structure and fire hazard in dry forests of the western United States. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-628.

Peterson, D.L., Evers, L., Gravenmier, B., and Eberhardt, E. 2007. A consumer guide: tools to manage vegetation and fuels. U.S. For. Serv. Gen. Tech. Rep. PNW-GTR-690.

Raymond, C.L., and Peterson, D.L. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Can. J. For. Res. **35**(12): 2981–2995. doi:10.1139/x05-206.

Riebau, A.R., and Fox, D. 2001. The new smoke management. Int. J. Wildland Fire, **10**(4): 415–427. doi:10.1071/WF01039.

Ritchie, M.W., Skinner, C.N., and Hamilton, T.A. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. For. Ecol. Manag. **247**(1–3): 200–208. doi:10.1016/j.foreco.2007.04.044.

Safford, H.D., Schmidt, D.A., and Carlson, C.H. 2009. Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. For. Ecol. Manag. **258**(5): 773–787. doi:10.1016/j.foreco.2009.05.024.

Sall, J., Creighton, L., and Lehman, A. 2007. JMP start statistics: a guide to statistics and data analysis using JMP. 4th ed. SAS Press Series. SAS Institute Inc., Cary, N.C.

Schwilk, D.W., Keeley, J.E., Knapp, E.E., McIver, J., Bailey, J.D., Fettig, C.J., Fiedler, C.E., Harrod, R.J., Moghaddas, J.J., Outcalt, K.W., Skinner, C.N., Stephens, S.L., Waldrop, T.A., Yaussy, D.A., and Youngblood, A. 2009. The National Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecol. Appl. **19**(2): 285–304. doi:10.1890/07-1747.1. PMID:19323191.

Stephens, S.L., and Moghaddas, J.J. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. For. Ecol. Manag. **215**(1–3): 21–36. doi:10.1016/j.foreco.2005.03.070.

Stephens, S.L., and Ruth, L.W. 2005. Federal forest-fire policy in the United States. Ecol. Appl. **15**(2): 532–542. doi:10.1890/04-0545.

Strom, B.A., and Fulé, P.Z. 2007. Pre-wildfire treatments affect long-term ponderosa pine forest dynamics. Int. J. Wildland Fire, **16**(1): 128–138. doi:10.1071/WF06051.

Thompson, J.R., and Spies, T.A. 2009. Vegetation and weather explain variation in crown damage within a large mixed-severity wildfire. For. Ecol. Manag. **258**(7): 1684–1694. doi:10.1016/j.foreco.2009.07.031.

US Department of the Interior National Park Service. 2003. Fire monitoring handbook. Fire Management Program Center, National Interagency Fire Center, Boise, Idaho.

US Forest Service. 2008. Final environmental impact statement. Methow Valley Ranger District, Winthrop, Wash.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science, **313**(5789): 940–943. doi:10.1126/science.1128834. PMID:16825536.