Stand- and landscape-level effects of prescribed burning on two Arizona wildfires

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Abstract: Performance of fuel treatments in modifying behavior and effects of the largest wildfires has rarely been evaluated, because the necessary data on fire movement, treatment characteristics, and fire severity were not obtainable together. Here we analyzed satellite imagery and prescribed fire records from two Arizona wildfires that occurred in 2002, finding that prescribed fire treatments reduced wildfire severity and changed its progress. Prescribed burning in ponderosa pine forests 1–9 years before the Rodeo and Chediski fires reduced fire severity compared with untreated areas, despite the unprecedented 1860-km^2 combined wildfire sizes and record drought. Fire severity increased with time since treatment but decreased with unit size and number of repeated prescribed burn treatments. Fire progression captured by Landsat 7 enhanced thematic mapper plus (ETM+) clearly showed the fire circumventing treatment units and protecting areas on their lee side. This evidence is consistent with model predictions that suggest wildland fire size and severity can be mitigated by strategic placement of treatments.

Résumé : L'impact de la réduction des combustibles sur le comportement et les effets des incendies de forêt de grande envergure a rarement été évalué parce qu'il n'était pas possible de rassembler les données nécessaires sur le mouvement du feu, les caractéristiques du traitement et la sévérité du feu. Les auteurs ont analysé des images satellitaires et des données de brûlages dirigés associés à deux incendies de forêt qui sont survenus en Arizona en 2002. Les résultats montrent que les brûlages dirigés ont réduit la sévérité des incendies de forêt et modifié leur progression. Des brûlages dirigés dans les forêts de pin ponderosa, un à neuf ans avant que surviennent les incendies de Rodeo et Chediski, ont réduit la sévérité du feu comparativement aux zones non traitées, malgré la dimension combinée sans précédent de ces incendies, soit 1860 km^2, et une sécheresse record. La sévérité du feu a augmenté en fonction du temps écoulé depuis le traitement mais a diminué en fonction de la dimension et du nombre de fois que les brûlages dirigés avaient été répétés. La progression des incendies captée par Landsat 7 (appareil de cartographie thématique amélioré) a clairement démontré que le feu a contourné les aires traitées et que les zones situées du côté sous le vent des aires traitées ont ainsi été protégées. Cette observation est consistante avec les prédictions du modèle qui indique que la dimension et la sévérité des incendies de forêt peuvent être atténuées en disposant les traitements de façon stratégique.

[Traduit par la Rédaction]

Introduction

Prescribed burning and thinning treatments are of particular interest for wildfire hazard reduction in ponderosa pine forests now altered after 20th century fire exclusion (Cooper 1960; Arno and Brown 1991; Covington and Moore 1994). Treatments deny fuel to future wildfires and can thereby reduce fire severity (Biswell et al. 1973; Wagle and Eakle 1979; Pollet and Omi 2002; Fernandes and Botelho 2003). Fire severity is a general term for biological and ecological effects of different fire behaviors (e.g., vegetation, soil, etc.) (Ryan and Noste 1985; Reinhardt et al. 2001; Graham et al. 2004). Scorching and ignition of tree crowns (Van Wagner 1973, 1977) are related to fireline intensity, which depends on fire spread rate and fuel availability in flaming combustion (Byram 1959; Alexander 1982). Heating of tree stems, roots, and soil is related to fuel consumption and duration of smoldering combustion that depends on fuel loading and moisture content (Ryan and Frandsen 1991; Albini et al. 1996). Injuries to trees from both fireline intensity and fuel consumption can ultimately cause mortality, depending on interactions with tree physiology and insect and disease agents (Ryan 1990; Reinhardt et al. 2001).

Fuel treatments specifically attempt to reduce fuel quantity, depth, and continuity (vertical and horizontal) to mitigate potential fire behaviors and their ecological and management impacts (Graham et al. 2004). Treatment by prescribed fire removes surface fuels, kills small trees and shrubs, and scorches lower limbs to reduce vertical continuity of the forest stand. Prescribed burning has been used to mitigate wildfire behavior and effects in dry conifer forests (ponderosa pine and mixed conifer) of the southwestern United States for decades (Weaver 1943; Kallander et al. 1955; Cooper 1961; Biswell et al. 1973; Wagle and Eakle 1979). Prescribed burns are consistent with effects of low-intensity fires that occurred in these forests every 2–10 years before 19th century settlement (Weaver 1943; Swetnam and Baisan 1996). Continued exclusion of these surface fires through fire suppression has permitted forest stands to become dense

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with accumulated living and dead fuels across large landscapes (10^4–10^5 km^2) (Weaver 1943; Cooper 1960; Fulé et al. 1997; Allen et al. 2002). Modern wildfires now burn only under extreme weather conditions, when suppression efforts fail, and when fuel and forest structure contribute to severe crown fires (Biswell et al. 1973; Wagle and Eakle 1979; Arno and Brown 1991; Covington and Moore 1994). Although fuel modifications may physically change fire behavior, the changes may be insufficient to produce the desired modification of severity under extreme weather conditions.

Fuel treatment effectiveness under extreme weather conditions is open to a number of questions, namely the longevity of treatment effects, requirements of maintaining or repeating treatments, the importance of the size of treatment units, effects of treatments on wildfire growth and progress, and the amount of treatment required to change large fire behavior. These issues span a range of spatial scales, from the stand level, where treatments are intended to improve forest survival, to the landscape level, where treatments have potential for disrupting fire growth and reducing fire movement and ultimate size. This paper reports on analysis, at several spatial scales, of fuel treatment effects on two wildfires that encountered prescribed burn units conducted over a range of years, sizes, and with repetition.

Materials and methods

The opportunity to evaluate fuel treatment effects following extreme wildfires was provided in summer of 2002, when the ponderosa pine forests on part of the White Mountain Apache lands and the Apache-Sitgreaves National Forest experienced the largest fire events in Arizona history. The Rodeo and Chediski fires began approximately 15 km apart (Fig. 1*a*) on 18 and 20 June and eventually burned more than 1860 km^2 (460 000 acres) under record drought conditions (Kipfmueller 2003). Strong winds pushed the fires north into fuel treatments on White Mountain Apache lands and then across the Apache-Sitgreaves National Forest. The Limestone weather station (RAWS No. 020309), located within the final fire perimeter, recorded afternoon wind gusts above 40 km·h^{-1} (25 mph) for most days and 73 km·h^{-1} (45 mph) on 21 June, sustained relative humidity below 10% for most afternoons, and calculated moisture content of dead fuels for all size classes below 4%.

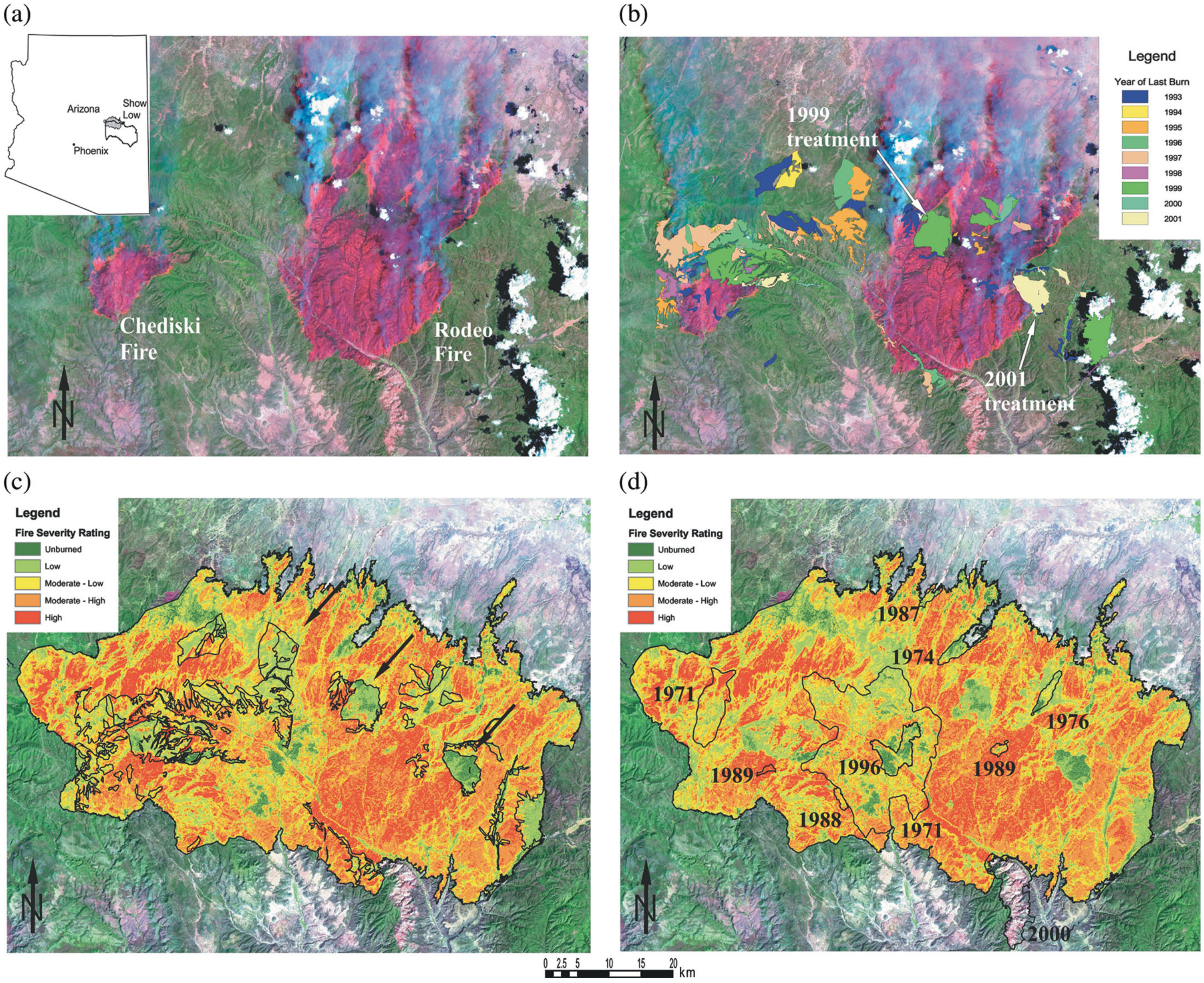
The White Mountain Apache Tribe located in central Arizona, USA (Fig. 1*a*), has been conducting prescribed burning, thinning, and harvest operations on their commercial timberlands since the early 1940s (Weaver 1943; Cooper 1961; Biswell et al. 1973; Wagle and Eakle 1979). The US Forest Service had also conducted prescribed fire treatments in conjunction with various forest management activities on the adjacent Apache-Sitgreaves National Forest. Management records contained the date and boundaries of prescribed fire treatment units (Fig. 1*b*). Our analysis focused only on effects of the prescribed fire treatments, because these had relatively well-defined boundaries and dates of completion. Treated areas received the most recent prescribed burn between 1993 and 2001, providing 157 polygons that ranged in size from 0.02 to 22.6 km^2 (5–5600 acres). These polygons overlapped with smaller units receiving previous prescribed fire treatments, which resulted in 811 polygons burned one to six times since 1950.

Fire severity for the treated and untreated areas burned by the Rodeo–Chediski fires was inferred from the differenced normalized burn ratio (dNBR) developed from Landsat 7 enhanced thematic mapper plus (ETM+) imagery at 30-m resolution provided by the National Park Service – US Geological Survey Burn Severity Mapping Project (http://burnseverity.cr.usgs.gov/fire_main.asp). The ratios of near-infrared to mid-infrared spectral reflectance (band 4, 0.76–0.90 μm; and band 7, 2.08–2.35 μm) are calculated on images before and after a fire (Miller and Yool 2002; van Wagtendonk et al. 2004). Large differences between the pre- and post-fire ratios (dNBR) indicate high fire severity because of lower near-infrared reflectance associated with foliage on green vegetation (trees and understory) and higher mid-infrared reflectance associated with increased exposed and blackened soil, and decreased moisture content of surface materials (White et al. 1996; Miller and Yool 2002). The dNBR index and similar band combinations have been found to correspond well with burn severity in Arizona, Colorado, Montana, and New Mexico (White et al. 1996; Bertolette and Spotskey 2001; Miller and Yool 2002; van Wagtendonk et al. 2004). Ranges of dNBR are typically classified with respect to levels of tree damage visible from ground observation (Fig. 1*c*), varying from unburned to complete foliar consumption (Key and Benson 2005).

We analyzed a subset of the 30-m dNBR pixels, sampled on a regular spacing of 90 m, to minimize artifacts from coregistration of the separate satellite images taken just before the wildfire (5 June 2002) and soon after the wildfire (7 July 2002) used to calculate dNBR. The selected pixels were then identified as inside or outside of treatment units. The large number of pixels outside of treatment units was reduced to 21 421 by resampling at a regular spacing of 270 m to accommodate statistical software limitations. Pixels inside (34 867) were assigned values of time since treatment (years), number of repeated prescribed burns, size of the most recent treatment unit (square kilometres), and nearest distance from the edge of the defining polygon (metres). Having these nominal treatment descriptors in common qualifies the pixels as pseudoreplicates within treatment units and even the whole Rodeo–Chediski wildfire (van Mantgem et al. 2001). Retaining a large sample size, however, was important to our objective of understanding variation in local fire severity within this data set. There are many independent sources of variation in local severity that are only partially related to the nominal treatment descriptors or the wildfire event itself, including (1) the characteristics and variability of the prescribed fire treatment (e.g., amount of fuel consumption, intensity) within a given treatment unit, (2) the structure of the forest and fuels at the time of the treatment and in 2002 at the time of the wildfire, and (3) the behavior characteristics, timing, and movement direction of the wildfire as it encountered each pixel location.

Spatial linear regression was used to explore general relationships of the independent variables to dNBR. We used conditional spatial autoregression (CAR) (Kaluzny et al. 1998), which relaxes the assumption of independent residuals used in ordinary least-squares regression by accounting explicitly for spatial covariance. Variogram modelling indicated spatial

Fig. 1. Landsat 7 enhanced thematic mapper plus (ETM+) images (path 36, row 36) displayed as a false color composite using bands 6, 4, and 3 show (*a*) the general location of the study area and the positions of the Chediski and Rodeo fires spreading north at 1100 h on 21 June 2002; (*b*) locations and dates of the most recent prescribed fire treatments (since 1993) on White Mountain Apache Tribal and Apache-Sitreaves National Forest lands reveal that fire spread has circumnavigated a 3-year-old area of treatment and is contacting a 1-year-old treatment unit on the right side; (*c*) fire severity for the entire Rodeo–Chediski fire area was indexed by the differenced normalized burn ratio (dNBR) and displayed on a background image from 24 August 2002. The dNBR index is the difference between ratios of near-infrared to mid-infrared spectral reflectance (band 4, 0.76–0.90 μm; and band 7, 2.08–2.35 μm) before the fire (5 June 2002) and after the fire (7 July 2002). Values of dNBR were classified into general fire severity categories (Key and Benson 2005) based on ranges that correspond with visible indications of fire damage to tree crowns. Unburned (dNBR ≤50), low (51–200, foliage still green), moderate–low (201–350, green and brown foliage), moderate–high (351–605 mostly brown with some foliage consumed by fire), and high (>605, complete consumption of foliage). Treatments reduced fire severity within treatment units (outlined in black) and in three cases, marked by an arrow, outside the units on their lee side because heading fire spread was diverted; (*d*) historic fires greater than 78 ha (200 acres) within 30 years of the Rodeo–Chediski fire including the Carrizo (1971, 24 708 ha), Day (1974, 1056 ha), Cottonwood (1976, 567 ha), Elks (1987, 247 ha), and White Springs (1996, 1663 ha).



autocorrelation out to approximately 3 km, suggesting patchiness related to topography, wildfire behavior, and the treatments themselves. The CAR routine in the S+ software program (Kaluzny et al. 1998) estimates spatial covariance from the dNBR values of neighboring pixels. The regression partitions the variance according to three sources: the fitted trend, the spatial covariance component, and residual error. Before analysis, the dNBR data were normalized with a square-root transformation and range-shifted to offset negative values $(\mathrm{dNBR} + 700)^{0.5}$.

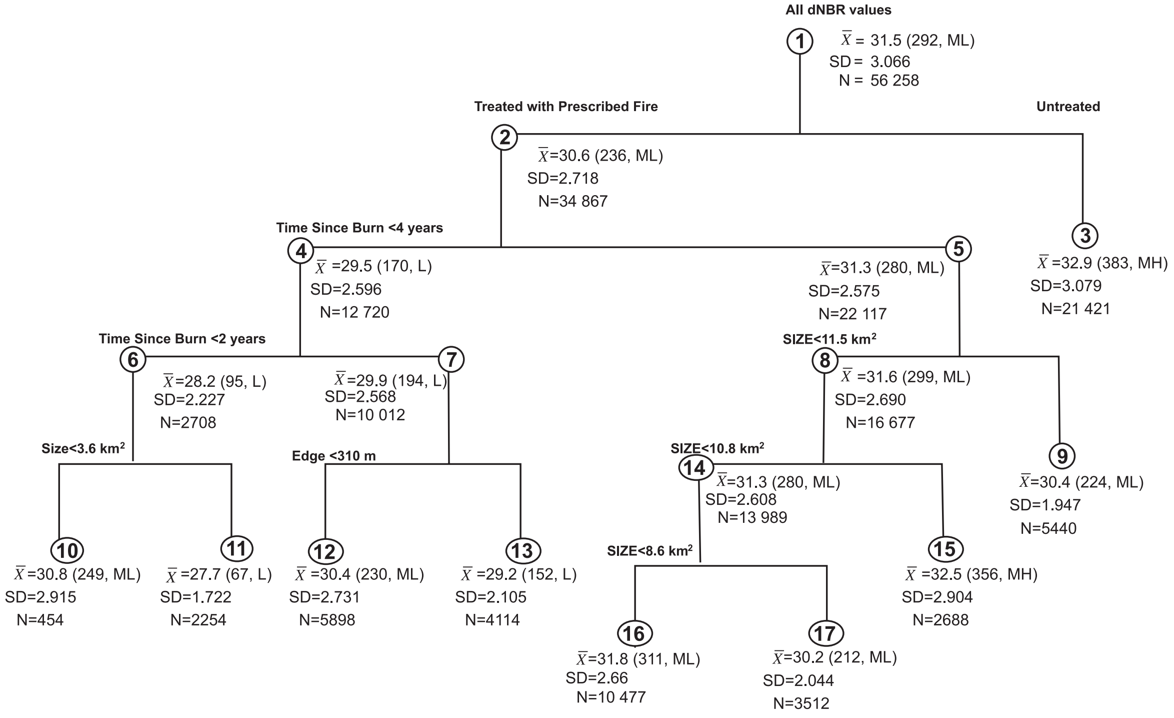
Possible nonlinear or discontinuous relationships between the independent variables and dNBR were then explored using least-squares regression trees (Breiman et al. 1998). Regression trees are fit by sequentially splitting data into two subsets. Each split is based on the independent variable that minimizes the squared deviance from the mean of a continu-

Table 1. Results of conditional spatial autoregression relating fire severity (dNBR + 700)$^{0.5}$ of 30-m pixels to general treatment descriptors.

Variable	Coefficient	SE	*t* value	*P*(>|*t*|)
Intercept	30.6725	0.136	226.202	0
Treatment	–0.5533	0.22	–2.5150	0.01
Time since treatment (years)	0.1433	0.02	5.953	0
Treatment size (km)	–0.0363	0	–4.9421	0
Distance to nearest edge (m)	–0.0013	0	–4.1313	0
No. of burns	–0.3493	0.05	–7.1390	0

Note: Proportional variance explained by the model was 0.518, which includes the contribution from fitted variables (0.074) and spatial covariance (0.444), leaving a residual error of 0.482. dNBR, differenced normalized burn ratio.

Fig. 2. Regression tree results of differenced normalized burn ratio (dNBR) for the fire area contained within the White Mountain Apache Tribal Lands and Apache-Sitgreaves National Forest. Listed at each node are the mean transformed dNBR values ((dNBR + 700)$^{0.5}$) with untransformed dNBR and abbreviation for nominal severity category in parentheses (L, low; ML, moderate–low; MH, moderate–high), standard deviation of transformed data, and the number of 30-m data at each split. Variables labelled as size and edge refer to the size of treatment unit and distance from nearest edge of treatment boundary, respectively.



ous dependent variable. The tree forms terminal nodes when the fractional reduction in total error falls below a specified limit, in this case 0.01. The procedure diagrams a hierarchy of relative explanatory value of predictors within subsets of the data without requiring an explicit nonlinear model form to be specified. Thus, regression trees are becoming more commonly used in modelling and exploring spatial data (Yang et al. 2003; Lawrence and Labus 2003). Since the regression tree analysis could not account for spatial autocorrelation of the dNBR data (it has the same assumptions of data independence as standard linear regression), the splits were evaluated for significance using the CAR analysis by including dummy variables to distinguish the subgroups. Relative mean-squared error was estimated for the regression tree (generally scaled from 0.0 to 1.0, where 0.0 indicates perfect agreement) by methods of resubstitution (using mean-squared error (MSE) for the regression tree from the entire data set) and cross-validation (using MSE for regression trees from random subsamples of the data, which are cross-validated with remaining subsamples).

Results

The spatial linear regression suggested dNBR of 30-m pixels within treatments was significantly lower than outside treated areas (Table 1). All coefficients were significant, suggesting that fire severity in treated areas was positively related with time since treatment and negatively related to number of repeated prescribed burns, treatment size, and distance from the edge of the treatment (Table 1). A low proportion of variance was explained by linear functions of the

Table 2. Results from conditional spatial autoregression used for testing significance of splits between nodes identified in the regression tree (Fig. 2).

Node splits	Variable[a]	Coefficient[b]	SE[b]	*t* value	$P(>\lvert t\rvert)$
2–3	Constant	30.6816	0.11359	225.7646	0
	Treatment	–0.8258	0.0793	–10.4188	0
4–5	Constant	31.4142	0.7047	420.5321	0
	Age <4 years	–1.3630	0.068	–20.0448	0
6–7	Constant	30.5604	0.0877	348.566	0
	Age <2 years	–1.1477	0.1237	–9.2798	0
8–9	Constant	30.793	0.1184	260.0137	0
	Age ≥4 years, size <11.5 km^2	0.8804	0.1049	8.389	0
10–11	Constant	28.6252	0.1963	145.8259	0
	Age <2 years, size <3.6 km^2	1.5052	0.2184	6.8291	0
12–13	Constant	30.4715	0.1311	232.386	0
	2< age ≤4 years, edge <310 m	0.1895	0.0939	2.0181	0.04
14–15	Constant	32.2215	0.1738	185.3966	0
	Age ≥4 years, size <10.8 km^2	–0.6717	0.1609	–4.1733	0
16–17	Constant	30.5982	0.1615	189.489	0
	Age ≥4 years, size <8.6 km^2	0.9686	0.1526	6.3466	0

[a] Variables labelled as age, size, and edge refer to time since treatment, size of treatment unit, and distance from nearest treatment edge, respectively.

[b] Results presented for data in transformed units $(\text{dNBR} + 700)^{0.5}$.

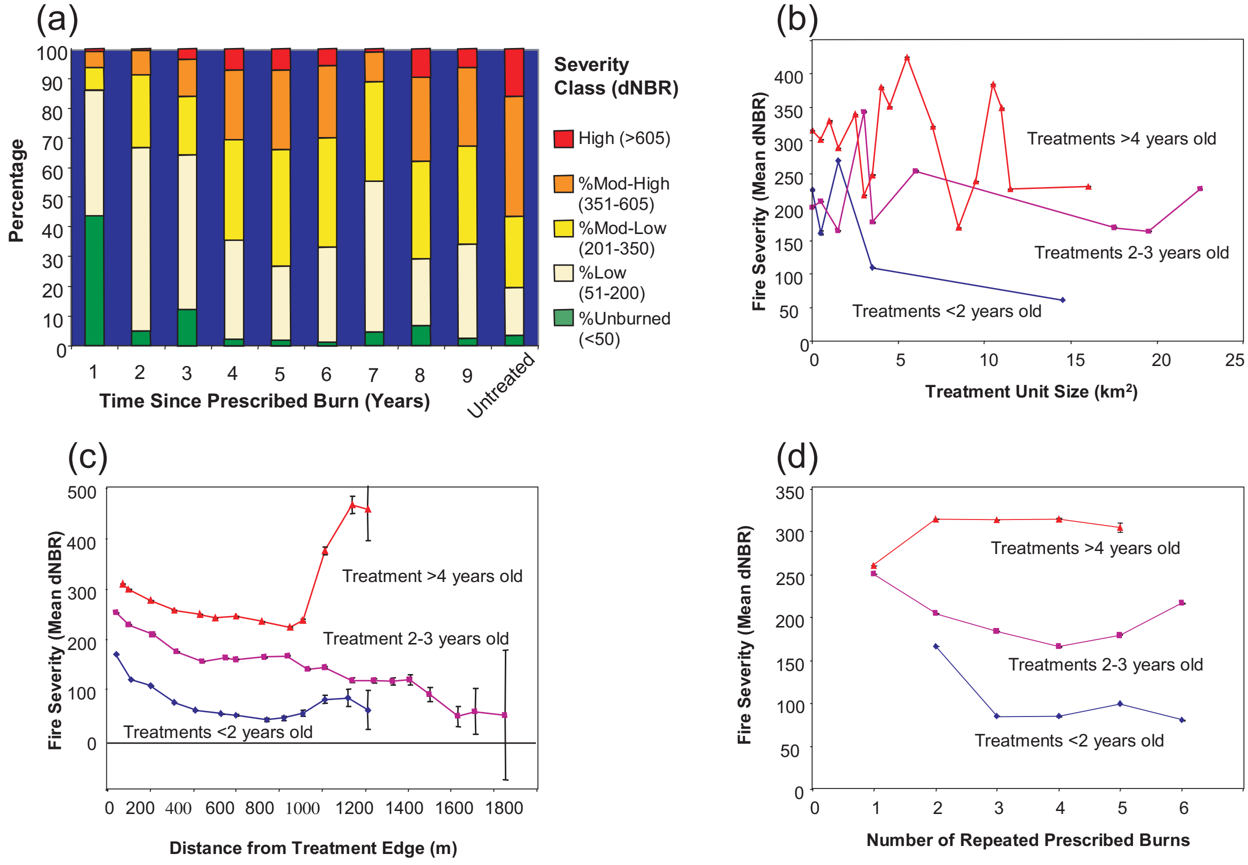


Fig. 3. The 30-m data from the Rodeo and Chediski wildfires are summarized to show single-factor treatment effects on burn severity (differenced normalized burn ratio, dNBR). Standard error bars are included but may not be visible at every data point. (*a*) Severity inside treatments was less than untreated areas and decreased as a function of the time since treatment. (*b*) Mean dNBR (with standard errors) decreased with distance inside the edge of treatments younger than 4 years old but not in older treatment units. (*c*) Mean dNBR (with standard errors) decreased with the size of units for treatments older than 3 years. (*d*) Mean dNBR decreased significantly with number of repeated prescribed fire treatments for those units treated 2–4 years and <2 years before the wildfire but not for treatments conducted earlier (see Table 3).

Table 3. Conditional spatial autoregression suggested fire severity $(\mathrm{dNBR} + 700)^{0.5}$ of 30-m pixels decreased significantly with number of repeated prescribed burns only for those units burned less than 4 years before the wildfire (see Fig. 3*d*).

Variable	Coefficient	SE	*t* value	$P(>\|t\|)$
Intercept	31.2094	0.1356	226.2024	0
Treated ≥4 years	0.2414	0.1422	1.6977	0.09
No. of burns, ≥4 years since last treatment	–0.0281	0.038	–0.7442	0.457
Treated <2 years	–1.0638	0.2962	–3.5916	0
No. of burns, <2 years since last treatment	–0.3363	0.07	–4.7877	0
No. of burns, 2–4 years since last treatment	–0.3527	0.037	–9.4383	0

Note: Proportional variance explained by the model was 0.655, which includes the contribution from fitted variables (0.079) and spatial covariance (0.576), leaving a residual error of 0.34. dNBR, differenced normalized burn ratio.

fitted variables (0.073) compared with the spatial covariance (0.444).

Further analysis with regression trees and spatial regression suggested fire severity responded differently to the independent variables depending on time since treatment. Where prescribed burning was conducted less than 4 years before the wildfire, dNBR was consistently reduced in relation to time since treatment (Fig. 2, nodes 4 and 6; Table 2; Fig. 3*a*). In these recent treatments, dNBR was then reduced among pixels located farther from the nearest treatment edge (Fig. 2, node 12; Fig. 3*b*) and in units larger than 3.6 km^2 (Fig. 2, node 10). For treatments conducted 4 years or more prior to the wildfire, dNBR decreased significantly for treatments larger than about 8.5 km^2 (Fig. 2; Table 2; Fig. 3*c*), except between nodes 14 and 15 (Fig. 2), which corresponds with particular data variability in treatment unit size around the split point of about 10 km^2 (Fig. 3*c*). Fire severity was reduced compared with untreated areas even in units treated 9 years before the wildfire, as indicated by a χ^2 test among severity categories in Fig. 3*a* ($P < 0.001$). The number of repeated treatments was not identified in the regression tree, but spatial regression analysis suggested that dNBR decreased significantly with more repeated treatments where the final treatment occurred less than 4 years before the wildfire (Table 3, Fig. 3*d*). The similarity of standard errors among nodes in the regression tree suggests the data conformed to assumptions of constant variance. The relative MSE of the regression tree was estimated at 0.74 by methods of resubstitution and a ninefold cross-validation.

At the broadest landscape scale, effects of fuel treatments were found in the fortuitous Landsat 7 (ETM+) overpass that occurred at approximately 1100 h local time on 21 June 2002. This image provided a rare glimpse of the fire, as it actively encountered and circumvented several of the fuel treatment units. Unburned inclusions are visible within the spreading fire (Fig. 1*a*), each displaying a chevron-shaped edge on its leeward northern side. The largest of these inclusions on White Mountain Apache land was found to correspond with an area treated 3 years before the wildfire (Fig. 1*b*). Smaller inclusions on the Apache-Sitgreaves National Forest each had the same shape characteristics and were each associated with prescribed burn treatment units conducted 2 and 6 years before the Rodeo–Chediski fires. In all cases, the chevron-shaped fire front occurred outside of the treatment boundaries and downwind of the leeward treatment edge. The image (Figs. 1*a* and 1*b*) also shows the right-angled east flank of the wildfire was formed as the fire encountered a 1-year-old treatment unit. Compared with adjacent untreated lands, lower dNBR values appear within the leeward shadow of the largest three large treatment units (Fig. 1*c*).

Discussion

Satellite data from the Rodeo–Chediski fires provided exceptionally clear examples of both stand-level and landscape-level effects of prescribed fire fuel treatments in these southwestern ponderosa pine forests. The complete coverage and large sample sizes of dNBR permitted analysis of fire severity in relation to stand-level variables including “time since treatment” and number of repeated treatments. Broader-scale effects of unit size and edge proximity would have been difficult and impractical to obtain for such large wildfires and treatments from ground sampling alone. Nonlinear relationships of all of treatment variables to fire severity were revealed by the significance of the splits in the regression tree (Fig. 2; Table 2) and low proportion of explained variance in the spatial regression (Table 1). As with other studies relying on remote sensing of operational fuel treatments (Weatherspoon and Skinner 1995; Graham 2003), the high relative MSE of the regression tree revealed that local fire effects were dependent upon many factors not represented by the independent variables available. For landscape-level effects, information on changes in fire movement caused by treatment units could only be obtained by remote sensing.

The results of this study were consistent with reports from more than a half-century of research showing reduced fire severity following fuel treatment in ponderosa pine forests (Weaver 1943; Kallander et al. 1955; Cooper 1961; Biswell et al. 1973; Wagle and Eakle 1979; Pollet and Omi 2002; Graham 2003; Schoennagle et al. 2004). Compared with ground-based data, analysis of the satellite data suggested a more complex picture of fuel treatment effects, including the diminishing of treatment effectiveness over time (Fig. 3*a*), which has been difficult to quantify and only rarely been documented (Biswell et al. 1973; van Wagtendonk and Sydoriak 1987). Repeated treatment was also related to lower fire severity in more recent treatments (Table 3; Fig. 3*d*) but was not represented in the regression tree. This suggested that treatment history was less important than the characteristics of the last treatment, including time since treatment and unit size. Weak trends related to treatment history may partially reflect the high variability in the data set in which treatments occurred on irregular intervals and over inconsistent time spans, some as long as five decades. But, the strong influence of the most recent treatment emphasizes the importance of repeating treatments to maintain fuel conditions that mitigate wildfire severity.

The decreasing fire severity with distance from the treatment edge and in larger units indicated the importance of spatial scales broader than the local or stand level. Edge proximity likely reflected the abrupt reduction of fireline intensity as the fire moved from untreated areas into recent treatments (Weatherspoon and Skinner 1995) (Fig. 3*b*). Reduced intensity is responsible for lower scorching and consumption of tree crowns that are represented in dNBR fire severity data. Recent treatments likely limited fire severity more than older treatments, because patchy fuel accumulation and vegetation recovery was not yet sufficient for intense surface fire and initiation of crown fire (Van Wagner 1977). In units having treatment 1 year prior to the wildfire, about 40% of the area was indicated in the dNBR data as remaining unburned (Fig. 3*a*), similar to reports by Wagle and Eakle (1979) and Graham (2003). Thus, the regression tree and spatial regression suggested that unit size was relatively less important in these recent treatments than in older treatments (Figs. 2 and 3*c*). The role of unit size in older treatments may reflect the effects of greater fuel and topographic heterogeneity that partially compensated for fuel recovery by collectively slowing fire movement (Weatherspoon and Skinner 1995). The fine-scale “fingering” of the wildfire produced by such heterogeneity has been shown to increase the proportion of flanking and backing fire within the area as a whole (Finney 2003), thus, reducing fireline intensities and tree crown damage or ignition within the unit. The analysis suggests that this effect was distinct from edge proximity, which was only significant in treatments occurring less than 4 years before the wildfire. Larger treatment units also require longer burn times and, thus, better chances that weather will moderate as the fire burns through these areas (e.g., wind shifts, nighttime).

All studies of fuel treatment effects on wildfire behavior or severity are necessarily opportunistic, because large wildfires cannot be set to experimentally test treatment performance. This leads to high variance in treatment effects and typically anecdotal kinds of information restricted to the stand level (e.g., Biswell et al. 1973; Wagle and Eakle 1979; Helms 1979; Martin et al. 1989). Some of the variability in dNBR in this study was likely related to the widespread, but unknown, forest harvest and thinning activities that occurred throughout the Tribal and Forest Service lands. Thinning and harvesting can reduce vertical and horizontal continuity of the tree canopy and limit initiation and spread of crown fires, especially in conjunction with prescribed burning (van Wagtendonk 1996; Stephens 1998; Graham et al. 2004). The high variance and high relative MSE of the regression tree likely reflects the combined influence of these and other factors not controllable or knowable for this study. For example, we did not have site-specific information on stand structure, the silvicultural or burning prescriptions within the treatment units, or the wildfire characteristics as it crossed the location of every 30-m pixel. Furthermore, the boundaries of the prescribed fire units were largely independent of the many other management activities that have occurred throughout the wildfire and treatment areas. Thus, the large size of the prescribed burn units and inherent variability of prescribed fire within the treated areas precludes a simple characterization of the burn prescription or stand structure existing at the time of the fire. The interaction of different harvesting and burn combinations certainly warrants more study.

Some of the variations in dNBR outside the recorded treatments were associated with past wildfires (Fig. 1*d*). In particular, the Day Fire (1974) center-top, the Cottonwood fire (1976) center-right, and the recent White Springs fire (1996) within the larger Carrizo fire (1971, described by Biswell et al. 1973) are coincident with apparently lower severity in the Rodeo–Chediski fires. In these cases, the reduced dNBR likely results, because little forest vegetation had developed by 2002 limiting the changes in NBR that would be detectable between images taken before and after the Rodeo–Chediski fires.

Evidence of landscape-level effects of treatment units was visible at several places in the Landsat image from 21 June. Most notably, the chevron-shaped holes within the actively spreading fire resulted as a wake effect when the wildfire flanked around the leeward side of the treatment units. Similar lee-side and adjacency effects were reported by Graham (2003) and Weatherspoon and Skinner (1995). Fire growth modeling has demonstrated the reasons for these chevron-shaped fire growth patterns around slower-burning patches (Richards and Bryce 1995; Finney 1998, 2001). By burning more slowly than untreated stands, these recent treatments disrupted fire growth, slowing local fire progress by diverting it laterally. Lateral detours around the downwind sides of treated areas burn by flanking and backing with much lower intensity (Catchpole et al. 1982) and consequently produce less crown damage (Van Wagner 1973, 1977) detectable by the satellite imagery. Such diversions of fire spread are consistent with assumptions of models of landscape-level treatment effects (Finney 2001; Hirsch et al. 2001), where certain patterns of treatment units efficiently retard fire growth across a landscape by causing repeated diversions of fire growth. Within the Rodeo–Chediski fires, however, the units were not arranged to test or produce collective effects at the landscape level, and the units acted similarly to random patterns that disrupt fire growth only when large fractions of the landscape are treated (Finney 2003; Bevers et al. 2004; Loehle 2004; Gill and Bradstock 1998). Even with random patterns, decades of free-burning fires in large wilderness areas can produce a jigsaw puzzle mosaic that becomes complete enough to limit the growth of new fires (van Wagtendonk 1995; Parsons and van Wagtendonk 1996; Rollins et al. 2001).

Landscape level effects of multiple units will depend on complex spatial and temporal interactions between the frequency of new or repeated treatment, the sizes of the units, and the time-dependent lapsing of treatment benefits. The single satellite image provided no opportunity to evaluate effects on fire spread rate of treatments conducted more than 3 years before the wildfire, although prescribed burning reduced fire severity for treatments through 9 years old. After an unknown period of time, fuel recovery will probably allow fire spread rate and intensity to return to pretreatment potential, but prescribed burns conducted on a regular cycle would create a perpetual pattern of many recent and slow-burning fuel patches (Kallander et al. 1955; Biswell et al.

1973; Wagle and Eakle 1979) that can collectively reduce overall fire growth rates. Such mosaic treatments have long been advocated as a landscape fuel management strategy (Kallander et al. 1955; Brackebusch 1973; van Wagtendonk 1995; Gill and Bradstock 1998) to limit rapid fire spread over large distances (Finney 2001; Hirsch et al. 2001) and impose spatial heterogeneity consistent with presettlement fire regimes (Kallander et al. 1955; Cooper 1960; Swetnam and Baisan 1996; Fulé et al. 1997).

Conclusions

Data analyzed for this study suggested that fire growth and severity of a large wildfire under extreme weather conditions were mitigated by fuel treatments that included prescribed burning. Longevity of treatment benefits was suggested to improve with unit size, perhaps because the increased spatial heterogeneity in larger units compensated for varying treatment effects and fuel recovery. High-resolution satellite imagery of fire activity, although rare, revealed fuel treatments in process of diverting fire movement. This is consistent with modelling of landscape treatment patterns that indicates overall fire growth and large fire sizes can be reduced (Finney 2001). The prescribed fire units analyzed here reflect the commitment by land managers to implementing large-scale prescribed burning for fuel treatment. Prescribed fire alone, however, may not be sufficient to achieve structural goals of forest restoration (Weaver 1943; Cooper 1960; Swetnam and Baisan 1996; Fulé et al. 1997), although it will certainly be necessary for long-term maintenance of ecological process.

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