

Comparison of burn severity assessments using Differenced Normalized Burn Ratio and ground data

Allison E. Cocke^{A,B}, Peter Z. Fulé^{A,B,C} and Joseph E. Crouse^B

^ASchool of Forestry, PO Box 15018, Northern Arizona University, Flagstaff, AZ 86011, USA.

^BEcological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011, USA.

^CCorresponding author. Telephone: +1 928 523 1463; fax: +1 928 523 0296, email: pete.fule@nau.edu

Abstract. Burn severity can be mapped using satellite data to detect changes in forest structure and moisture content caused by fires. The 2001 Leroux fire on the Coconino National Forest, Arizona, burned over 18 pre-existing permanent 0.1 ha plots. Plots were re-measured following the fire. Landsat 7 ETM+ imagery and the Differenced Normalized Burn Ratio (Δ NBR) were used to map the fire into four severity levels immediately following the fire (July 2001) and 1 year after the fire (June 2002). Ninety-two Composite Burn Index (CBI) plots were compared to the fire severity maps. Pre- and post-fire plot measurements were also analysed according to their imagery classification. Ground measurements demonstrated differences in forest structure. Areas that were classified as severely burned on the imagery were predominantly *Pinus ponderosa* stands. Tree density and basal area, snag density and fine fuel accumulation were associated with severity levels. Tree mortality was not greatest in severely burned areas, indicating that the Δ NBR is comprehensive in rating burn severity by incorporating multiple forest strata. While the Δ NBR was less accurate at mapping perimeters, the method was reliable for mapping severely burned areas that may need immediate or long-term post-fire recovery.

Additional keywords: Arizona; mixed conifer forest; ponderosa pine.

Introduction

Burn severity is a function of physical and ecological changes caused by fire. Fires burn heterogeneously across landscapes, with unburned and lightly burned patches interspersed among severely burned patches, due to variability in weather and landscape patterns (Hall *et al.* 1980; Van Wagner 1983; Turner and Romme 1994; Cochrane and Schulze 1999). Fire spread and severity have been associated with abiotic factors including weather, moisture and slope (Romme and Knight 1981; Christensen *et al.* 1989). Severity can also be highly influenced by biotic conditions including tree size, successional stage and pathogens (Turner *et al.* 1999). Mapping of burn severity provides information to target recovery activities efficiently (Lachowski *et al.* 1997; Sunar and Ozkan 2001; Miller and Yool 2002). Large burned patches may negatively impact wildlife nesting and browsing (Romme and Knight 1981). Vegetation mortality changes water loss through evapotranspiration, surface flow and subsurface flow. High-severity burns often increase hydrophobic soil conditions, leading to increased runoff and erosion compared to less severely burned areas (Robichaud *et al.* 2000). Unburned and low burn areas are seed sources for more severely impacted

areas, which usually have fewer surviving and re-sprouting individuals (White *et al.* 1996).

In this study, burn severity is being measured in the context of the fire's ecological impacts (e.g. plant mortality, understory and forest floor effects, etc.). Unfortunately, burn severity is difficult to define and quantify. Key and Benson (2005) observed that 'no common standard' exists. Therefore, a number of quantitative and qualitative estimates are often used to rate areas and the choice of fire-related variables depends largely on management and ecological objectives, and sampling scale (Ryan and Noste 1985; Key and Benson 2005). Differences may exist between assessing burn severity from the ground compared to remotely sensed data. Imagery integrates changes in all parts of the forest, such as those on the ground and in the tree canopy (White *et al.* 1996); therefore, at least some field assessment is usually necessary to clarify which parts of the forest strata were affected.

Image differencing is one of the most accurate methods of change detection (Muchoney and Haack 1994; Coppin and Bauer 1996; Kushla and Ripple 1998) and data normalization may lead to higher accuracy (Bertolette and Spotskey 2001). The most frequently used technique in detecting

burn severity is the Normalized Difference Vegetation Index (NDVI), which uses bands in visible and infrared parts of the spectrum (Salvador *et al.* 2000). However, NDVI is inaccurate where fires occur after vegetation has died (Eva and Lambin 1998) as well as in areas that had little vegetation before the disturbance (Rogan and Yool 2001). Wilson and Sader (2002), however, found that differencing bands 4 and 5 had high accuracy to detect forest harvest. Likewise, Xiao *et al.* (2002) found this combination useful when classifying forest types. Chuvieco *et al.* (2002) examined indices using combinations of bands 3 and 5 as well as bands 3 and 7 to estimate water content of live fuels for fire danger. However, any method using bands in the visible part of the spectrum is susceptible to atmospheric interference from dust and smoke (Avery and Berlin 1992; Eva and Lambin 1998). Accordingly, several studies have concluded that using short-wave infrared bands to analyse burn severity provides highest accuracies (White *et al.* 1996; Roy *et al.* 1999; Rogan and Yool 2001).

Recently, the Joint NPS-USGS National Burn Severity Mapping Project implemented a method called the Normalized Burn Ratio (NBR) of bands 4 and 7 to map fires (Key and Benson 2005). The difference between pre-fire and post-fire NBR, ΔNBR , is now the primary method for mapping large remote fires on public lands. A ground assessment method, the Composite Burn Index (CBI), was developed along with the ΔNBR . This method rates all layers of the forest that are affected in a fire, resulting in a single value that can be compared to the satellite imagery. Because there is no universal definition of burn severity, neither ΔNBR nor CBI can be said to represent the 'true' severity. However, the degree to which these two systems are related to each other is an important question because of the high cost of fire rehabilitation activities that are based on burn severity maps.

We compared ΔNBR , CBI and permanent plots measured before and after fire on a wildfire that burned over previously measured plots covering a broad range of elevation, fuels, and community types, resulting in varying burn severity levels. We re-measured the permanent plots and compared the fire severity with satellite imagery classified with ΔNBR . Our objectives were: (1) to assess the agreement between ΔNBR and CBI in differentiating burn severity levels; (2) to compare pre-fire and post-fire measurements on permanent plots with severity type as classified by the ΔNBR ; and (3) to evaluate the characteristics of forest areas that burned with different severity levels.

Study area

The study area was the Leroux fire on the south side of the San Francisco Peaks, Coconino National Forest, north of Flagstaff, Arizona (lat. $35^{\circ}18' \text{ N}$, long. $111^{\circ}41' \text{ W}$). Tree species included ponderosa pine (*Pinus ponderosa* var. *scopulorum* P. & C. Lawson), quaking aspen (*Populus tremuloides* Michx.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca* (Beissn.) Franco), Limber pine (*Pinus flexilis*

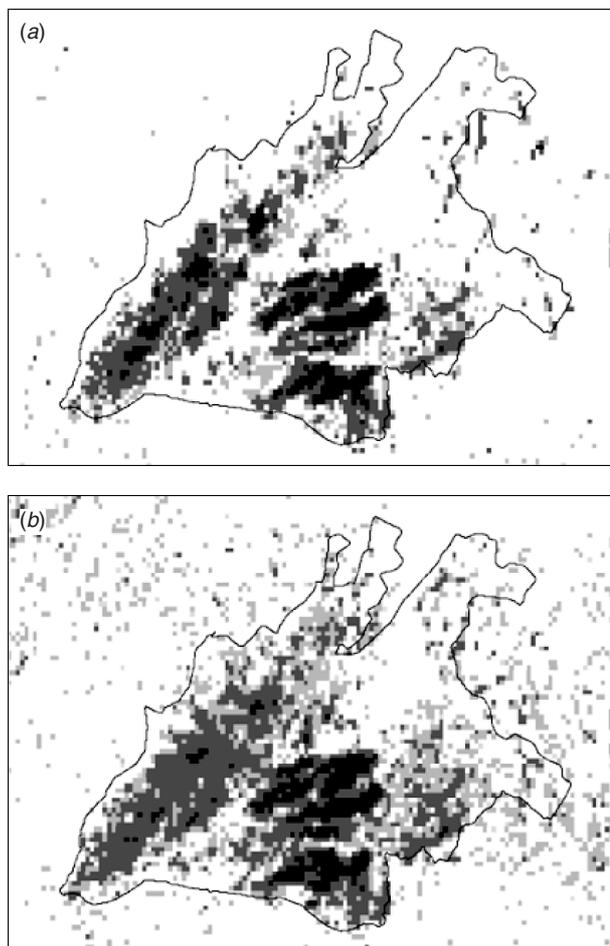


Fig. 1. Burn severity maps from 2001 (a) and 2002 (b). Dark areas are most severely burned and white areas are unburned.

James), and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). The closest available weather data were from the Fort Valley weather station (www.wrcc.dri.edu); 1909–2001 mean January temperatures were 5.2°C maximum and -12.3°C minimum. Mean July temperatures were 26.7°C maximum and 7.1°C minimum. Mean annual precipitation was 56.9 cm.

The Leroux fire started on 11 June 2001 and was contained by 19 June 2001. The interior continued to burn through late June with some flare-ups in early July, eventually covering over 500 ha (Fig. 1). Maximum daily temperatures measured at the Fort Valley weather station from 11 to 19 June 2001 ranged from 21.1°C to 29.4°C , with average maximum temperature of 26.5°C . Minimum temperatures ranged from -6.1°C to 3.8°C , with an average of -0.19°C . Precipitation was minimal with less than 0.03 cm daily or a total of 0.18 cm during the week before containment. Wind data were not available at Fort Valley, but wind speeds averaged 13.5 km h^{-1} (kph) at Pulliam Airport in Flagstaff. Maximum wind speeds that held constant for 5 s reached up to

64.4 kph, and maximum wind speeds that held constant for 2 min reached 48.3 kph.

Methods

Image processing

Pre-burn imagery was acquired with Landsat 7 ETM+ path 37, row 35 on 6 June 2000. Following the recommendation of Key and Benson (2005), we used a post-burn image (2001) for immediate assessment after the fire as well as for choosing ground-truthing sites (CBI), and a later image (2002) for a 1-year post-fire assessment. The 2002 image coincided with re-measurement of permanent plots in that year. Post-burn images were Landsat 7 ETM+ for path 37, row 35 from 27 July 2001 and 12 June 2002. Image date can affect ΔNBR analysis, so the 2000 and 2002 images were selected as close together as possible (June). The July image in 2001 was the earliest available after the fire. All images had 30-m resolution. Images were received terrain-corrected; this involved an algorithm using digital elevation models to correct for displacement. ERDAS Imagine (Erdas, Inc., Atlanta, GA, USA) was used to perform all image processing functions. The images were registered to each other using nearest neighbor re-sampling and a second-order polynomial model (Lillesand and Kiefer 1994). We used at least 80 ground control points for each image. Root mean square errors were 0.5 m for the 2000–2002 registration, and 4.0 m for the 2000–2001 registration (Lillesand and Kiefer 1994; Jensen 1996).

Raw DN values were converted to radiance values as in Markham and Barker (1986). This conversion accounted for gain and bias, daily sun angle variation, earth–sun distances, and exo-atmospheric solar irradiance. The need for atmospheric normalization was tested (Eckhardt *et al.* 1991; Jensen 1996) but found unnecessary because the coefficient of determination was larger than 0.98 in each case (Jensen 1996; Key and Benson 2005).

The NBR was calculated for all three images using the equation $(\text{TM4} - \text{TM7})/(\text{TM4} + \text{TM7})$, where TM4 and TM7 were Thematic Mapper bands 4 and 7 respectively (Key and Benson 2005). Band 4 covered wavelengths 0.76–0.90 μm (near-infrared) and band 7 covered wavelengths 2.08–2.35 μm (middle-infrared). We calculated $\Delta\text{NBR} = \text{NBR}_{\text{prefire}} - \text{NBR}_{\text{postfire}}$, for both 2000–2001 and 2000–2002. Values of zero indicated no change and numbers farther from zero indicated greater change. Resulting digital number values from ΔNBR were divided into four burn severity classes following the procedures suggested by the Fire Effects Inventory and Monitoring Protocol (Key and Benson 2005), except that we used only four rather than seven categories: unburned (≤ 50), low (51–240), moderate (241–570), and high (≥ 571). Aerial photos and field notes were used to help interpret the satellite image and select burn thresholds. High-severity areas were those that experienced the most alteration

following the fire, such as high tree mortality, high consumption of ground fuels and lack of post-fire regeneration. Low-severity areas had lower mortality, low fuel consumption and higher amounts of regeneration. From here on, the 2000–2001 differenced image will be referred to as the 2001 burn map, and the 2000–2002 differenced image will be referred to as the 2002 burn map.

Composite Burn Index plots

The CBI, a rating of up to 22 factors from overstory, shrubs and saplings, herbaceous understory, soils and fuels, was used to collect ground data (Key and Benson 2005). We selected CBI locations from the 2001 burn map by stratified random sampling in the four severity levels, choosing sites within 3×3 pixels (0.81 ha) (Congalton 2001) to reduce global positioning system error and edge effects. A four-pixel filter was used where CBI plots fell on severity level edges. Key and Benson (2005) recommended sampling 20–40 plots per severity type. However, the small size of the fire constrained sample size because there were insufficient homogeneous 3×3 pixel areas. Therefore we carried out CBI sampling with 17 unburned plots, 35 low severity plots, 25 moderate severity plots, and 15 high severity plots.

The ΔNBR and CBI values were compared with Kappa analysis (KHAT). ‘Errors’ were defined as misclassifications in which the ΔNBR analysis indicated burning at a point that was found not to have been burned, or vice versa, when visited on the ground for CBI sampling. Other instances of differences in classification between the ΔNBR and CBI systems were referred to as ‘inconsistencies’. KHAT was also used to determine whether inconsistency matrices were significantly different than each other (Congalton and Green 1999). An α level of 0.05 was used for the Kappa statistic.

Permanent plots: pre-fire and post-fire measurements

Before the fire, we had established permanent study plots in 2000 for research on forest structure of the San Francisco Peaks (Cocke 2004). Sampling plot centers were located from a systematic grid 300 m N–S and 300 m or 600 m E–W. Eighteen plots were within the perimeter of the Leroux Fire. Plots were 0.1 ha (20×50 m) in size. Tree species, diameter at breast height (dbh), height, and condition were measured. Seedling trees, those below 2.5 cm dbh, were tallied by species, conditions, and height class in a 50 m^2 subplot. Importance values (the sum of the relative frequency and relative abundance for each species) were calculated for each plot to determine dominant species (Taylor 2000). Understory vegetation cover and tree canopy cover were sampled along point line–intercept transects (the two 50-m sidelines of each plot). Canopy cover and understory herbaceous vegetation measurements had been completed on only 14 of the 18 plots before the Leroux Fire. Forest floor and woody debris were measured along four 15.24 m planar intersect transects per plot (Brown 1974). Woody debris was recorded

by size/timelag classes (Anderson 1982): 1, 10, 100, and 1000-h (sound and rotten) fuels and litter (L layer, undecomposed material) and duff (F and H layers, decomposing materials or humus) depths were measured.

In 2002, all 18 of the burned plots, and 6 unburned plots that were randomly selected from near the fire, were re-measured. For trees, we recorded condition class, char and scorch heights, and percentage crown scorch following procedures outlined by NPS (2003). Fuels were re-measured along the original transects. We also recorded substrate burn severity levels at the litter and duff measurement points. These were rated on a scale of 1–4, with 1 being the most affected (NPS 2003).

We used the 2002 Δ NBR burn severity map to classify the 24 permanent plots by severity level. Because permanent plots were 50 × 20 m and centerline azimuth was based on topography rather than on a specific bearing, plots did not coincide with individual pixels. We used the pixel around plot centre, as this 30 × 30 m area covered the greatest proportion of the plot. However, if plot locations appeared unburned according to the map, but were within one pixel of a burned plot, then the plot was considered low severity. For the 2002 image, there were six low severity plots, eight moderate severity plots, and four high severity plots. From here on, the combination of high severity plots will be referred to as HI. The other categories will be referred to as MD, LO and UN.

Statistical findings are presented only where there was significance. Normality of the permanent plot data was assessed graphically and values were logarithmically transformed where necessary to meet assumptions of ANOVA. Pre-fire differences in live tree density, live tree basal area, snag density, seedling density, substrate, canopy cover, litter depths, duff depths, fine fuels, coarse fuels, percentage scorch, and scorch and char heights between severity levels were compared with ANOVA (e.g. to compare live tree densities between severity levels before the fire). Following an overall significant ANOVA result, Tukey's Honest Significant Difference test was used to test for significant differences between severity levels. Paired *t*-tests were used to test differences before and after the fire on variables within each severity type including live tree density, live tree basal area, snag density, seedling density, canopy cover, litter depths, duff depths, fine fuels, and coarse fuels. The α level for all tests was 0.05.

Results

Comparison of Δ NBR and CBI

The Δ NBR and CBI methods had an overall agreement of 75% for the 2001 burn map and 73% for the 2002 burn map (Table 1). Producer's and user's accuracies, calculated with values in the error matrix (Table 2), present agreement between the Δ NBR and CBI in each severity level. For example in 2001, 100% of the plots unburned on the ground were

also found to be unburned on the map. However, only 71% of the plots that were unburned on the map were also unburned on the ground. These accuracies show the inconsistencies between all severity levels.

Scatter plots of Δ NBR v. CBI by image year showed a relatively strong correlation; *r* was 0.84 ($P < 0.001$) for both 2001 and 2002 (Fig. 2). In 2001, the largest source of error was confusion between unburned and low severity areas (32% of errors) when some low severity areas appeared unburned on the imagery (Table 2). In 2002, most misclassifications also occurred between unburned and low severity areas (40%) but, unlike 2001, the analysis showed burns in unburned areas. In 2001, there were two cases where classifications differed by more than one severity level (the ground data suggested that these two plots had high severities while they appeared as low severity on the map). Differences of more than one class did not occur in 2002. High severity areas had the lowest degree of inconsistent classification in both years.

Table 1. Agreement between Differenced Normalized Burn Ratio (Δ NBR) and Composite Burn Index (CBI) for 2001 and 2002 burn maps

The term 'accuracy' refers to the degree to which Δ NBR values matched CBI values. KHAT, kappa analysis

	2001		2002	
	Producer's accuracy	User's accuracy	Producer's accuracy	User's accuracy
Severity (%)				
Unburned	100	70.8	58.8	76.9
Low	71.4	78.1	74.3	70.3
Moderate	60	78.9	76	67.9
High	80	70.6	80	85.7
Overall	75.0		72.8	
KHAT	0.659		0.619	
Variance	0.0038		0.0043	
Z-statistic	10.65		9.40	

Table 2. Error matrices between Differenced Normalized Burn Ratio (Δ NBR) and Composite Burn Index (CBI) for 2001 and 2002

	Ground				Row total
	Unburned	Low	Moderate	High	
2001 matrix					
Image unburned	17	7	0	0	24
Image low	0	25	5	2	32
Image moderate	0	3	15	1	19
Image high	0	0	5	12	17
Column total	17	35	25	15	92
2002 matrix					
Image unburned	10	3	0	0	13
Image low	7	26	4	0	37
Image moderate	0	6	19	3	28
Image high	0	0	2	12	14
Column total	17	35	25	15	92

KHAT (kappa analysis) statistics were 66% for the 2001 burn map and 62% for the 2002 burn map, showing that the agreement of Δ NBR and CBI in both maps was statistically better than chance (Table 1) (Lillesand and Kiefer 1994; Congalton and Green 1999). Classifications for 2001 and 2002 were not significantly different from each other ($Z = 0.442$) (Congalton and Green 1999).

Permanent plot data: overstory

As measured on the 18 burned permanent plots, the fire burned more severely in areas dominated by ponderosa pine and areas located on flatter slopes and lower elevations. Ponderosa pine was always dominant in HI (in all cases, importance value was >91% ponderosa pine). For MD, four of the plots were predominantly ponderosa pine, two were predominantly aspen, and two were mixed conifer (Douglas-fir, limber pine, ponderosa pine). For LO, four were dominated by ponderosa pine, one was mixed conifer, and one was aspen. For HI plots average slope = 15%, followed by MD = 17.8%, and LO = 18.3%. Elevations were also lowest for HI, with average elevation 2594 m, MD = 2648 m, and LO = 2624 m. All plots were south-facing and aspect differences were minor.

Tree mortality was greatest in areas of high pre-fire tree density, especially dense ponderosa pine (Fig. 3). Pre-fire densities were greatest in HI (1400 trees ha⁻¹) and lowest in LO (638 trees ha⁻¹) (Table 3). The fire reduced live tree

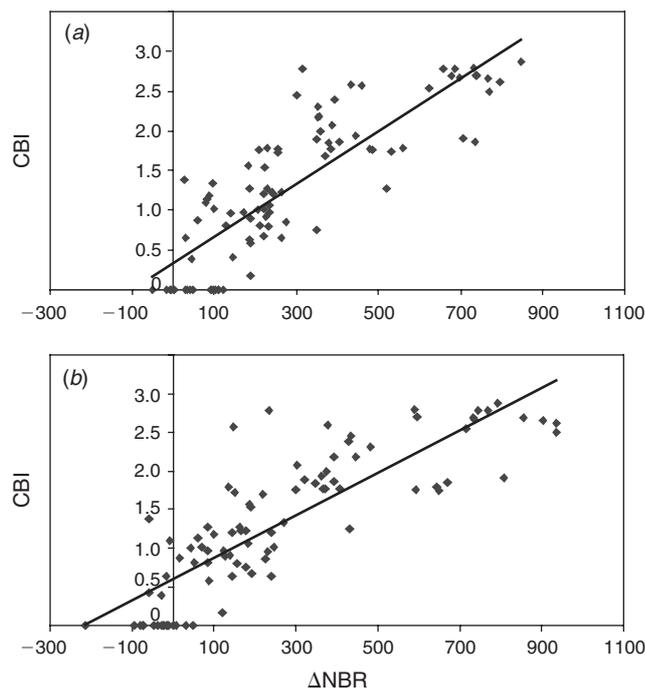


Fig. 2. Differenced Normalized Burn Ratio (Δ NBR) v. Composite Burn Index (CBI) for 2001 (a) and 2002 (b) showing correlation between satellite data and ground measurements.

density in all severity levels. Because the HI plots were predominantly ponderosa pine before the fire, this resulted in only 41% mortality of ponderosa, while limber pine experienced 86% mortality. Similarly, all *P. menziesii* in HI plots were killed. Thus, a higher proportion of the fire resistant ponderosa pine was killed in MD v. HI (Fig. 4). Overall percent decrease was greatest in MD (69%).

High burn severity was associated with high pre-fire density and basal area of snags (Table 4). Pre-fire differences were significant between HI and LO (Tukey, $P = 0.027$) and HI and MD (Tukey, $P = 0.006$). Post-fire snag density was greatest in HI (880 trees ha⁻¹), although post-fire snag basal area was slightly lower in HI (19.9 m² ha⁻¹) than MD (20.1 m² ha⁻¹). However, relative increase in snags was greatest in MD (1162%) compared to HI (123%), LO (196%) and UN (decreased by 25%). Snags with dbh ≥ 50 cm, often the most important for wildlife, had high survival rates (Table 5). About half of these large snags fell during the fire, but more new large snags were created. On the 18 permanent plots, only one of the 18 large trees that died during the fire also fell; 17 remained standing.

Fire effects on individual trees, crown scorch, and bole char were greatest in higher burn severity areas. Crown scorch occurred on 72% of trees for HI, 63% for MD and 49% for LO. Charring occurred on 99.6% of trees in HI, 76.1% in MD and 83.8% in LO. The percentage of crown volume lost to scorch was 50%, 53% and 29% for HI, MD and LO respectively. Average scorch height for surviving trees that scorched were 9.9 m, 9.1 m and 7.1 m for HI, MD and LO, respectively, while average char on affected trees was 2.2 m, 2.2 m and 1.1 m.

The highest burn severity occurred in areas with low tree regeneration density. Before the fire, density in HI was 809 seedlings ha⁻¹, MD had 1257 seedlings ha⁻¹, LO had 2564

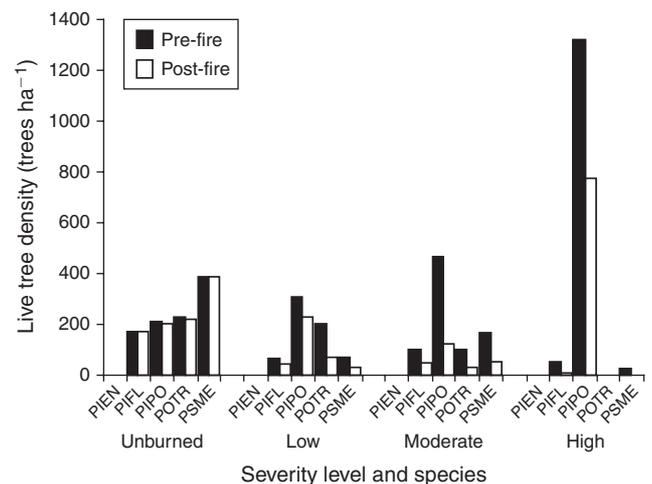


Fig. 3. Live tree density (trees ha⁻¹) by severity level and species in the 18 burned and six unburned permanent plots. PIEN, *Picea engelmannii*; PIFL, *Pinus flexilis*; PIPO, *Pinus ponderosa*; POTR, *Populus tremuloides*; PSME, *Pseudotsuga menziesii*.

Table 3. Changes in live tree density and basal areas on 18 burned and six unburned permanent plots with pre- and post-fire measurements

Severity	Density			Basal area			Sample size
	Pre-fire (trees ha ⁻¹)	Post-fire (trees ha ⁻¹)	Change (%)	Pre-fire (m ² ha ⁻¹)	Post-fire (m ² trees ha ⁻¹)	Change (%)	
Unburned	1000.9	969.9	3.1	32.3	31.0	4.0	6
Low	637.9	372.1	41.7	37.0	32.2	13.0	6
Moderate	829.1	256.7	69.0	38.9	19.4	50.1	8
High	1400.1	786.0	43.9	48.0	33.8	29.6	4

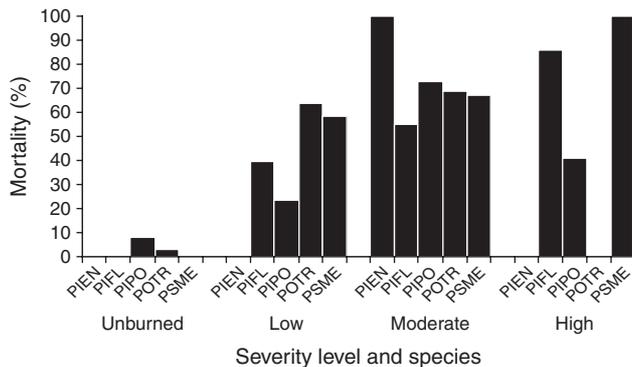


Fig. 4. Percentage mortality of each species within each severity level in the 18 burned and six unburned permanent plots. PIEN, *Picea engelmannii*; PIFL, *Pinus flexilis*; PIPO, *Pinus ponderosa*; POTR, *Populus tremuloides*; PSME, *Pseudotsuga menziesii*.

Table 4. Density and basal area of standing dead trees on 18 burned and six unburned permanent plots with pre- and post-fire measurements
BA, basal area

Severity	Pre-fire snag (trees ha ⁻¹)	Post-fire snag (trees ha ⁻¹)	Pre-fire snag BA (m ² ha ⁻¹)	Post-fire snag BA (m ² ha ⁻¹)
Unburned	138.7	103.4	4.8	5.2
Low	93.9	277.8	4.2	6.2
Moderate	44.6	563.2	4.6	20.1
High	394.7	880.0	6.7	19.9

seedlings ha⁻¹ and UN had 3063 seedlings ha⁻¹. All severity levels included four species (limber pine, ponderosa pine, aspen and Douglas-fir), except that HI did not include limber pine (Table 6). After the fire, there was a 44% decrease in seedlings in HI, while there was a 156% increase in LO and a 429% increase in MD.

Permanent plot data: surface fuels, soil, and understory

Forest floor consumption was greatest in the areas that had deepest pre-fire litter and duff layers. Before the fire, litter depths averaged 2.3 cm for HI, 1.4 cm for MD and 1.5 cm for LO. Duff depths averaged 4 cm for HI, 2.3 for MD and 2.6 for LO. HI litter decreased by 50.1% and duff decreased by 82.7%. Declines in MD were 22.0% and 71.1% while changes

Table 5. The fate of snags and large trees (≥50 cm dbh) on 18 burned permanent plots with pre- and post-fire measurements

	Limber pine	Aspen	Ponderosa pine	Douglas-fir	Total
Snags					
Remained standing	1	17	65	3	86
Fell	3	27	42	2	74
Large trees (≥50 cm)					
Remained alive	21	12	4	10	47
Died during fire	3	1	13	1	18
Dead and remained standing	0	0	5	0	5
Dead and fell	1	0	6	1	8

Table 6. Pre- and post-fire conifer seedlings and aspen sprouts per hectare categorized by severity level and species on 18 burned and six unburned permanent plots with pre- and post-fire measurements
Standard deviations are in parentheses

Severity	Species	Pre-fire	Post-fire
Unburned	Limber pine	291.3 (713.6)	291.3 (713.6)
	Ponderosa pine	34.1 (83.6)	34.1 (83.6)
	Aspen	2495.8 (2809.7)	2183.8 (3427.6)
	Douglas-fir	241.6 (416.2)	444.2 (891.2)
Low	Limber pine	101.0 (247.3)	0
	Ponderosa pine	2019.5 (3221.1)	0
	Aspen	374.8 (734.5)	6568.4 (14436.6)
	Douglas-fir	68.3 (105.8)	0.0
Moderate	Limber pine	50.6 (143.0)	0
	Ponderosa pine	153.8 (286.7)	0
	Aspen	1001.2 (2596.0)	6650.4 (9764.1)
	Douglas-fir	51.1 (94.6)	0
High	Limber pine	0	0
	Ponderosa pine	404.5 (572.0)	0
	Aspen	353.9 (707.8)	455.0 (910.1)
	Douglas-fir	50.6 (101.1)	0

in LO were 29.7% and 62.8% in litter and duff respectively. Decreases in litter were significant only in HI (paired *t*-test, *P* = 0.009). Differences in duff were significant in HI (paired *t*-test, *P* = 0.038), LO (*P* < 0.001) and MD (*P* < 0.001). Following the fire, litter depths averaged 1.1 cm for all three severity levels. MD and HI both had post-fire average duff

Table 7. Percentage change or rating of several variables in the different burn severity levels on 18 permanent plots with pre- and post-fire measurements

Changes were not always greatest per factor in HI areas, although overall differences were greatest in HI. HI, high severity plot; LO, low severity plot; MD moderate severity plot

Variable	HI	MD	LO
Overstory mortality (%)	52	56	28
Regeneration change (%)	-28	>467	352
Understory cover (%)	69	41	49
Substrate rating ^A	2.0	2.4	2.3

^ALower number = greater burn effect.

depths of 0.7 cm, while LO maintained a slightly deeper duff layer of 1.0 cm.

Fire severity had little relation to coarse woody debris. Pre-fire fuels less than 7.6 cm diameter (0–100 h fuels) averaged 8.9 Mg ha⁻¹ in MD, 7.0 Mg ha⁻¹ in LO, 6.1 Mg ha⁻¹ in HI and 9.5 Mg ha⁻¹ in UN. Decreases were significant only in LO (paired *t*-test, $P < 0.001$), with post-fire values of 2.7 Mg ha⁻¹ for LO (62% decrease), 6.0 Mg ha⁻¹ for MD (32%) and 3.1 Mg ha⁻¹ for HI (49%). Similar to the finer fuels, moderately burned areas had highest pre-fire heavy fuels (greater than 7.6 cm diameter, 1000-h fuels), but experienced the greatest change and had least fuels following the fire. MD had 119.8 Mg ha⁻¹, LO had 94.8 Mg ha⁻¹ and HI had 22.9 Mg ha⁻¹ of 1000-h fuels. UN had 60.0 Mg ha⁻¹ before the fire. Change was greatest in MD (93%), then LO (80%), and lowest in HI (47%). Decreases were significant in LO (paired *t*-test $P \leq 0.001$). Post-fire 1000 h fuel values were 18.6 Mg ha⁻¹ for LO, 8.3 Mg ha⁻¹ for MD and 12.1 Mg ha⁻¹ for HI.

Understory herbaceous cover was lowest in severely burned plots, both before and after the fire, but still experienced greatest overall change. HI experienced 69% average cover decrease (from 18% to 5%), whereas MD and LO decreased by 41% (from 40% to 24%) and 49% (from 28% to 15%) respectively.

Summarizing the changes on permanent plots, most variables changed in a manner consistent with the burn severity assigned to each plot in the Δ NBR analysis (Table 7). The substrate burn severity rating system, a qualitative measurement, showed greatest severity in HI. The HI plots also experienced the highest decline in understory cover and regeneration (Table 7).

Discussion

Comparison of Δ NBR and CBI

The Δ NBR and CBI were relatively consistent in mapping burn severity, especially in high severity areas, similar to the findings of Van Wagendonk *et al.* (2004) in a California fire. Inaccuracies in Δ NBR occurred between unburned and low

burn areas. One type of error, when areas that had burned appeared unburned on the imagery, occurred on 7.6% of the CBI plots in the 2001 map and 3.3% in the 2002 map. This misclassification may be due to re-growth of vegetation after the fire. Fuller and Fulk (2001) found that post-fire vegetation re-growth in Indonesia altered reflectances causing error between unburned and burned areas; this has also occurred within 1 year of a fire in Alaska tundra (Hall *et al.* 1980). Detecting accurate fire perimeters is difficult if the post-burn imagery is acquired at least one growing season following the fire. Thus, if mapping fire perimeters is the main objective, it should be done soon after the fire (White *et al.* 1996). In northern Arizona, most fires occur in early summer (Grissino-Mayer *et al.* 1995) before the monsoonal rains, when most vegetation growth occurs. Within a few months of the fire, some areas of the Leroux experienced high re-growth and the burn became difficult to detect, especially in meadows. Rapid initial assessment is therefore important for burn perimeter mapping in the Southwest.

In the 2002 burn map, the largest errors occurred where the imagery showed low severity burns in areas that did not burn, occurring on 6.5% of the plots. During drought, moisture content may be as low in areas that did not burn as areas that were lightly burned. Because the two bands used in the Δ NBR are sensitive to vegetation and soil moisture, low severity burns and unburned areas are less distinguishable in extreme drought (Key and Benson 2005). Furthermore, 2001 was not an extremely dry year; there were no errors where the Δ NBR showed burns in areas that had not burned on the 2001 burn map. However, perhaps the most common reason to study burn severity is to target areas for recovery. Detecting high burn areas was the most accurate and these areas changed only 12.5% from 2001 to 2002. The borders of severely burned areas continued to be distinct, while other severity classes blurred at a faster rate, similar to the findings of Hall *et al.* (1980). In sum, extended assessment performed equally as well as initial assessment for high severity mapping for the Leroux fire.

The use of fewer severity classes, such as combining low and unburned classes, should increase consistency but may reduce the utility of the map for managers. Miller and Yool (2002) found that three burn classes had higher agreement (KHAT > 0.7) than four burn classes. However, we used four burn classes but obtained agreement similar to Miller and Yool's supervised classification.

Overall, the Δ NBR was useful for examining immediate effects of the fire and longer-term effects, as the 2001 and 2002 burn maps were not statistically different. However, there were several sources of inconsistencies. The qualitative series of estimates that comprise the CBI may have varied over time and between measurers. Another concern in northern Arizona results from the timing of fire season prior to monsoonal rains. In 2001, rain caused considerable erosion in the burned areas, as evidenced by exposed drainages and

roots, as well as very heavy litter and duff deposition on the uphill sides of trees. Therefore, some evidence of fire severity may have been lost. The issue of edge was also a concern. While we avoided edges when placing the CBI plots, this was not possible with the 24 pre-existing permanent plots, so some plots were on severity level edges. Using different size filters (4 pixels and 9 pixels) produced variable results. Therefore, scale must be carefully considered when performing this type of analysis.

Comparing Δ NBR with detailed ground measurements

Ground-based fire severity from permanent plots was strongly associated with satellite-based severity in which multiple variables, not just tree mortality, comprise burn severity. The greatest tree mortality occurred in MD rather than HI, but species composition played a large role. Many trees that were killed in lower severity levels were aspen, which are more susceptible to heat (Brown and DeByle 1987). For example, one HI plot had 29% mortality but was dominated by ponderosa pine. Likewise, one MD plot had 80% mortality but was dominated by aspen. Because less heat is required to kill aspen (Jones and DeByle 1985), burn severity was not necessarily higher where mortality was higher. Clearly, tree mortality is not the only important factor in burn severity and the imagery did detect a combination of factors. For example, the HI plot with 29% overstory mortality experienced 70% decrease in understory cover, whereas the MD plot with 80% overstory mortality experienced an understory decrease of only 5%. Similarly, plots with greatest mortality did not necessarily have the highest substrate severity ratings. The highest severity rating occurred on a plot with low tree mortality. Regeneration also demonstrated these patterns. Although mortality was high on some MD plots, large amounts of aspen re-growth may have dominated in the imagery. HI plots had very little aspen regrowth. The data suggest that one attribute of a plot can be severely affected while other attributes are minimally affected and that the imagery is detecting these combinations (Table 7).

Examining the multiple effects of a fire becomes a challenge as imagery cannot distinguish whether severity ratings come from overstory, soils, or understory. Because the Δ NBR comprehensively assesses burn severity, managers must understand the consequences of using this method. Before management objectives are clarified, it is important to assess areas on the ground. Procedures followed in Burned Area Emergency Rehabilitation (BAER) include immediate analysis of burned areas and rehabilitation (Robichaud *et al.* 2000). BAER measurements include severity, intensity, soil color changes, grass root crowns, shrubs, channel bottoms, water resources values and recovery. This type of ground assessment can be used to select appropriate management actions, minimizing the use of less desirable methods such as using non-native seeds (Caetano 1995).

Can we determine what caused some areas to burn with more severity?

The present study cannot be applied to predict effects of other fires in the region, but it is of interest to evaluate the association between pre-fire forest structure, composition, and fuels and fire severity. Because the size and intensity of wild-fires are increasing in south-western forests (Covington 2000; Swetnam and Baisan 2003), links between forest characteristics and potential fire behavior could be useful for prioritizing fuel treatments.

Despite its small size, the Leroux Fire burned in a mosaic of unburned to severely burned areas at fairly fine scales, but with some clear differences in severity that were related to pre-fire conditions.

Burn severity was greatest in dense areas with high basal areas, especially those that were dominated by ponderosa pine. Ponderosa pine density is very high in the Southwest due to fire suppression policies of the last century (Weaver 1951; Cooper 1960; Covington and Moore 1994). Increases in tree density have led to increases in canopy cover, fuel loadings, and vertical and horizontal fuel continuity (Anderson and Brown 1988; Covington and Moore 1994). Severely burned areas were also characterized by high pre-fire snag densities and greater pre-fire litter and duff depths than other severity levels. The loose arrangement of needles in ponderosa pine stands fosters greater flammability, compared with shorter-needle pines (Anderson and Brown 1988) and aspen stands (Jones and DeByle 1985; Dahms and Geils 1997). Duff serves as a relatively long-burning fuel, although residence time is affected not only by depth (Sackett 1988) but also by soil moisture content, duff moisture content, and the ratio of organic to inorganic content (Frandsen and Ryan 1986; Frandsen 1987; Ryan and Frandsen 1991; Hartford and Frandsen 1992).

In contrast, severe burning was not associated with steeper slopes, higher elevation, or pre-fire coarse woody debris, which was actually lowest in the most severely burned areas. These counter-intuitive results suggest that the influence of flammable ponderosa pine vegetation and surface fuels was greater than other factors in affecting severity of the Leroux fire. As many mountain ranges in the Southwest share similar elevational gradients from ponderosa pine up through mixed conifer and aspen forests, fuel reduction treatments might be most beneficial for the entire landscape if focused on the low-elevation ponderosa pine vegetation type.

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