



Relative suitability of indices derived from Landsat ETM+ and SPOT 5 for detecting fire severity in sagebrush steppe

J. Norton^a, N. Glenn^{b,*}, M. Germino^c, K. Weber^d, S. Seefeldt^e

^a Power Engineers, 3940 Glenbrook Dr, Hailey, ID 83333, United States

^b Idaho State University, Department of Geosciences, 322 E. Front St, Suite 240, Boise, ID 83702, United States

^c Idaho State University, Department of Biological Sciences, Box 8007, Pocatello, ID 83209, United States

^d Idaho State University, GIS TRC, Pocatello, ID 83209, United States

^e USDA-ARS Subarctic Agricultural Research Unit, Rm. 355 O'Neill Bldg, University of Alaska Fairbanks, Fairbanks, AK 99775, United States

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ABSTRACT

Remote sensing indices of burn area and fire severity have been developed and tested for forest ecosystems, but not sparsely vegetated, desert shrub-steppe in which large wildfires are a common occurrence and a major issue for land management. We compared the performance of remote sensing indices for detecting burn area and fire severity with extensive ground-based cover assessments made before and after the prescribed burning of a 3 km² shrub-steppe area. The remote sensing indices were based on either Landsat 7 ETM+ or SPOT 5 data, using either single or multiple dates of imagery. The indices delineating burned versus unburned areas had better overall, User, and Producer's accuracies than indices delineating levels of fire severity. The Soil Adjusted Vegetation Index (SAVI) calculated from SPOT had the greatest overall accuracy (100%) in delineating burned versus unburned areas. The relative differenced Normalized Burn Ratio (RdNBR) using Landsat ETM+ provided the highest accuracies (73% overall accuracy) for delineating fire severity. Though SPOT's spatial resolution likely conferred advantages for determining burn boundaries, the higher spectral resolution (particularly band 7, 2.21 μm) of Landsat ETM+ may be necessary for detecting differences in fire severity in sparsely vegetated shrub-steppe.

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1. Introduction

Sagebrush steppe communities evolved with regular and expansive wildfires, but wildfires are becoming an increasingly widespread agent of change making it a dominant land management issue in some parts of the world (Whisenant, 1990). Satellite data are useful for examining fire effects because they (1) can be used to qualitatively and quantitatively evaluate vegetation over multi-temporal and -spatial scales, (2) can be cost effective, (3) systematically cover large and inaccessible areas, and (4) capture data from parts of the electromagnetic spectrum (i.e. infrared) that provide useful information specific to vegetation and soils. Remote detection of burns and their severity requires sensitivity of imagery and calculations of vegetation change.

Definitions of fire severity differ among studies, as does the amount of time between the fire and severity assessment (Key and

Benson, 2006; Lentile et al., 2006; Miller and Yool, 2002; Roy et al., 2006; Ryan and Noste, 1983). Fire severity is defined for the current study as the completeness of above-ground vegetation removal due to fire, measured immediately following fire. Our study occurred in sparsely vegetated, desert shrub-steppe, where wildfires occur frequently from mid-summer through autumn. Shrubs and herbs co-dominate foliar cover before fire, while after fire grasses and non-woody forbs increase in abundance and shrubs are temporarily absent as they reestablish by seed over decades (Harniss and Murray, 1973). In some cases, post-fire green-up by herbs can occur in the same growth season as the fire. The objective of this research was to compare different spectral indices for mapping the extent and severity of burn areas against robust ground-based data for a sparsely vegetated rangeland. While studies have been performed in forest ecosystems to reliably detect fire severity, there have not been any established efforts in sparsely vegetated, cold desert shrub-steppe, an ecosystem type in which fire is common, and is a major factor in management. Fire management would benefit profoundly from research and monitoring of fires, which in turn could be enhanced with efficient remote sensing techniques.

* Corresponding author. Tel.: +1 208 345 1994; fax: +1 208 345 8353.
E-mail address: glennanc@isu.edu (N. Glenn).

1.1. Remote sensing of semiarid vegetation

Detecting vegetation change in sparsely vegetated semiarid rangeland ecosystems is challenging due to nonlinear mixing, spectrally similar desert plants, open shrub canopies and varying phenological status of plant canopies across space and time (Asner, 2004; Asner and Heidebrecht, 2002; Okin et al., 2001). In addition, in burned areas soil reflectance is high and little vegetation remains, thus the bare ground signature 'dilutes' the vegetation signature.

Vegetation indices may be used to detect biomass change and thereby map burn areas and estimate fire severity (Santos et al., 1999) such as the normalized difference vegetation index (NDVI) (Flasse et al., 2004; Epting and Verbyla, 2005; Roy, 1999; Ruiz-Gallardo et al., 2004; van Wagtenonk et al., 2004; Salvador et al., 2000), soil adjusted vegetation index (SAVI; Huete, 1988; Epting et al., 2005), modified soil adjusted vegetation index (MSAVI; Qi et al., 1994; Epting et al., 2005), atmospherically resistant vegetation index (ARVI; Kaufman and Tanre, 1992; Santos et al., 1999), and normalized difference shortwave infrared (NDSWIR; Gerard et al., 2003). Alteration of the vegetation:soil balance is a substantial characteristic of fire; therefore soil adjustments in vegetation indices (e.g. SAVI or MSAVI) are likely to be critical for mapping burn areas and severity. Lopez Garcia and Caselles (1991) developed a simple band ratio, later adopted as the normalized burn ratio (NBR; Eq. (1)) using Landsat sensor imagery (Key and Benson, 1999b, 2004a, 2006; Salvador et al., 2000). Since then, the Landsat sensor-based NBR is the most widely used method on large fires (>200 ha) for perimeter and burn severity detection (Cocke et al., 2005; Key and Benson, 2006).

$$\text{NBR} = \frac{\text{NIR} - \text{SWIR}_{(2.21 \mu\text{m})}}{\text{NIR} + \text{SWIR}_{(2.21 \mu\text{m})}} \quad (1)$$

The NBR technique uses the near-infrared (Landsat band 4, 0.76–0.90 μm) and shortwave infrared (Landsat band 7, 2.08–2.35 μm) because these bands are generally the most sensitive to vegetation change due to fire.

A differenced NBR (dNBR) can be used to offer a more quantitative measure of environmental change due to fire (Key and Benson, 1999b, 2004a). The dNBR represents a scaled index of the magnitude of change caused by fire (van Wagtenonk et al., 2004). The dNBR is composed of the post-fire NBR subtracted from the pre-fire NBR (Eq. (2)).

$$\text{dNBR} = \text{NBR}_{\text{pre-fire}} - \text{NBR}_{\text{post-fire}} \quad (2)$$

There are two types of dNBR severity measures, an initial assessment in which post-fire measures occur immediately after fire and are not influenced by biotic recovery, and an extended assessment in which post-fire assessments are made in subsequent growth seasons and thereby reflect biotic recovery. The NBR and dNBR may or may not be applicable in rangeland ecosystems due to vegetation re-growth times with respect to the seasonality of the burn. For instance, it takes longer for forest ecosystems to recover to pre-fire conditions (i.e. having the same reflectance) than rangelands. Likewise, Miller and Thode (2007) found that a Landsat-based relative dNBR (RdNBR, Eq. (3)) performs better than the absolute dNBR at detecting high fire severity areas from moderate fire severity in mixed forest/shrubland study areas.

$$\text{RdNBR} = \frac{\text{dNBR}}{\sqrt{|\text{NBR}_{\text{pre-fire}}|}} \quad (3)$$

Fire severity has also been assessed by comparing several single-date and multi-date approaches. For instance, Roy et al. (2006) and Epting et al. (2005) agree that the dNBR may not be the most optimal for estimating fire severity in non-forested areas. Yet

Brewer et al. (2005) stated dNBR has the advantage of applying it without input error (i.e. human bias). In addition, Gerard et al. (2003) developed an algorithm termed the normalized difference SWIR (NDSWIR, Eq. (4)) to map fire scar burns using SPOT NIR (band 3, 0.78–0.89 μm) and SWIR (band 4, 1.58–1.75 μm).

$$\text{NDSWIR} = \frac{\text{NIR} - \text{SWIR}_{(1.66 \mu\text{m})}}{\text{NIR} + \text{SWIR}_{(1.66 \mu\text{m})}} \quad (4)$$

Many studies have been performed in forest ecosystems to determine fire severity within a burn perimeter (Brewer et al., 2005; Epting and Verbyla, 2005; Epting et al., 2005; Miller and Thode, 2007; Patterson and Yool, 1998; Turner et al., 1994; White et al., 1996; Wimberly and Reilly, 2007). However, few studies have been carried out in areas with sparse vegetation cover (Roy et al., 2006; Smith et al., 2005) or specifically within semiarid sagebrush steppe ecosystems and with a robust field dataset for validation.

2. Data and methods

2.1. Study area

This study took place within the Hitching Post pasture, a 3.24 km² fenced parcel within the U.S. Sheep Experiment Station (USSES) located in Clark County, ID, USA (approximately 1800 m elevation) (Fig. 1). Average annual precipitation ranges from 250 to 530 mm with up to 70% falling as snow (Seefeldt, 2005). Average annual temperatures are 5–6 °C, with a 70–90 day frost-free season. The pasture is a sagebrush steppe ecosystem characterized by extreme seasonal variability and a co-dominance of *Artemisia* with several grass species; thickspike wheatgrass (*Elymus lanceolatus* [Scribn. and J.G. Sm] Gould ssp. *lanceolatus*), bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Love ssp. *spicata*), and plains reedgrass (*Calamagrostis montanensis* Scribn.) (Seefeldt, 2005; West and Young, 2000). The Hitching Post pasture has two primary shrub species: mountain big (*A. tridentata* ssp. *vaseyana*), and antelope bitterbrush (*Purshia tridentata*). Sheep and horses have grazed this pasture for the last decade, but it had not been domestically grazed for 2.5 years prior to the burn. This study area was chosen because it offered an opportunity to take advantage of a prescribed burn, allowing a high degree of control for pre- and post-fire field sampling.

2.1.1. Fire

The prescribed fire was performed on September 14 and 15, 2005 and consistently burned most of the northern 4/5 of the pasture (approximately 2.82 km², Fig. 2) delineated with a bulldozed safety line. Wind direction and speed were monitored every 30 min throughout the burn using a hand-held anemometer. Winds were consistently observed at approximately 20 m/s in a predominantly northeast direction. Flame lengths ranged from approximately 0.3 to 4.0 m in height as the fire moved from grass and forbs to shrubs. Afterward, nine strip burns and spot fires were ignited in the southern portion of the pasture and allowed burned to the north (Fig. 2, south of the middle bulldozed line). The prescribed fire burned approximately 85% of the pasture area including 173 of the sampling sites (described below).

2.2. Field methods

This study utilized pre- and post-fire field-based sampling which included a description of the vegetation, amount of bare ground, and fire severity observed at each site. These data were collected for both training and validation of the remote sensing indices. Two field methods were performed: ocular (visual) and

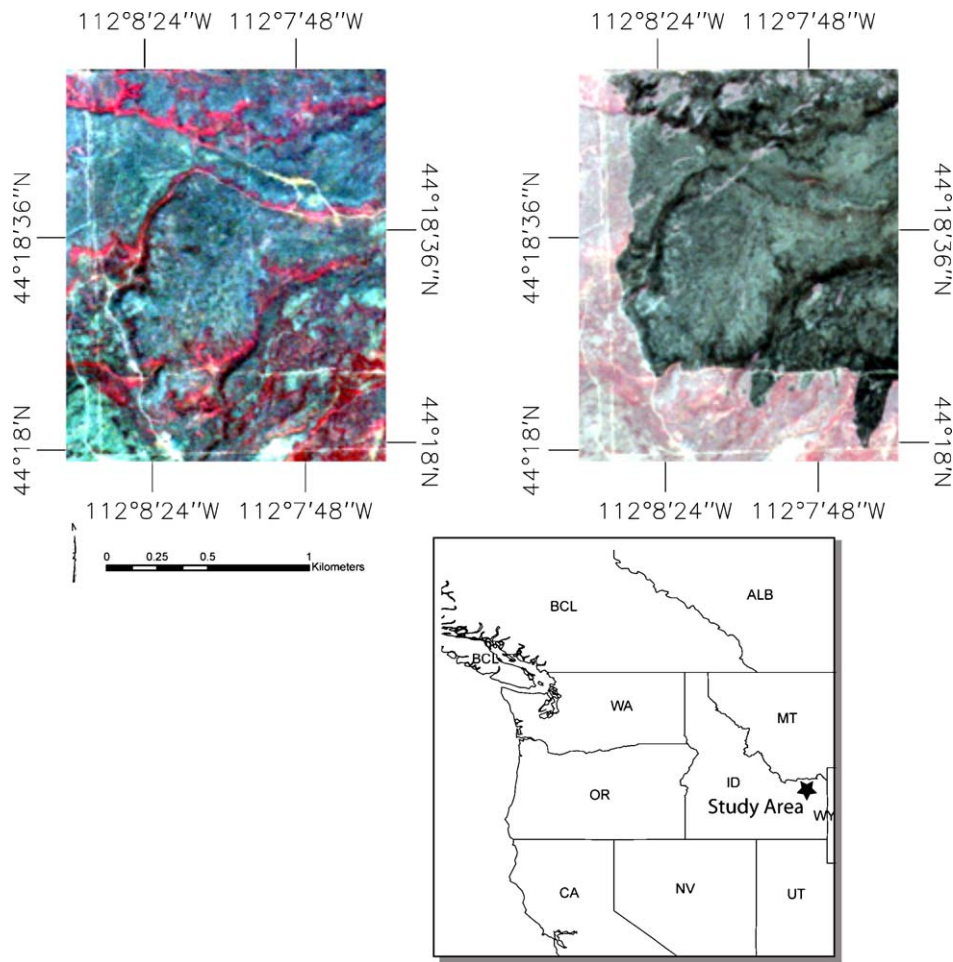


Fig. 1. Study area, USDA Sheep Experiment Station, Dubois, ID. SPOT 5 images (NIR, red, green) of pre-burn (left) and post-burn (right) of the Hitching Post Pasture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

point frame. The ocular method was used to quickly estimate percent cover of the upper-most canopy of ground cover across a $60\text{ m} \times 60\text{ m}$ plot with qualitative, coarse resolution. In the ocular method, categorical percent cover (0, 1–5%, 6–15%, 16–25%, 26–35%, 36–50%, 51–75%, >75%) for six categories (shrub, grass, forb, litter, rock, and bare ground) were estimated after thoroughly walking the plot area. Each sample site ($n = 206$) was randomly located within the pasture (Fig. 2; points) to ensure adequate replication across fire severity classes. The point frame method was used to provide a more accurate and statistical representation of true ground cover (Floyd and Anderson, 1982, 1987). The point frame establishes a dot grid overlooking underlying vegetation and bare ground. Observers view vegetation from a near-nadir standing position and record the cover types that are beneath 36 intercepted points (cross-hairs). Plots of $20\text{ m} \times 40\text{ m}$ were sampled with the point frame. The sampling frequency necessary to capture variability was determined using sample effort curves for all cover categories. A maximum of 15 frames of point data were needed within each $20\text{ m} \times 40\text{ m}$ plot to ensure adequate representation of cover in this study area. Point frame data (Fig. 2; rectangles) were collected at 45 of the 206 sample sites (centered over the sites where ocular estimates were used) as well as 20 additional sample sites (total of 65 point frame samples).

Pre-fire field data collections occurred between mid-June and early August 2005 and included 206 ocular plots and 65 point frame measurements. Post-fire sampling began immediately following the prescribed burn (September 16, 2005) and continued for approximately 1.5 months, prior to any green-up. Post-fire field

surveys, intended to provide field validation of fire severity levels, included resampling all pre-fire sampling sites. The same field methods were followed as used for pre-fire sampling and the same sample points were revisited by navigating with a Trimble GeoXT GPS receiver ($\pm 0.7\text{ m}$ @ 95% CI corrected). Because real-time correction was not available, the post-fire sample point may have been located $\pm 4.0\text{ m}$ from the pre-fire sample point. Even with this margin of error however, both pre- and post-fire sample points were most probably located within the same pixel-space. Fire severity was assessed at each post-fire sample site using an ocular method developed by modifying the field methods of the US Forest Service (Bobbe et al., 2001), the US Park Service (USDI NPS, 2003), and composite burn index (CBI) of Key and Benson (1999a, 2004b). Each of these methods incorporates qualitative and quantitative measurements to detect and categorize fire severity; the three methods above were incorporated and modified according to burn conditions in the study area in the context of a semiarid rangeland site. Attributes such as litter condition, shrub condition, surface rock (USDA FS), organic substrate, and vegetation (USDI NPS) were incorporated from the USDA and USDI burn severity. Key and Benson's (1999a) CBI places a $\sim 50\%$ change in the herb/low shrub/tall shrub strata into the moderate burn severity category. The study area predominantly fits into the shrub strata, so this $\sim 50\%$ change severity category was incorporated and referred to herein as 'incompletely burned'. In most plots and pixels, the fire either burned all vegetation (except stumps) or none; there was a small amount of partly burned vegetation. Therefore, severity at each plot was assessed based on the percent cover of consumed, above-ground vegetation and litter versus the



Fig. 2. Location of ocular and point frame plots in relation to the fire in the Hitching Post Pasture.

amount of bare ground and rock. Fire severity classes included unburned, incompletely burned (moderate), and completely burned (high) (Table 1).

2.3. Remote sensing methods

2.3.1. Image acquisition

Landsat 7 ETM+ and SPOT 5 imagery were used in this study. In addition to visible and NIR bands, SPOT 5 provides a SWIR band (1.58–1.75 μm) with 20 m spatial resolution. Pre- and post-fire images were acquired from Landsat ETM+ (July 4 and October 24, 2005) and SPOT (August 27 and September 28, 2005). All images were chosen as close to the date of the prescribed burn (September 14–15, 2005) as possible with no cloud cover.

Imagery were processed to at-satellite reflectance. The SPOT 20 m SWIR band was resampled to 10 m to coregister with the SPOT 10 m red and NIR bands. Image rectification was performed after remote sensing indices (see below) were calculated in order to reduce error during resampling. The resulting Root Mean Square Error (RMSE) was less than 1/2 pixel for both the Landsat ETM+ (0.2621) and SPOT (0.3489) imagery using a linear affine transformation with nearest neighbor resampling. For the most accurate georegistration and best ensure co-registration between

Table 1 Description of burn severity categories.

Burn severity	Definition
Unburned	Vegetation is in same condition as pre-fire
Incompletely burned (moderate)	Any amount less than 100% of vegetation was burned within the plot
Completely burned (high)	100% vegetation was burned within the plot

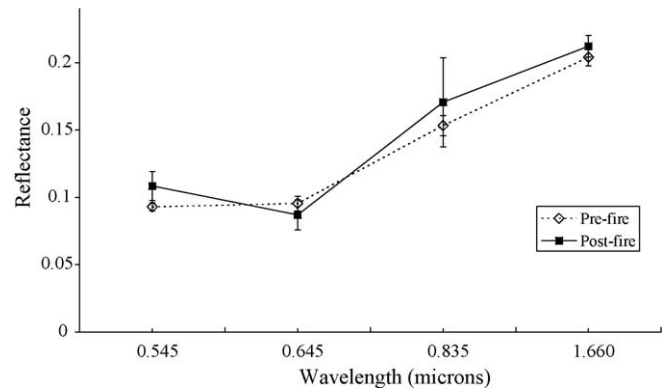


Fig. 3. The average value of SPOT 'at satellite' reflectance for 36 plots, pre- and post-fire. Error bars represent one standard deviation.

all imagery and field site data (Weber, 2006; Weber et al., 2008), National Agricultural Imagery Program (NAIP) aerial imagery was used as the base layer against which all other layers were registered. The horizontal positioning accuracy of the 1 m NAIP imagery does not exceed 5 m, which is less than 1/2 pixel for both the Landsat ETM+ and SPOT imagery. A minimum of four control points were used with at least one control point located in each corner bounding the immediate area of the prescribed fire. This local georectification process best ensures precise co-registration and minimizes the effect of such errors propagating through the analysis.

2.3.2. Image processing

We investigated 36 field plots in both pre- and post-fire images in order to identify the Landsat ETM+ and SPOT bands that were most sensitive to change due to fire (Figs. 3 and 4). These 36 sites were chosen for their pre-fire homogeneity (vegetation type and percent cover) and similar post-fire severities. The spectral separability of the pixels associated with these 36 plots was investigated using the M-statistic (absolute value) where an M-statistic >1 indicates good separation of the data (Kaufman and Remer, 1994) (Table 2). While other separability tests are available and frequently used (Kolmogorov Smirnov, Transformed Divergence, Bhattacharyya Distance, and Jeffreys-Matusita (Richards and Jia, 2005)), the M-statistic has been successfully applied in other fire related studies (Holden et al., 2005; Pereira, 1999; Smith et al., 2007).

Based on initial investigations of the SPOT and Landsat ETM+ data, 5 indices were implemented including single-date and multi-date (pre- and post-burn imagery) calculations. Indices were applied to determine burned from unburned areas, and then assessed for their ability to differentiate the same levels of fire

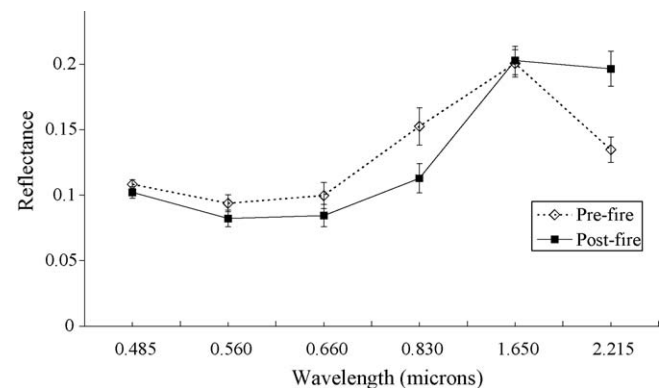


Fig. 4. The average value of Landsat 'at satellite' reflectance for 36 plots, pre- and post-fire. Error bars represent one standard deviation.

Table 2
M-statistic comparing pre- and post-fire separability for Landsat ETM+ and SPOT.

Sensor, band, region, center wavelength (μm)	M-statistic (>1 indicates good separation)
Landsat, band 1, blue, 0.485	0.79
Landsat, band 2, green, 0.560	0.90
Landsat, band 3, red, 0.660	0.83
Landsat, band 4, NIR, 0.830	1.55
Landsat, band 5, SWIR, 1.650	0.10
Landsat, band 7, SWIR, 2.215	2.68
SPOT, band 1, green, 0.545	1.12
SPOT, band 2, red, 0.645	0.51
SPOT, band 3, NIR, 0.835	0.43
SPOT, band 4, SWIR, 1.660	0.57

severity identified in the field. The multi-date indices include a dNBR (Eq. (2)) and relative dNBR (Eq. (3)) with Landsat ETM+ imagery. SPOT was not used for the dNBR and RdNBR because of the lack of a SWIR band comparable to band 7 (2.08–2.35 μm) of Landsat ETM+. The single-date indices, using post-fire imagery only, include the SAVI, MSAVI, and normalized difference short-wave-infrared index (Eq. (4)). Both Landsat ETM+ and SPOT imagery were used for the SAVI, MSAVI, and NDSWIR indices. A soil adjustment factor of 0.5 was used for the SAVI calculation, which can be applied across varying vegetation biomass environments (Huete, 1988).

2.3.3. Relating remote sensing indices to field data

Training data were used to relate remote sensing index values to fire severity values. For training purposes, 119 index values from plots (including both ocular and point frame, none of which overlapped) were used. The fire severity index values were then separated into fire severity classes by first placing all plot values into their respective fire severity classes as determined in the field. The minimum, maximum, and mean index values of each class were determined. The classes were separated by splitting the difference between the maximum of one class with the minimum of the next class. Likewise, if there was a gap between fire severity class data values, then a break was determined by splitting the difference between the maximum of one class with the minimum of the next class. To encompass the variability across the study area, training plots were randomly selected within each burn severity class and the same training plots were used within each burn severity class for each index.

2.3.4. Validation

Accuracy assessments were used to quantitatively determine how well the remotely sensed indices corresponded with the field data (Congalton and Green, 1999). Fifty plots of unburned and 100 plots of burned were used for the unburned versus burned validation. For the fire severity validation, 50 plots for each class (unburned, incompletely burned, completely burned) (n = 150) were used for the validation. To ensure independence, no training data were used for the validation. The remote sensing burn severity values of the validation plots were then compared to the field fire severity classes. Accuracy results were calculated for each index, including a standard error matrix reporting User, Producer's, and overall accuracies, Kappa statistic, and a Z-test statistic for significance (of a single error matrix).

A pairwise test of significance (Eq. (7)) (Congalton and Green, 1999) was performed for the matrices that had highest accuracies as well as for those that shared similar overall accuracies. This test is a Kappa analysis that determines if two error matrices are significantly different by comparing their KHAT statistics.

$$Z_{\text{pairwise}} = \frac{|K_1 - K_2|}{\sqrt{\text{var}(K_1) + \text{var}(K_2)}} \quad (7)$$

where K_1 and K_2 are the Kappa statistics for error matrices 1 and 2 and $\text{var}(K_1)$ and $\text{var}(K_2)$ are estimates of variance for matrices 1 and 2. The Z_{pairwise} critical value at the 95% confidence interval is 1.96.

3. Results

In the SPOT imagery, the green (0.50–0.59 μm) and NIR (0.78–0.89 μm) reflectance had the greatest change for the 36 homogeneous plots, increasing 1.6% and 1.7%, respectively, after the fire (Fig. 3). The SPOT red (0.61–0.68 μm) decreased 0.85% and the SWIR (1.58–1.75 μm) increased 0.82%. The SPOT pre-fire image was collected in late August, at a time when most herbs/grasses were senesced and soil exposure was high. Alternatively, the Landsat ETM+ data were acquired at the beginning of July before the onset of seasonal drought and senescence of herbaceous species. In comparing the pre- and post-fire Landsat ETM+, the NIR and SWIR (band 7, 2.08–2.35 μm) bands demonstrated the greatest change (Fig. 4). The NIR decreased 4% and the SWIR band increased 6.2% after the fire.

The M-statistic results indicate Landsat ETM+ NIR and SWIR (2.08–2.35 μm) and SPOT green bands had good separability between the unburned and burned areas (Table 2). Because of the difference in the green SPOT bands, a simple change difference between the multi-date SPOT green bands was evaluated for burn area and fire severity. The remaining SPOT bands had relatively low separability (near 0.5). Other Landsat ETM+ bands had M-statistics near 0.8, with the exception of SWIR (1.58–1.75 μm) with a separability of 0.1.

3.1. Burned versus unburned

The SPOT-derived indices for burned versus unburned using NDSWIR, MSAVI, and SAVI had 95% or better overall accuracies and high User and Producer's accuracies (Table 3). Four burned versus unburned indices (dNBR, RdNBR, MSAVI, and SAVI) using Landsat sensor data performed nearly equally well, though with slightly lower User and Producer's accuracies (Table 4).

The SPOT dGreen and Landsat ETM+ NDSWIR had the lowest User and Producer's accuracies and the lowest overall accuracies (87% and 89%, respectively). SPOT SAVI provided the highest overall, User, and Producer's accuracies (100%). A pairwise test of significance indicated that the SPOT SAVI index was significantly different than the SPOT MSAVI, NDSWIR, and dGreen ($Z_{\text{pairwise}} > 1.96$; data not

Table 3
Burned vs. unburned remote sensing index accuracies using SPOT 5 imagery.

Accuracy type	NDSWIR	MSAVI	SAVI	dGreen
Overall accuracy	96%	95%	100%	87%
Producer's unburned	96%	98%	100%	86%
User unburned	92%	86%	100%	72%
Producer's burned	96%	93%	100%	87%
User burned	98%	99%	100%	94%
KHAT	0.91	0.88	1.00	0.69
Z	25.02	21.10	*	10.68

* No Z-test statistic calculated due to 100% accuracy.

Table 4
Burned vs. unburned remote sensing index accuracies using Landsat ETM+ imagery.

Accuracy type	dNBR	RdNBR	NDSWIR	MSAVI	SAVI
Overall accuracy	94%	95%	89%	95%	95%
Producer's unburned	96%	98%	90%	94%	94%
User unburned	86%	86%	74%	90%	90%
Producer's burned	93%	93%	88%	95%	95%
User burned	98%	99%	96%	97%	97%
KHAT	0.86	0.88	0.73	0.88	0.88
Z	19.31	20.67	12.13	21.10	21.10

Table 5

Fire severity (unburned, moderate or incompletely burned, high or completely burned) remote sensing index accuracies using Landsat ETM+ imagery.

Accuracy type	dNBR	RdNBR	NDSWIR	MSAVI	SAVI
Overall accuracy	66%	73%	58%	66%	67%
Producer's unburned	96%	98%	90%	94%	94%
Producer's moderate	50%	61%	37%	50%	52%
Producer's high	55%	63%	52%	55%	57%
User unburned	86%	86%	74%	90%	90%
User moderate	38%	56%	34%	42%	44%
User high	74%	76%	66%	66%	68%
KHAT	0.49	0.59	0.37	0.49	0.51
Z	8.43	10.77	6.04	8.45	8.89

shown). A pairwise test for significance indicates that none of the indices using Landsat sensor data were significantly different from each other ($Z_{\text{pairwise}} < 1.96$; data not shown). Pairwise tests for significance between the SPOT-based SAVI index and the Landsat sensor-based RdNBR, dNBR, MSAVI, and SAVI indices indicated that the SPOT-based SAVI was significantly different than the indices from the Landsat sensor data ($Z_{\text{pairwise}} > 1.96$; data not shown).

3.2. Fire severity

The best fire severity index differentiating pixels between unburned, incompletely burned, and completely burned was the Landsat ETM+ RdNBR. This index had a 73% overall accuracy and User accuracies of 56% and 76% for incompletely and completely burned, respectively (Table 5). The Producer's accuracy was 61% and 63% for incompletely and completely burned, respectively. The best overall accuracy for the SPOT burn severity indices was the SAVI index at 71% overall accuracy (Table 6). Pairwise tests for significance between matrices indicate that SPOT fire severity indices were not significantly different from each other ($Z_{\text{pairwise}} < 1.96$; data not shown).

The fire severity indices from Landsat sensor data were also not significantly different from each other with the exception of the RdNBR and NDSWIR (Table 7). Because the majority of Landsat sensor-based RdNBR's accuracies (overall, Producer's and User) were higher than those of the other indices from Landsat ETM+ the RdNBR was then compared to the SPOT-based indices. The

Table 6

Fire severity (unburned, moderate or incompletely burned, high or completely burned) remote sensing index accuracies using SPOT 5 imagery.

Accuracy type	NDSWIR	MSAVI	SAVI	dGreen
Overall accuracy	65%	67%	71%	63%
Producer's unburned	95%	98%	100%	88%
Producer's moderate	49%	51%	61%	41%
Producer's high	56%	55%	55%	58%
User unburned	82%	86%	100%	72%
User moderate	40%	38%	38%	26%
User high	74%	76%	76%	90%
KHAT	0.48	0.50	0.57	0.44
Z	8.20	8.45	10.39	7.51

Table 7

Pairwise test of significance between matrices for fire severity.

Pairwise comparison	Z_{pairwise} (critical value at 95% confidence interval = 1.96)
Landsat RdNBR vs. Landsat NDSWIR	2.68
Landsat RdNBR vs. SPOT NDSWIR	1.37
Landsat RdNBR vs. SPOT MSAVI	1.26
Landsat RdNBR vs. SPOT SAVI	0.26
Landsat RdNBR vs. SPOT dGreen	1.86

pairwise test of significance indicated that the accuracy of the RdNBR was not significantly different than the SPOT-based indices for fire severity (Table 7).

4. Discussions and conclusions

As indicated by the highest overall, User, and Producer's accuracies, the best index for determining burned from unburned areas was SPOT SAVI (100% overall accuracy) and the best index for differentiating fire severity within a burn was RdNBR from Landsat ETM+ (73% overall accuracy). SPOT SAVI was significantly different than other burned versus unburned indices. In general, the SPOT and Landsat sensor-based indices for fire severity were not significantly different from one another. While this conclusion is less compelling to place the Landsat ETM+ RdNBR as the best index, the high User and Producer's accuracies in the moderate and high fire severity categories indicate its superiority. Covariance between the error matrices was not accounted for; but should be noted since the data and thus the significance testing, are not independent.

Consistent with Sannier (1999), Epting et al. (2005), and Miller and Yool (2002), accuracies were better with fewer severity categories. In all cases, unburned versus burned indices had better results than fire severity indices. We were able to successfully determine if an area was burned or not in rangelands using SPOT-based NDSWIR, MSAVI, and SAVI indices and dNBR, RdNBR, NDSWIR, MSAVI, and SAVI indices using Landsat ETM+.

Our best fire severity index, the Landsat ETM+ RdNBR, supports Miller and Thode's (2007) results. In a mixed ecosystem study area, they concluded that this index performed better at separating high burn severity from other burn severity classes. Our incompletely and completely burned fire severity User accuracies (56% and 76%, respectively) and Producer's accuracies (61% and 63%, respectively) were higher for RdNBR than all other indices. These results are important to land managers given that high severity areas often require greater rehabilitation efforts.

Timing of imagery acquisition is important in relation to the seasonality of fire and field sampling dates due to phenological vegetation changes. Our fire took place in late summer when vegetation had already senesced. Reflectance (and resultantly, changes in reflectance) values were not as high as if the fire occurred in early to mid-summer (although fire in early to mid-summer is less common than fires in late summer in this ecosystem). While there was less vegetation post-fire in 2005, the type of vegetation that typically reestablishes (grasses and shrubs [rabbitbrush]), can result in a greener response than reflectance values acquired shortly before the fire. This is due to the ratio of actively photosynthesizing plant biomass (including abundant young rabbitbrush leaves and stems) relative to the amount of woody and decadent non-photosynthesizing vegetation. In general nearly all post-fire plant biomass was actively photosynthesizing, while only a portion of pre-fire plant biomass was actively photosynthesizing near the end of the growing season in 2005. Comparing the different indices when the sensors sampled on different days creates the possibility for a confounding factor of change in vegetation over time. Landsat ETM+ imagery spanned 112 days between pre-fire and post-fire scenes, whereas SPOT imagery spanned only 32 days. Furthermore the Landsat ETM+ pre-fire image was acquired when vegetation was not entirely senesced while the SPOT imagery was collected in late summer when there was a greater degree of senesced herbs in the plant community. Additionally, the Landsat ETM+ post-fire image was collected 39 days after the fire whereas the SPOT post-fire image was collected 13 days after the fire.

The longer SWIR band (band 7, 2.08–2.35 μm) of Landsat ETM+ provided the highest sensitivity (compared to other bands) to the

burn. This response is consistent with an increase in soil exposure and a loss of vegetation cover. However, the increase in SPOT's green and NIR reflectances in response to an increase in soil exposure and a decrease in vegetation cover after the fire was not expected. The low sensitivity and direction of change in reflectances of SPOT may be explained by white mineral ash (silica) due to timing of imagery acquisition close after the fire (Smith et al., 2005). Pre-fire conditions (senesced vegetation) and a short revisit time of the satellite will also result in low reflectance differences between pre- and post-fire imagery. Another explanation could be that small changes in SPOT reflectance values are within the error bound due to a combined effect of sensor signal to noise ratio and atmospheric path radiance. Reflectance changes in SPOT's SWIR band pre- and post-fire were similar to Landsat ETM+ band 5. In general, this portion of the electromagnetic spectrum may not have the sensitivity to fire effects for rangelands, regardless of the time span between image acquisitions. In summary, the multitemporal indices between Landsat ETM+ and SPOT carry different relationships.

Though SPOT did not provide fire severity accuracies as high as Landsat ETM+ (RdNBR), its spatial resolution may provide other attributes that are useful to land managers, such as burn perimeter. The results of the Landsat ETM+ RdNBR verify that the 30 m spatial resolution is high enough to capture spectral variability between the coarse fire severity classes examined here.

Our results with SAVI are contradictory to those of Epting et al. (2005), whereas their SAVI and MSAVI severity indices performed worse than their indices incorporating mid-infrared bands (2.21 μm). This can be explained by the sparse vegetation pre-fire in our cold desert site in contrast to their study areas in forest ecosystems with higher standing biomass pre-fire. An extended assessment may delineate areas of high severity better, either where perennial vegetation has not recovered or where introduced annuals have established.

The SAVI and RdNBR indices are reproducible and straightforward. Our findings support the use of SPOT SAVI for delineating burn versus unburned areas and Landsat ETM+ RdNBR for delineating fire severity. A 73% overall accuracy for the RdNBR fire severity index encourages future research. Before this index is entirely recommended, however, more studies need to be performed using the RdNBR in rangelands that have heterogeneous fuel loads, and within burns that have variable fire severities.

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