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Evaluation of novel thermally enhanced spectral indices for mapping fire perimeters and comparisons with fire atlas data

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We evaluated the potential of two novel thermally enhanced Landsat Thematic Mapper (TM)-derived spectral indices for discriminating burned areas and for producing fire perimeter data (as a potential surrogate to digital fire atlas data) within two wildland fires (1985 and 1993) in ponderosa pine (*Pinus ponderosa*) forests of the Gila Wilderness, New Mexico, USA. Image-derived perimeters (manually produced and classified from an index image) were compared to fire perimeters recorded within a digitized fire atlas. For each fire, the highest spectral separability was achieved using the newly proposed Normalized Burn Ratio-Thermal ($NBRT_1$) index ($M=1.18$, 1.76, for the two fires respectively). Correspondence between fire atlas and manually digitized fire perimeters was high. Landsat imagery may be a useful supplement to existing historical fire perimeters mapping methods, but the timing of the post-fire image will strongly influence the separability of burned and unburned areas.

1. Introduction

Wildfires are a major disturbance agent in many parts of the World (Morgan *et al.* 2001). The occurrence of wildfires has important management and research implications spanning a wide range of scientific disciplines. Numerous studies have sought to determine the extent of burned area (Pereira 1999, Smith *et al.* 2002) and the long-term effects of fires on ecosystem health (Morgan *et al.* 2001). The broad extent and remote nature of many fires makes remotely sensed imagery an obvious tool for fire science and management. Satellite sensor imagery has been used to map areas burned in a diverse range of vegetation types, including shrublands (Pereira 1999), chaparral (Minnich 1983), boreal forests (Fraser *et al.* 2001), and savannahs (Smith *et al.* 2002). Recent burned area mapping studies have used spectral indices that employ a two-band combination of near-infrared (NIR) with short-wave infrared (SWIR) or thermal-infrared (TIR) bands. These 'two-dimensional' indices have been demonstrated in several environments to provide greater discrimination between burned and non-burned areas compared to two-dimensional indices that only use visible and NIR bands (Chuvieco and Congalton 1988, Eva and Lambin 1998, Trigg and Flasse 2001).

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Researchers typically only use Landsat visible to SWIR bands in supervised classifications, and generally exclude the TIR bands. Landsat imagery is also used widely by natural resource managers in the USA, and is now being used to produce perimeter databases or 'fire atlases', which are frequently used to assess fire hazard and risk and departure of fire regimes from historical conditions. Fire atlases are typically constructed weeks to years after fire events using personal accounts, maps of the area burned, aerial photographs and, in recent years, satellite sensor imagery (Minnich 1983, Morgan *et al.* 2001). Fire atlases do not typically include information on the internal variations within the burned area but instead provide land managers with the location and overall extent (i.e. the overall perimeter) of the area burned (Morgan *et al.* 2001).

The objective of this letter is to provide an initial evaluation of two novel spectral indices, which incorporate changes in the NIR, SWIR and TIR bands, for discriminating between burned and unburned areas using spectral separability statistics. This letter assesses both a new variant of an existing two-dimensional index and evaluates several variations of a novel 'three-dimensional' index that uses all of the NIR, SWIR and TIR Landsat bands. A secondary objective is to assess the potential of archived Landsat imagery to derive fire perimeters as surrogates for historical fire perimeter data for two surface fires in a ponderosa pine forest of the south-western USA.

2. Methods

2.1 *Study area*

The Iron Creek Mesa area is located within the 230 800 ha Gila Wilderness, and is part of the Gila–Aldo Leopold Wilderness Complex in west-central New Mexico (figure 1). Elevations in the Gila range from 1300 to 3300 m, and this study focuses on the mid-elevation ponderosa pine forests that dominate Iron Creek Mesa and surrounding drainages. We selected two fires for analysis, using historical fire atlases of the region. The 28 000 ha Gilita Fire burned across Iron Creek Mesa from June 1993 to 10 September 1993, and the 18 000 ha Iron Fire burned across the northern part of the Gila Wilderness from July 1985 until 15 August 1985. These large fires killed few of the dominant large ponderosa pine and thus represent a challenge for mapping perimeters from space.

2.2 *Imagery preparation*

Landsat 5 Thematic Mapper (TM) scenes corresponding to the first available cloudless post-fire image dates were selected for both fires (Iron Fire TM image acquired 22 October 1985; Gilita Fire TM image acquired 26 September 1993). We converted the reflective and thermal bands of each Landsat TM scene into top-of-atmosphere reflectance and brightness temperature respectively. Using both the fire perimeter maps and visual interpretation of the Landsat imagery, we randomly selected 300 pixels. We classified selected pixels as either burned or unburned and subsequently used them for separability analyses and image classification. Pixels from burned and unburned areas for each index-derived image were assessed for and generally met assumptions of normality (figure 2). Following Pereira (1999), the *M*-statistic was then used to assess the utility of each Landsat band and spectral index listed in table 1 to discriminate between burned and unburned areas. The optimal index was identified as the index with the highest consistent *M*-statistic over both

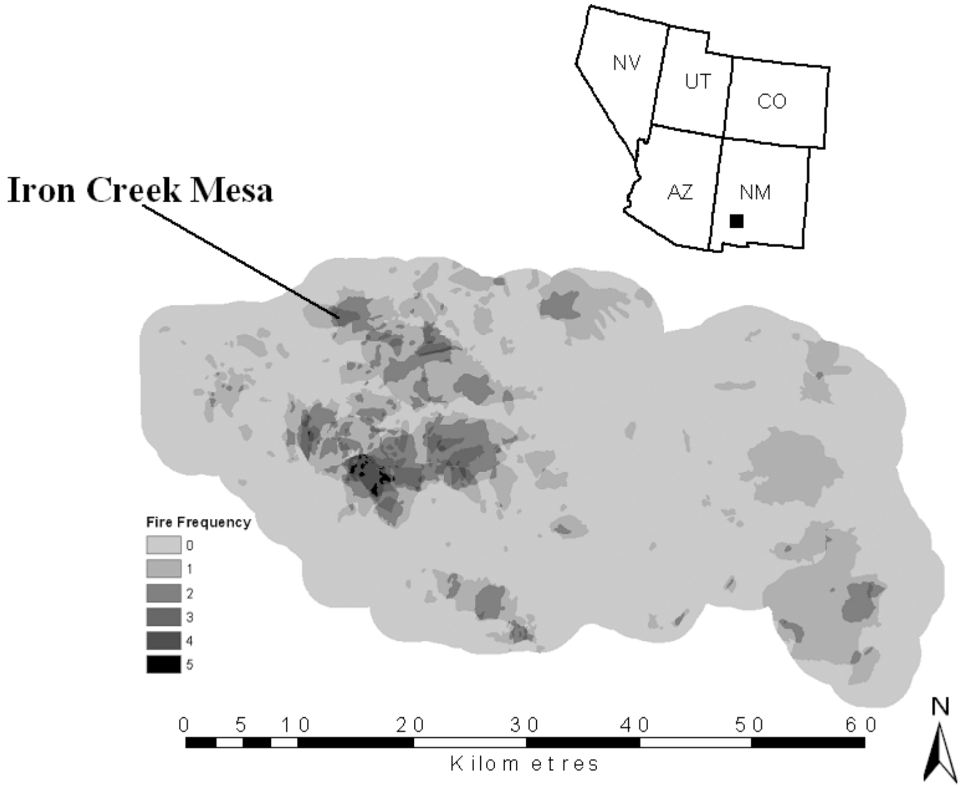

Figure 1. Study area within the Gila–Aldo Leopold Wilderness fire atlas.

fires. Using this optimal index, the TM images were then classified as burned if they fell within the mean ± 2 standard deviations of the burned index values.

Following previous studies that incorporated the TIR bands of satellite sensors (e.g. Eva and Lambin 1998), we assessed the potential of incorporating the Landsat TIR band into the existing Normalized Burn Ratio (NBR) index. NBR and several other fire indices rely on the principle that burning an area results in a lowering of the NIR reflectance with a corresponding increase in both the mid-infrared reflectance (Chuvieco and Congalton 1988) and brightness temperature (Eva and Lambin 1998). Therefore, we sought to enhance the expected post-fire changes in the NBR by incorporating the Landsat thermal band. These indices are referred to hereafter as $NBRT_i$ (table 1). Furthermore, a modified version of the VI3T spectral index (Barbosa *et al.* 1999), referred to herein as the VI6T index (Smith 2004), was applied by replacing the Advanced Very High Resolution Radiometer (AVHRR) band 3 values with the Landsat TIR band (band 6).

2.3 *Accuracy assessment*

Historical fire atlas data are generally coarse-scale data that show the spatial extent of a fire. As we were primarily interested in comparing Landsat-derived fire perimeters with a coincident fire atlas, we did not attempt to assess the unburned patches within the overall fire perimeter. Therefore, we calculated the accuracy of

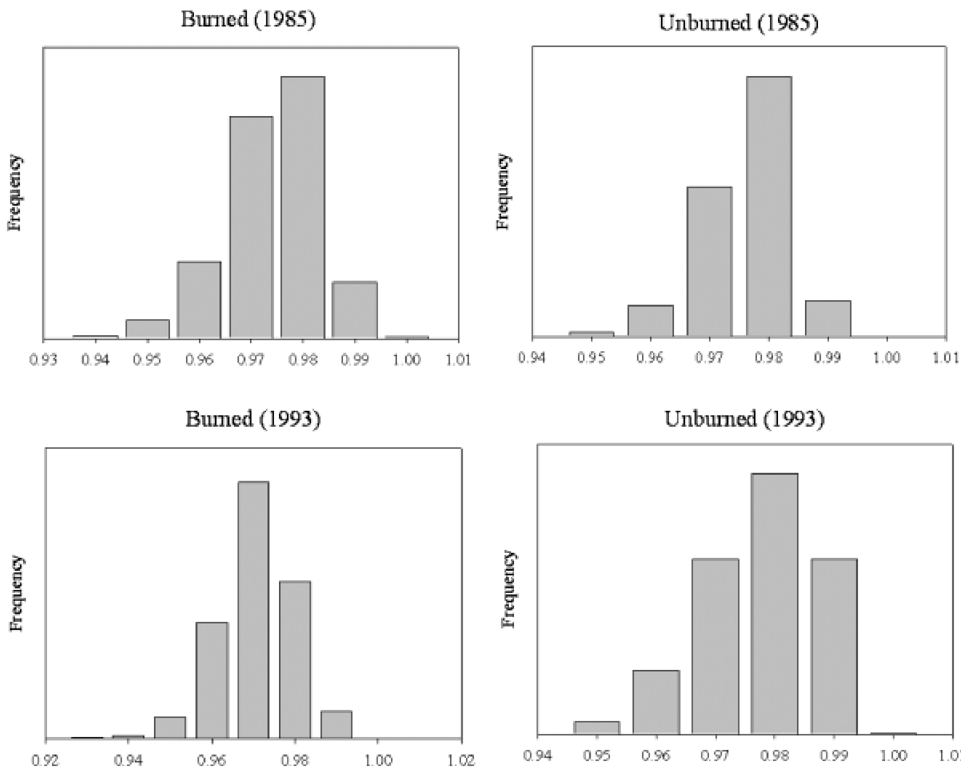

Figure 2. Histograms of NBRT index image region of interest data for assessment of normality.

Table 1. Spectral indices applied to determine the area burned.

Method	Equations	References
NDVI[a]	$\left(\frac{\rho_2-\rho_1}{\rho_2+\rho_1}\right)$	Pereira 1999, Smith *et al.* 2002
VI6(T)[b]	$\frac{(\rho_2-SB_{TM6})}{(\rho_2+SB_{TM6})}$	Smith 2004
NBR	$\left(\frac{\rho_4-\rho_7}{\rho_4+\rho_7}\right)$	Chuvieco and Congalton 1988, Key and Benson 2002
$NBRT_1$	$\left(\frac{(\rho_4-(\rho_7*SB_{TM6}))}{(\rho_4+(\rho_7*SB_{TM6}))}\right)$	
$NBRT_2$	$\left(\frac{\left(\frac{\rho_4}{SB_{TM6}}\right)-\rho_7}{\left(\frac{\rho_4}{SB_{TM6}}\right)+\rho_7}\right)$	
$NBRT_3$	$\left(\frac{(\rho_4-SB_{TM6})-\rho_7}{(\rho_4-SB_{TM6})+\rho_7}\right)$	

[a]ρ denotes the top-of-atmosphere reflectance of band X, where X is given by the Landsat sensor.
[b]SB_{TM6} denotes scaled brightness temperature of the Landsat band 6 thermal band. In this study the band 6 brightness temperature was divided by 10 000.

Table 2. Spectral separability of Landsat TM-derived indices for mapping burned and unburned areas.

TM band or spectral index	Iron fire (1985)	Gilita fire (1993)
Visible–SWIR bands		
TM1	0.02	0.41
TM2	0.04	0.13
TM3	0.07	0.37
TM4	0.43	0.78
TM5	0.12	0.67
TM6	0.71	0.99
TM7	0.28	1.07
NDVI	0.75	1.09
NBR	1.08	1.66
Inclusion of thermal bands		
VI6T	0.65	1.10
$NBRT_1$	1.18	1.76
$NBRT_2$	0.86	1.57
$NBRT_3$	1.05	1.59

the index-derived technique by measuring the degree of omission and commission along the image-derived and fire atlas perimeters.

3. Results

The *M*-statistic values for each Landsat band and spectral index for both fires are displayed in table 2. For the 1985 and 1993 fires, the $NBRT_1$ index was most spectrally separable. *M*-statistic values of all the indices for the 1993 fire were notably higher than for the 1985 fire (table 2).

The correspondence between the fire atlas and manually digitized burned area perimeters was high for both the 1985 and 1993 fires (84% and 89% overlap, respectively, figure 3). In contrast to the time-consuming manual digitizing method, the faster index-based approach more often misclassified large non-burned areas (figure 3). If we assume that the hand-digitized perimeter is the true fire perimeter, the fire atlas data had errors of commission and omission of 12.4% and 26.8%, respectively, for the 1985 fire and 20.4% and 16.2% for the 1993 fire (table 3).

4. Discussion

Given the limited dataset used in this analysis these results may not generalize to other areas, as two fires from the same environment (albeit different fire seasons) will not capture all possible variations in topographic, fire and environmental characteristics. However, our results indicate that timing of the post-fire image acquisition affected the ability of the spectral indices to identify area burned. Indeed, the separability of the Normalized Difference Vegetation Index (NDVI) and NBR indices were greatly improved in the post-fire image acquired only three weeks after the 1993 fire, compared to the image acquired more than two months following the 1985 fire.

The ability of spectral techniques to discriminate between burned and unburned areas likely depends strongly on the vegetation type, the fire severity (i.e. the

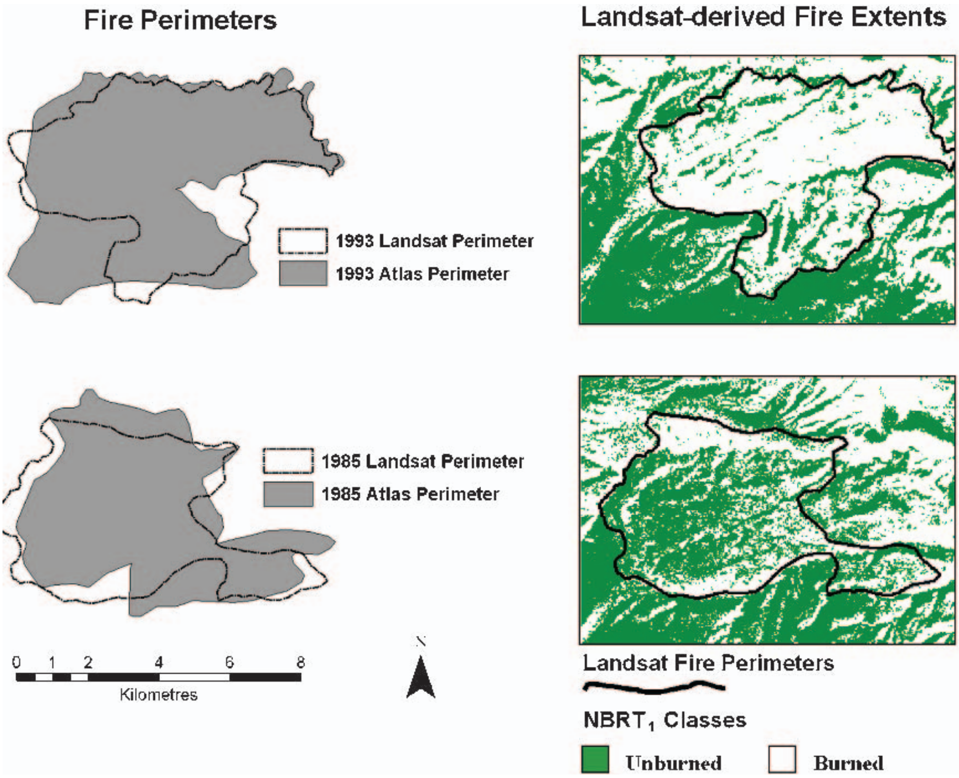

Figure 3. Comparison of 1985 and 1993 fire perimeters derived from fire atlas data and hand-digitized from Landsat TM imagery.

vegetation mortality), the speed of vegetation recovery, and the temporal availability of the imagery.

In this region of the south-western USA, the decrease in spectral separability with acquisition time after the fire could be due to the onset of the monsoon rains, which often signal the end of the fire season. The resulting new vegetation growth and recovery that follows the rain can be rapid and would quickly act to reduce brightness temperatures.

The ability to detect burned forested areas might be improved in fires that are largely 'stand-replacing' and where vegetation recovery is slow. As the rise in surface brightness temperature is probably due to the reduction in evapotranspiration, reduced surface albedo and increased soil cover (i.e. due to vegetation removal) (Eva and Lambin 1998), the brightness temperature could potentially be considered a measure of the vegetation recovery. As such, the NBRT indices could provide

Table 3. Accuracy of fire atlas perimeter data compared to image-derived fire perimeters.

	Iron fire (1985)	Gilita fire (1993)
Overlap (%)	84.0	89.0
Commission	12.4	20.4
Omission	26.8	16.2

pertinent information on the burn severity (i.e. post-fire ecological effects) beyond that provided by the non-thermal NBR index.

The correspondence between the burned areas derived from Landsat and mapped in the fire atlas was high. Clearly, considering either fire atlases or imagery-derived perimeters as 'truth' is questionable. The digitized Gila Wilderness fire atlas used in this study was produced retrospectively using 12-year-old field maps and educated guesses on where the perimeter was likely to be based on geographic features and local expert knowledge (Rollins, personal communication). Errors in fire atlas mapping are particularly likely for older fires that occurred prior to the widespread application of Global Positioning System (GPS) technology in resource and fire management. Despite such limitations, several land management agencies in the USA have begun developing fire atlases from satellite imagery and field maps as part of fire management efforts. As yet, no standardized protocol has been developed for building digital fire perimeter layers and the quality and accuracy of potential data sources are highly variable.

5. Conclusions

The apparent errors present within the fire atlas perimeter data indicate the need for alternative methods to refine the accuracy of current fire perimeter maps. The proposed new $NBRT_1$ index series shows promise for identifying burned areas within environments where fire-induced vegetation mortality is low. Future research should evaluate how timing of post-fire image acquisition influences discrimination between burned and unburned areas using these and similar two- or three-dimensional indices. The indices demonstrated herein should also be tested across a range of vegetation types, fire regimes, fire sizes, and geographic areas to assess their utility and accuracy. Although the degree of NBRT commission errors observed in this study suggests that Landsat data should be manually digitized to produce historical fire perimeters at the quality needed by natural resource managers, the temporal dependence of the surface temperature to parameters such as the vegetation recovery and fractional pixel cover warrant further assessment.

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