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A new burn severity index based on land surface temperature and enhanced vegetation index

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ABSTRACT

Remotely sensed data have already become one of the major resources for estimating the burn severity of forest fires. Recently, Land Surface Temperature (LST) calculated from remote sensing data has been considered as a potential indicator for estimating burn severity. However, using the LST-based index alone may not be sufficient for estimating burn severity in the areas that has unburned trees and vegetation. In this paper, a new index is proposed by considering LST and enhanced vegetation index (EVI) together. The accuracy of the proposed index was evaluated by using 264 composite burn index (CBI) field sample data of the five fires across different regional eco-type areas in the Western United States. Results show that the proposed index performed equally well for post-fire areas covered with both sparse vegetation and dense vegetation and relatively better than some commonly-used burn severity indices. This index also has high potential of estimating burn severity if more accurate surface temperatures can be obtained in the future.

1. Introduction

Forest fire, as a major disturbance agent in ecological community, yearly affects and even totally removes millions of hectares of forest land around the world (Quintano et al., 2013). It is considered as a major cause of biodiversity reduction, soil fertility loss, gaseous pollutants emission, and other environmental impacts (Vasconcelos et al., 2013). Measurements of the post-fire damage levels over burned areas are critical to quantifying fire's impact on landscapes (van Wagtendonk et al., 2004) and improving post-disaster management (Veraverbeke et al., 2012a), which have been widely used by environmental scientists, forest fire researchers, and policy makers.

The preferable term burn severity has become a standard measurement of environmental damage levels after forest fires (Keeley 2009; Key and Benson, 2006). It can be measured accurately by conducting the field investigations (Parks et al., 2014), and also estimated by using remote sensing technologies (Keeley, 2009). For widespread forest fires, the remote sensing technology has been considered as the most appropriate method to estimate the burn severity, due to the fact that it does not need a great amount of time, money and resources (Loboda et al., 2013). The remote sensing technology for burn severity estimation is primarily based on the quantitative relationships between field-observed data and severity-related indicators derived from remote sensing images, e.g., spectral index (i.e., calculated using spectral band reflectance, see also (Veraverbeke et al., 2012a)) and LST. Among these indicators, the spectral index has been used more widely, since it can be easily calculated and straightforwardly applied (Quintano et al., 2015). There are several typical spectral indices: Normalized Difference Vegetation Index (NDVI), Normalized Burn Ratio (NBR) and Enhanced Vegetation Index (EVI) (Chen et al., 2011; De Santis et al., 2010; Escuin et al., 2008; Key and Benson, 1999), which have been used to estimate burn severity using remote sensing images. Further, their differenced versions (e.g., deltaNBR) have been introduced to indicate the change level of forest community before and after fires (i.e., burn severity) (Key and Benson, 2006). As an effective and popular spectral index, the assessment ofi performance has been reported in many studies (Epting et al., 2005; Hall et al., 2008; Parks et al., 2014; Soverel et al., 2010). Following that, some researchers have taken into consideration the effects of the pre-fire vegetation on estimating burn severity and introduced the relative versions of differenced spectral indices (e.g., RdNBR and RNBR) (Miller and Thode, 2007; Parks et al., 2014). However, it has been

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argued that many spectral indices like dNBR have limitations on extracting characteristics related to burn severity (De Santis and Chuvieco, 2007; Quintano et al., 2013) and the performances of these spectral indices in estimating burn severity still are actively debated (Soverel et al., 2010; Veraverbeke et al., 2012a).

More recently, several studies have indicated that the land surface temperature (LST), as a surface biophysical parameter describing the balance of water, energy and CO_2 on the forest land surface, may be another attractive indicator for estimating burn severity of forest fires (Quintano et al., 2015; Veraverbeke et al., 2012b; Vlassova et al., 2014). For examples, Veraverbeke et al. (2012b) evaluated the LST change in forest before and after fire and assessed its potential as an indicator for burn severity using MODIS images. Subsequently, Vlassova et al. (2014) assessed the spatio-temporal patterns of LST and burn severity, and found that the magnitude of LST differences was directly related to the burn severity of burned areas. Recently, Quintano et al. (2015) evaluated the usefulness of post-fire LST for mapping the spatial distribution of burn severity in Mediterranean forests. However, the forest fire not only altered the spatial distribution of land surface temperature, but also the vegetation condition. It is imperfect to only use LST to estimate burn severity. Especially, in areas that have undergone less severe forest fire, trees and vegetation might still cover some burned areas after fire. Therefore, it is certainly needed to combine LST with vegetation index to assess burn severity of forest fire.

In order to address limitations of current methods for more accurately estimating burn severity, we try to build a new index of burn severity by combing LST and vegetation index, which can fully use multi-spectral remote sensing data. This paper is structured as follows. This section introduces background of burn severity estimation. The methods used in this study are described in Section 2, followed by a brief description of study area, field data, and remotely sensed data in Section 3. Results and discussion are presented in Section 4 and Section 5, respectively. Finally, Section 6 gives the conclusion of this study.

2. Methodology

In order to build a new index for estimating burn severity, we firstly calculated Land surface temperature (LST) and enhanced vegetation index (EVI) in pre- and post-forest fires. Then, a new index for estimating burn severity (i.e., deltaLST/EVI) was proposed by combining LST and EVI together. To test the effectiveness of the proposed approach, an independent validation between deltaLST/EVI and CBI field data was conducted and compared with several other indices. Finally, we classified the burn severity levels by using the deltaLST/EVI-based nonlinear regression model and assessed their accuracy using the confusion matrix. The primary operations of the methodology are shown in Fig. 1.

2.1. Calculation of land surface temperature and vegetation index

In this study, land surface temperature (LST) was calculated based on the thermal infrared band of TM/ETM+ images and the generalized single-channel method, described by Quintano et al. (2015) in turn based on Jiménez-Muñoz and Sobrino (2003) and on Jiménez-Muñoz et al. (2009). The general equation is as follows:

$$\mathrm{LST} = \gamma\left[\frac{1}{\epsilon}\left(\varphi_1 L_{\mathrm{at-sensor}} + \varphi_2\right) + \varphi_3\right] + \delta \quad (1)$$

$$T_{\mathrm{at-sensor}} = \frac{K_2}{\ln\left(\frac{K_1}{L_{\mathrm{at-sensor}}} + 1\right)} \quad (2)$$

$$\gamma \approx \frac{T^2_{\mathrm{at-sensor}}}{b_\gamma L_{\mathrm{at-sensor}}} \quad (3)$$

$$\delta \approx T_{\mathrm{at-sensor}} - \frac{T^2_{\mathrm{at-sensor}}}{b_\lambda} \quad (4)$$

where $L_{\mathrm{at-sensor}}$ means the at-sensor radiance of thermal infrared band (band 6 for TM and band 6L for ETM+); $T_{\mathrm{at-sensor}}$ indicates the at-sensor brightness temperature of thermal infrared band; for TM image band 6, $K_1 = 607.76\,\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$, $K_2 = 1260.56\,\mathrm{K}$, and $b_\lambda = 1256\,\mathrm{K}$; for ETM+ image band 6, $K_1 = 666.09\,\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$, $K_2 = 1282.71\,\mathrm{K}$, and $b_\lambda = 1277\,\mathrm{K}$.

For the three atmospheric functions (i.e.,φ_1, φ_2, and φ_3), we calculated them by using the atmospheric water vapor content (w), which was obtained from Total Precipitable Water product of MODIS (MOD 05) because it was required at the time near to TM and ETM+ images. The calculation of atmospheric functions are shown as follows:

$$\begin{bmatrix}\varphi_1\\ \varphi_2\\ \varphi_3\end{bmatrix} = \left[C_{ij}\right]_{3\times3}\begin{bmatrix}\mathrm{w}^2\\ \mathrm{w}\\ 1\end{bmatrix} \quad (5)$$

where the $\left[C_{ij}\right]_{3\times3}$ is the coefficients matrix. Its elements were obtained from TIRG 61 atmospheric sounding databases in this study.

Finally, the land surface emissivity (ϵ) was calculated by using vegetation cover (P_v) based on the following formula:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{nir}} + \rho_{\mathrm{red}}} \quad (6)$$

$$P_v = \begin{cases} 0 & \mathrm{NDVI} < \mathrm{NDVI}_s \\ \left[\dfrac{\mathrm{NDVI} - \mathrm{NDVI}_s}{\mathrm{NDVI}_v - \mathrm{NDVI}_s}\right]^2 & \mathrm{NDVI}_s \le \mathrm{NDVI} \le \mathrm{NDVI}_v \\ 1 & \mathrm{NDVI} > \mathrm{NDVI}_v \end{cases} \quad (7)$$

$$\epsilon = \epsilon_s(1 - P_v) + \epsilon_v P_v \quad (8)$$

where ρ_{nir} and ρ_{red} refer to the reflectance of near-infrared and red spectral bands; ϵ_s and ϵ_v refer to soil and vegetation emissivity, which are assumed to be of 0.97 and 0.99, respectively; $\mathrm{NDVI_s}$ and $\mathrm{NDVI_v}$ are the NDVI of soil and vegetation, which were visually extracted from the NDVI histogram of each study area.

Since the EVI is suitable for monitoring the vegetation characteristics across a variety of vegetation types (Rocha and Shaver, 2009), we selected it to indicate the vegetation characteristics and calculated the pre-fire EVI ($\mathrm{EVI_{pre-fire}}$) and post-fire EVI ($\mathrm{EVI_{post-fire}}$) values of burned areas using pre- and post-fire TM/ETM+ images. The EVI was calculated as follows:

$$\mathrm{EVI} = 2.5 \times \left(\frac{\rho_{\mathrm{nir}} - \rho_{\mathrm{red}}}{\rho_{\mathrm{nir}} + 6\rho_{\mathrm{red}} - 7.5\rho_{\mathrm{bule}} + 1}\right) \quad (9)$$

where ρ_{nir}, ρ_{red}, ρ_{bule}, and ρ_{swir} refer to the reflectance of near-infrared-, red spectral-, and blue spectral bands in TM/ETM+ images, respectively.

2.2. A new burn severity index based on LST and EVI (deltaLST/EVI)

After fire event, land surface biophysical parameters, such as land surface temperature and vegetation cover, were changed obviously and had been individually used to indicate burn severity of forest fires. After considering the variation characteristics of biophysical parameters in burned areas, a new burn severity index (deltaLST/EVI) was proposed by combining pre- and post-land surface temperature and enhanced vegetation index, which would