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GeoCBI: A modified version of the Composite Burn Index for the initial assessment of the short-term burn severity from remotely sensed data

Angela De Santis *, Emilio Chuvieco

Department of Geography, University of Alcalá, Calle Colegios 2, 28801 Alcalá de Henares, Madrid, Spain

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ABSTRACT

Burn severity estimation is a key factor in the post-fire management. Previous studies using remotely sensed data to retrieve burn severity, as measured by the Composite Burn Index (CBI), have found inconsistencies, since spectral indices work well in some ecosystems but not in others. These inconsistencies may be caused by the lack of spectral uniqueness in the CBI definition, or by the performance of the spectral indices used. This paper analyses the former aspect, using a simulation analysis to study the relationships between the CBI and reflectance. Subsequently, a modified version of this index, called GeoCBI, is proposed to improve the retrieval of burn severity from remotely sensed data. GeoCBI takes into account the fraction of cover (FCOV) of the different vegetation strata used to compute the CBI. Moreover, it also includes the changes in the leaf area index (LAI) for the intermediate and tall tree strata (D+E). Field and simulation results show that GeoCBI is more consistently related to spectral reflectance than CBI for different ranges of burn severities, while keeping its ecological meaning.

1. Introduction

Forest fires can be a major ecological disturbance agent that modifies landscapes, especially when normal fire frequencies and/or intensities are modified. The main negative fire effects are vegetation biomass loss, soil degradation (Doerr et al., 2006; García-Haro et al., 2001; Lewis et al., 2006; Salgado et al., 2004) and greenhouse gas emissions (Andreae & Merlet, 2001; Nagahamaa & Suzuki, 2007; Narayan et al., 2007). Due to the wide range of spatial and temporal scales, the interpretation of causal factors, fire effects and ecosystem responses are a growing challenge for both researchers and managers (Lentile et al., 2006).

To clarify the complex interaction between fires and ecosystems, two different orders of fire effects have been proposed (Key, 2006): the *first- and the second order effects.* First-order effects are caused directly by combustion, second-order effects are caused by agents other than fire, with those agents being created or established as a result of fire. First order effects tend to occur in the short-term after the fire, while the second-order effects occur mainly in a longer-term. Therefore, this temporal dimension could be expressed more appropriately using the terms short-term and long-term fire effects. Both *first* and *second-order* effects on vegetation and soil can be estimated in terms of "fire or burn severity" (Chuvieco et al., 2006; De Santis & Chuvieco, 2007; Jain, 2004a; Key & Benson, 2005; Lentile et al., 2006; van Wagtendonk et al., 2004; White et al., 1996). For this study the term "burn severity" will be used to account for the amount of changes on a burned area with respect to the pre-fire conditions (Key & Benson, 2005).

In the short-term after the fire, a detailed and rapid knowledge of the level of damage and its spatial distribution (burn severity map) is essential to quantify the impact of fires on landscapes (van Wagtendonk et al., 2004), select and prioritize treatments applied on site (Bobbe et al., 2001; Patterson & Yool, 1998), plan and monitor restoration and recovery activities and, finally, to provide baseline information for future monitoring (Brewer et al., 2005).

Several methods have been proposed to estimate burn severity from field assessments of post-fire soil and vegetation conditions, considering a wide range of variables (Table 1). The definition of a common field index is critical to quantify fire effects, since it would ensure consistent and comparable results (Key, 2006). A relevant attempt in this direction is the Composite Burn Index (CBI, Key & Benson, 2005), which was developed as an operational methodology for burn severity assessment on a national scale in the U.S, in the framework of the FIREMON (Fire Effects Monitoring and Inventory Protocol) project. The CBI was initially designed for long-term effects assessments, but it has been used also in short-term effects evaluation. This index is better adapted to estimate burn severity variations in forests than in shrubland or grassland (Key & Benson, 2005). CBI provides a balanced, continuous index of severity in ecological terms. Additionally, it was designed to be operationally retrieved from medium-resolution remotely sensed data, namely Landsat TM.

* Corresponding author.
E-mail addresses: angela.desantis@uah.es (A. De Santis), emilio.chuvieco@uah.es (E. Chuvieco).

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Table 1
Field variables assessed to estimate burn severity

Variables assessed in the field	Reference
Percentage of tree basal area mortality	(Chappell & Agee, 1996)
Decrease in plant cover	(Jain & Graham, 2004b; Rogan & Yool, 2001)
Volatilization or transformation of soil components to soluble mineral forms	(Turner et al., 1994; Wang, 2002; Wells & Campbell, 1979)
Proportion of fine branches remaining on the canopy	(Moreno & Oechel, 1989)
Degree of canopy consumption and mortality	(Doerr et al., 2006; Kokaly et al., 2007; Kushla & Ripple, 1998; Patterson & Yool, 1998; Rogan & Franklin, 2001; Ryan & Noste, 1985)
Char and ash cover	(Smith et al., 2005b)
Composite Burn Index (CBI, Key & Benson, 2005) and its modifications	(Chuvieco et al., 2007; Cocke et al., 2005; De Santis & Chuvieco, 2007; Epting et al., 2005; Key & Benson, 2005; Miller & Yool, 2002; Miller & Thode, 2007; Sorbel & Allen, 2005; van Wagtendonk et al., 2004; Wimberly & Reilly, 2006)

In the field protocol, average post-fire conditions of soil and plant communities are visually evaluated in 30 m-diameter field plots. The CBI field form considers five vertical strata, organized in a hierarchical structure (Table 2), and mainly takes into account litter and fuel consumption, changes in soil colour, foliage or cover alteration, canopy mortality and char height. These attributes are rated in numerical scores ranging from 0 (unburned) to 3 (completely burned), by at least two field observers. Different attributes per stratum are scored and averaged into understory, overstory and overall composite rating.

Numerous recent studies have attempted to estimate CBI from remotely sensed images using empirical models. The most common approach has been to correlate CBI values with spectral indices, such as the Normalized Burn Ratio (NBR, Key & Benson, 1999), the difference between pre- and post-fire NBR (dNBR, Key & Benson, 1999) and, more recently, the relative delta Normalized Burn Ratio (RdNBR, Miller & Thode, 2007):

$$\mathrm{NBR} = \frac{\rho 4 - \rho 7}{\rho 4 + \rho 7} \quad (1)$$

$$\mathrm{dNBR} = \mathrm{NBR}_{\mathrm{PRE-FIRE}} - NBR_{\mathrm{POST-FIRE}} \quad (2)$$

$$\mathrm{RdNBR} = \frac{\mathrm{NBR}_{\mathrm{PRE-FIRE}} - NBR_{\mathrm{POST-FIRE}}}{\sqrt{\mathrm{ABS}(\mathrm{NBR}_{\mathrm{PRE-FIRE}}/1000)}} \quad (3)$$

where ρ_4 and ρ_7 are the reflectance of band 4 (near infrared, NIR) and band 7 (short wave infrared, SWIR) of Landsat TM, respectively.

The results are very diverse, with determination coefficients ranging from 0.01 to 0.81 (Kasischke et al., 2008) although most studies have shown medium to high values ($R^2 > 0.55$). The lowest correlations were generally explained by the non-linear relationship between CBI and dNBR, together with a signal saturation when CBI > 2.3 (van Wagtendonk et al., 2004). Moreover, most studies do not consider the Root Mean Square Error (RMSE) between observed and estimated values or the presence of systematic biases (deviation from the 1:1 linear regression).

These inconsistencies found in the CBI-NBR relations may be caused by two factors. Either the CBI cannot properly be retrieved from reflectance measurements, or the NBR is not sensitive enough to CBI variations. There is not a consistent study in the literature which clarifies this point. Some papers have criticized the use of CBI as a good measure of burn severity, especially in boreal ecosystems (French et al., 2008). Instead, others have shown that the NBR may not properly represent transitions between pre and post-fire reflectance (Roy et al., 2006).

Table 2
Hierarchical structure of the CBI

CBI of total plot	Understory	A: Substratum
		B: Herbs, low shrubs and tree <1 m
		C: Tall shrubs and trees = 1 to 5 m
	Overstory	D: Intermediate trees = 5 to 20 m
		E: Large trees >20 m

The main purpose of this paper is to test the potential problems in retrieving CBI from reflectance measurements in the optical domain (0.4 to 2.5 µm). The main components of CBI affecting canopy and plot reflectance will be considered by using a simulation approach. As a result of this analysis, a new version of the CBI will be proposed, which should be more consistently retrieved from remotely sensed data. This new index should preserve both the ecological meaning and the straightforward approach of CBI. The differences between the original and new CBI will be presented using three different Mediterranean study areas in Spain and Portugal. Both the simulation and field data will be restricted to the initial assessment conditions. Since previous studies have shown the potentials of other retrieving approaches (Chuvieco et al., 2006; De Santis & Chuvieco, 2007; De Santis et al., 2009), this paper will not discuss the adequacy of the NBR as a predictor of CBI. However, the changes in NBR as a result of CBI factors controlling reflectance variations will be considered.

1.1. The effect of vegetation coverage on the spectral response: a simulation analysis

In the computation of the average CBI of the total plot, all vegetation strata are assigned the same weight, regardless of their degree of coverage within the field plot. However, from a remote sensing point of view, the spectral response of the total plot is strongly related to the vegetation coverage per stratum, which is not commonly used to compute the CBI. As a result, the same CBI value could be obtained from different vegetation cover fractions, which would have different reflectance. Consequently, a CBI value does not have a unique spectral signature, and therefore estimations based on remotely sensed data will inevitably produce errors, regardless the specific spectral technique applied (spectral indices, classification methods, etc).

The influence of vegetation cover on reflectance of different strata within a given plot can be described using two variables: Leaf Area Index (LAI), defined as the area of leaf surface per unit of soil surface (Ceccato et al., 2002a), and Fraction of Cover (FCOV), characterized as the percentage of vegetation coverage with respect to the total plot area. Within the CBI, the change in LAI caused by the fire is indirectly considered in the shrubs and small trees layer (named "percentage change in cover" in stratum C), and in the upper tree layer (D+E) as a percentage change of crown foliage volume (for green, scorched and torched leaves).

The fraction of vegetation cover per stratum within each plot (FCOV) is not considered in the CBI calculations, but it has an important effect on plot reflectance. In order to quantify this effect, a simulation analysis was carried out assuming a tree-covered plot. Two widely used radiative transfer models were linked for the simulation: PROSPECT (at leaf level, Jacquemoud, 1990) and GeoSail (at canopy level, Huemmrich, 2001).

At leaf level, the CBI field form records the percentage of two types of leaves which are present on the canopy: green (undamaged) and brown (damaged) leaves. PROSPECT was then run in forward mode to

Table 3
Input values of simulation at leaf level

Inputs	Green leaf	Brown leaf
Leaf structural parameter: *N*	2.5	2.5
Chlorophyll a+b content: Ca+b (µg/cm^2)	70	20
Equivalent water thickness: Cw (g/cm^2)	0.048	0.0008
Dry matter content: Cm (g/cm^2)	0.035	0.035
Brown pigments content: Cs (%SLW)	0.2	1.5