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Mapping burned areas and burn severity patterns in SW Australian eucalypt forest using remotely-sensed changes in leaf area index

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ABSTRACT

Remote sensing is the most practical method available to managers of fire-prone forests for quantifying and mapping fire impacts. Differenced Normalised Burn Ratio (ΔNBR) is among the most widely used spectral indices for the mapping of burn severity but is difficult to interpret in terms of fire-related changes in key biophysical attributes and processes. We propose to quantify burn severity as a change in the leaf area index (ΔLAI) of a stand. LAI is a key biophysical attribute of forests, and is central to understanding their water and carbon cycles. Previous studies have suggested that changes in canopy LAI may be a major contributor to ΔNBR and to the composite burn index (CBI) that is frequently used in combination with the NBR to assess burn severity on the ground. We applied remotely-sensed ΔLAI to map burn severity in jarrah (*Eucalyptus marginata*) forest in south-western Australia burnt during the January 2005 Perth Hills wildfires. Ground-based digital photography was used to measure LAI in typical stands representing the full range of canopy densities present in the study area as well as variation in the time since the last fire. Regression models for the prediction of LAI were developed using NBR, the Normalised Difference Vegetation Index (NDVI) or the Simple Ratio (SR) as the independent variable. All three LAI models had equally high coefficients of determination (R^2: 0.87) and small root mean squared errors (RMSE: 0.27–0.28). ΔLAI was calculated as the difference between pre- and post-fire LAI, predicted using imagery from January 2004 and February 2005, respectively. The area affected by the January 2005 fire and the burn severity patterns within that area were mapped using ΔLAI and ΔNBR. Landscape patterns of burn severity obtained from differencing pre- and post-fire LAI were similar to those mapped by ΔNBR. We conclude that fire-affected areas and burn severity patterns in the northern jarrah forest can be objectively mapped using remotely-sensed changes in LAI, while offering the important advantage over NBR of being readily interpretable in the wider context of ecological forest management.

1. Introduction

Improved management of fire-prone forest landscapes requires objective and repeatable methods for quantifying and mapping fire impacts in order to plan future fire prescriptions and other measures related to wildfire hazard reduction, biodiversity conservation, and the protection of water resources. Forest fires may alter a number of vegetation and soil attributes, some of which are short-lived and have minor impact on the ecological functioning of the stand (e.g., surface litter removal), while others may be long-lived and alter the fundamental dynamics of the system (e.g., shift in plant species composition) (Bradstock et al., 2002; Gill et al., 1981; Johnson & Miyanishi, 2001). The degree of environmental change caused by a vegetation fire is often loosely referred to as 'fire severity' or 'burn severity' (Key & Benson, 2006). Though the two terms are sometimes used interchangeably, a distinction is often made, such that fire severity refers to impacts observed immediately post-fire and burn severity characterises the degree to which an ecosystem has changed owing to the fire, thus incorporating longer term effects (see Lentile et al., 2006 for a review). In this paper we refer to burn severity as a measure of post-fire changes in forest canopy attributes. Within a particular vegetation type, burn severity is related to, but not to be confused with, 'fire intensity', which is a measure of the amount of heat released by the fire. Fire intensity, and more generally fire behaviour, is a function of multiple factors (e.g., fuel, weather, terrain) and therefore often highly variable in space and time (Johnson & Miyanishi, 2001), causing corresponding variation in

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environmental impacts across the burnt area (Knapp & Keeley, 2006). Owing to this variation, remote sensing is the most practical means for creating maps of burn severity for landscape scale fires (i.e., >>10 ha).

Fire changes the spectral response of the land surface by reducing the cover, density, greenness and water content of the vegetation, by partially or completely removing surface litter, and by exposing and altering the colour and brightness of the soil (Chuvieco et al., 2006; Lentile et al., 2006; Robichaud et al., 2007). Such changes in surface properties can often be readily detected as a decrease in spectral reflectance in the visible-near-infrared and an increase in the mid-infrared wavelengths (Epting et al., 2005; Lentile et al., 2006; Lopez Garcia & Caselles, 1991; Van Wagtendonk et al., 2004). One of the most widely used spectral indices for the mapping of burn severity, the Normalised Burn Ratio (NBR) (Key & Benson, 2006), therefore combines the reflectances in the near-infrared (ρ_{NIR}) and mid-infrared bands (ρ_{MIR}):

$$\mathrm{NBR} = \frac{(\rho_{NIR} - \rho_{MIR})}{(\rho_{NIR} + \rho_{MIR})} \tag{1}$$

The NBR is sometimes used to map fire-affected areas on a single post-fire image (e.g., Epting et al., 2005), but is more commonly applied to quantify burn severity as the difference (Δ) between pre- and post-fire index values observed on co-registered images:

$$\Delta\mathrm{NBR} = \mathrm{NBR}_{pre-fire} - \mathrm{NBR}_{post-fire} \tag{2}$$

The NBR was designed to maximise sensitivity to the most pronounced fire-related changes in the spectral reflectances detected by commonly used satellite sensors such as Landsat's Thematic Mapper (Lopez Garcia & Caselles, 1991) and was originally aimed at delineating burnt areas. Later, Key and Benson (2006) proposed using ΔNBR as an index of burn severity; ΔNBR is now widely applied with data from several space- and airborne sensors (e.g., Brewer et al., 2005; Cocke et al., 2005; Epting et al., 2005; Van Wagtendonk et al., 2004) and forms a key component of the current USDA Forest Service FIREMON system for the assessment and monitoring of fire impacts (Lutes et al., 2006).

Despite the widespread use of ΔNBR, interpretation of the index in terms of specific fire effects on the ground is not always straightforward (Kokaly et al., 2007; Smith et al., 2007). This situation is partly due to the type of ground measurements commonly used to verify or calibrate ΔNBR maps, but may also reflect the inherent difficulty (or impossibility) of expressing the full complexity of burn severity in a single quantitative measure (Lentile et al., 2006). The composite burn index (CBI) (Key & Benson, 2006), designed to be used in conjunction with ΔNBR, is among the most frequently used systems for assessing burn severity on the ground. The CBI combines ratings of fire-related changes in all vegetation strata and the soil substrate in a single figure. Remotely-sensed ΔNBR correlates reasonably well with ground-based CBI in a range of environments, including mixed conifer forest in Arizona (Cocke et al., 2005), chaparral woodland and conifer forests of the Californian Sierra Nevada (Van Wagtendonk et al., 2004), pine/oak forest of central Spain (De Santis & Chuvieco, 2007), and boreal forest in Alaska (Epting et al., 2005). Possibly ΔNBR could be calibrated against other types of ground measurements to map specific aspects of burn severity (e.g. change in forest canopy cover), but this is not common practice.

Uncertainty about how ΔNBR translates to changes in clearly defined biophysical attributes that can be objectively measured on the ground (e.g., Smith et al., 2007) limits the use of ΔNBR maps as a baseline data layer for the modelling and monitoring of ecological impacts of fire. As the climate changes and the timing, frequency, behaviour and impacts of fire in Australia and elsewhere are altered (Flannigan et al., 2000; Mouillot et al., 2002; Pitman et al., 2007; Westerling et al., 2006), it will become increasingly important to have remote sensing tools to not only map fires and their severity patterns but also to quantify the impacts of fire on basic ecological functions of the forests, such as hydrologic and carbon cycles. In south-west and south-east Australia, for example, fire impacts on water yields from forested catchments is already a major management issue (e.g., Benyon et al., 2007; Berti et al., 2004); in this context, the usefulness of remotely-sensed burn severity maps would be greatly enhanced if burn severity levels were readily converted to changes of biophysical stand attributes used in hydrological models such as leaf area index (LAI) (e.g., Band et al., 1991; Watson et al., 1999).

Change in green vegetation cover is arguably one of the most visible and ecologically significant impacts of fire (DeBano et al., 1998). This is already recognised in existing burn severity assessment methods; for example, changes in vegetation cover and foliage status/colour are key inputs to the CBI (Key & Benson, 2006) and contribute strongly to remotely-sensed ΔNBR (De Santis & Chuvieco, 2007; Kokaly et al., 2007; Robichaud et al., 2007; Van Wagtendonk et al., 2004).

Here, we propose to quantify burn severity as a fire-induced change in LAI. Several considerations underpin our focus on ΔLAI as a potentially useful measure of burn severity. Firstly, LAI is a clearly defined biophysical vegetation attribute that can be objectively measured in the field (Breda, 2003; Macfarlane et al., 2007c) as well as by remote sensing (e.g., Baret & Guyot, 1991; Gascon et al., 2004; Peddle et al., 1999; Turner et al., 1999). LAI is also a key input to process-based forest ecosystem models (e.g., Landsberg & Waring, 1997; Running & Gower, 1991), controlling fundamental processes such as photosynthesis and water use. Secondly, the magnitude of change in forest LAI is indicative of flame lengths and scorch heights during the pass of the fire, which in turn are a good proxy for fire intensity in a given forest type (Byram, 1959; Gould et al., 1997; Van Wagner, 1973). Thirdly, as recent results by Chuvieco et al. (2006) suggest, focusing on ΔLAI for the quantification of burn severity is justified from a spectral point of view. Chuvieco et al. (2006) used a radiative transfer model to simulate the spectral response of a range of hypothetical Mediterranean forest canopies with different burn severity levels quantified by a calculated CBI. By systematically varying key aspects of burn severity, such as removal of surface litter and changes in soil surface colour, foliage colour (from green to brown) and LAI, Chuvieco et al. (2006) quantified the relative contributions of each of these aspects of burn severity to the CBI and to the spectral response of the simulated stand. Chuvieco et al. (2006) found that changes in LAI contributed most strongly to the CBI of the stand and that near-infrared wavebands, because of their potential to detect reductions in LAI, were most sensitive for discriminating the CBI of the simulated canopies. Strong correlation between ground-based CBI and near-infrared reflectance was also observed by De Santis and Chuvieco (2007). These correlations suggest that burn severity assessments based on CBI and NBR may in fact be largely measuring changes in LAI.

The objective of this study was to develop and test a method for mapping burn severity as ΔLAI in typical stands of the northern Jarrah (*Eucalyptus marginata*) forest, in south-western Western Australia, and to compare the results with those obtained using ΔNBR. First, we explored empirical models for the prediction of LAI in northern jarrah forest using the NBR or a spectral vegetation index (SVI) as the predictor variable, and second, applied the models to pre- and post-fire imagery to map burn severity patterns in a ~27,700 ha area affected by the January 2005 Perth Hills wildfires. We evaluated the performance of the proposed methods by comparing ΔLAI-based mapping of the fire-affected area and of the spatial variation in burn severity with ΔNBR. Finally, we discuss the applicability of ΔLAI-based burn severity mapping in other fire-prone environments.

2. Materials and methods

2.1. Study area

The Perth Hills wildfires of 15–25 January 2005 affected ~27,700 ha of predominantly eucalypt forest in the Helena River catchment south