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Estimation and evaluation of multi-decadal fire severity patterns using Landsat sensors

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ABSTRACT

Retrospective identification of fire severity can improve our understanding of fire behaviour and ecological responses. However, burnt area records for many ecosystems are non-existent or incomplete, and those that are documented rarely include fire severity data. Retrospective analysis using satellite remote sensing data captured over extended periods can provide better estimates of fire history. This study aimed to assess the relationship between the Landsat differenced normalised burn ratio (dNBR) and field measured geometrically structured composite burn index (GeoCBI) for retrospective analysis of fire severity over a 23 year period in sclerophyll woodland and heath ecosystems. Further, we assessed for reduced dNBR fire severity classification accuracies associated with vegetation regrowth at increasing time between ignition and image capture. This was achieved by assessing four Landsat images captured at increasing time since ignition of the most recent burnt area. We found significant linear GeoCBI–dNBR relationships ($R^2 = 0.81$ and 0.71) for data collected across ecosystems and for *Eucalyptus racemosa* ecosystems, respectively. Non-significant and weak linear relationships were observed for heath and *Melaleuca quinquenervia* ecosystems, suggesting that GeoCBI–dNBR was not appropriate for fire severity classification in specific ecosystems. Therefore, retrospective fire severity was classified across ecosystems. Landsat images captured within ~30 days after fire events were minimally affected by post burn vegetation regrowth.

1. Introduction

Fire is an integral part of ecosystems across the world. However, improved understanding and management of fire regimes is required to minimise negative impacts on society, the environment and the economy while enhancing their beneficial effects on the ecosystems (Penman et al., 2011). A fire regime is the pattern of fires that occur in an environment over an extended period and can be characterised by frequency, seasonality, spatial pattern and intensity (Gill, 1975). Fire regimes have previously been quantified over extended time periods for some variables such as burnt area and frequency (Duncan, Shao, & Adrian, 2009; Russell-Smith, Ryan, & Durieu, 1997; Srivastava et al., 2013). Applying modern remote sensing techniques, for example, Landsat images can provide improved methods to get further insight into fire regimes behaviour and effects (Srivastava et al., 2013). While previous studies have estimated fire severity for the most recent fire event, the potentially compounding effects of fire severity over multiple-events have been typically ignored (Hammill & Bradstock, 2006). Further research is required to develop methods that can accurately estimate multi-decadal fire severity patterns while understanding retrospective limitations with such analyses.

Confusion exists in wildfire literature over the correct usage of fire and burn severity (Keeley, 2009). The fire disturbance continuum theory indicates that fire severity is the result of the active fire event and burn severity is the post fire response environment (Jain, 2004), or ecological change associated with a fire event (French et al., 2008). Fire severity can be defined as the magnitude of change caused to the ecosystem by a fire event (Key & Benson, 2006; Lentile et al., 2006), this is related to consumption of biomass, scorch, charring and potentially mortality of vegetation (Escuin, Navarro, & Fernández, 2008; Hammill & Bradstock, 2006). Remote sensing of fire severity can be a measure of the change between the pre and post fire environments up to the onset of first growing season after a fire event (Key & Benson, 2006). Burn severity is a measure of ecological responses to a fire that mostly occur in the extended post-fire environment following the onset of first growing season (Key & Benson, 2006; Lentile et al., 2006). Burn severity can be measured using remote sensing images as the recovery of an ecosystem, or ecosystem succession following a fire event (French et al., 2008; Key & Benson, 2006; Lentile et al., 2006). Fire severity is of interest as its role in the long-term dynamics of biota (Knox & Clarke, 2012; Ooi, Whelan, & Auld, 2006) and asset

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protection (Penman et al., 2011), and is relatively unknown and has been poorly researched.

Indices derived from spectral bands and other image classification algorithms have been extensively used to estimate the fire severity of individual fire events from remote sensing datasets (Chafer, 2008; Escuin et al., 2008; French et al., 2008). Landsat images are ideal for estimating fire severity due to the unique combination of moderate spatial resolution data captured in the near and shortwave infrared regions (Key & Benson, 2006). Furthermore, multi-decadal estimates of fire severity can be achieved using the radiometrically consistent temporal archive of Landsat images captured with the TM, ETM+ and OLI instruments since 1982 at near global coverage. The normalised burn ratio (NBR) was first developed by Lopez-Garcia and Caselles (1991), and has been extensively used for multi-date differenced NBR (dNBR) classification of burnt area and fire severity (French et al., 2008; Key, 2006; Key & Benson, 2006). Other classification algorithms have been used to assess the degree of change caused by fire events. These include the iterative self-organising data analysis technique (ISODATA) (Bowman, Zhang, Walsh, & Williams, 2003; Duncan et al., 2009), differenced normalised differenced vegetation index (Chafer, 2008; Hammill & Bradstock, 2006), relative dNBR (Miller & Thode, 2007; Soverel, Perrakis, & Coops, 2010), tasselled cap transformations (Crist & Cincone, 1984) and principal component analysis (Richards, 1984). Simulation modelling of reflectance using radiative transfer models is useful for understanding the physical basis of fire severity spectral responses. They can be used to achieve further insight into post-fire variables that influence the fire severity measure, such as under varying canopy covers and soil charring (Chuvieco, De Santis, Riaño, & Halligan, 2007; De Santis & Chuvieco, 2007). In recent times, the dNBR has become the standard fire severity measure using Landsat data due to its ease to implement and generally large spectral separation that can be attained between the near infrared and short-wave infrared bands (Key & Benson, 2006; French et al., 2008).

Studies utilising Landsat images for fire mapping indicate that linear regression R^2 values for models fitted between continuous Landsat dNBR fire severity and field data range from 0.14 to 0.85 (French et al., 2008). The large variation in accuracies is observed due to differences in vegetation types, validation data and topography within burnt areas (French et al., 2008; Hammill & Bradstock, 2006). Studies further indicate that the dNBR generally performs better in forested vegetation types than in vegetation that lacks persistent green cover, such as cured grasslands and sparse shrublands (French et al., 2008; Pereira, 2003; Veraverbeke, Lhermitte, Verstraeten, & Goosens, 2011).

Field data has been extensively used to calibrate and validate dNBR fire severity classifications (French et al., 2008). The geometrically structured composite burn index (GeoCBI) is a field based fire severity metric developed as a modified version of the popular composite burn index (CBI) (De Santis & Chuvieco, 2009). The GeoCBI was developed in Mediterranean European ecosystems, and varies from the CBI by taking into account measurements of the average vegetation fraction of coverage (FCOV) over four vegetation strata. The FCOV measurements are incorporated into the total plot severity score as weighting factors. This produces a total plot GeoCBI measurement that better aligns the Landsat dNBR reflectance signal with field fire severity measurements (De Santis & Chuvieco, 2007). In addition to the studies using GeoCBI and dNBR in Mediterranean Europe (Veraverbeke et al., 2011; Veraverbeke, Verstraeten, Lhermitte, & Goossens, 2010), it has been used once in boreal forests in Washington State (Cansler & McKenzie, 2012), Californian chaparral (De Santis, Asner, Vaughan, & Knapp, 2010) and European heath-grasslands (Schepers et al., 2014). Cansler and McKenzie (2012) assessed the GeoCBI–dNBR fire severity relationship in a boreal ecosystem and found the results were less correlated than the CBI–dNBR relationship. This is of importance, as the GeoCBI–dNBR relationship is relatively untested outside Mediterranean Europe. The appropriateness of GeoCBI–dNBR derived fire severity information to a range of structural vegetation types and environmental conditions requires further research.

Archived Landsat images are captured at return intervals of sixteen days (eight days when multiple Landsat satellites are operational) and remain useful for initial and retrospective fire severity analysis. However, persistent cloud cover can limit Landsat image capture to a month or more after the fire event (Bowman et al., 2003). This technical limitation can introduce uncertainty into the accuracy of retrospective fire severity measurements where field data is not used to calibrate the classification. Vegetation regrowth is problematic in productive ecosystems with high rainfall as the burnt area is quickly covered by vegetation and thus the fire severity spectral signal is reduced (Hammill & Bradstock, 2006; O'Neill, Head, & Marthick, 1993; Roy, Lewis, & Justice, 2002; Sever et al., 2012). This occurrence can lead to under-estimations of fire severity and a reduced capacity to discriminate between fire severity classes (Gill, Ryan, Moore, & Gibson, 2000). For multi-decadal studies, where retrospective images have been captured, knowledge of temporal change of the burnt area spectral signature can provide further insight into dNBR accuracies.

The objectives of this study were twofold. First, to evaluate the accuracy of fire severity estimates derived from GeoCBI and dNBR data. Second, to estimate fire severity over a 23 year period in Australian native woodland and heath ecosystems using the dNBR data. These objectives were tested with data from a recently burnt area by applying linear regression analysis to explain the variance across all ecosystems within the burnt area. As part of the accuracy evaluation exercise we used historical field photographs taken following two fire events to conduct a semi-quantitative analysis on historical dNBR classifications. Finally, we identified the temporal change of dNBR burnt area spectral signatures within individual ecosystems, to gain a better understanding of the fire severity classifications accuracies derived from Landsat images captured at extended post-fire intervals (i.e. one to six months).

2. Study area and data

2.1. Study area

Mooloolah River National Park (MRNP) covers 962 ha and is dominated by mixed species sclerophyllous woodland and heath, and small patches of tall open and closed *Eucalyptus* forest, and estuarine ecosystems (Fig. 1). In December 2013 a wildfire occurred in MRNP that burnt *Eucalyptus racemosa* and *Melaleuca quinquenervia* woodland, and heath ecosystems. Ecosystems were derived from the Queensland regional ecosystem (RE) vegetation dataset (Accad, Neldner, Wilson, & Niehus, 2008). The height, vertical structure and green canopy cover of woodlands was highly heterogeneous. Heath vegetation was around 1 to 2 m tall and distributed on a mixture of seasonally waterlogged peat soils and white mineral sands. Subsequent to fire events, heath and woodland species respond differently. In sub-tropical vegetation resprouting occurs soon after fire given appropriate growing conditions (e.g. warm temperature and moisture); this usually occurs initially in the herbaceous vegetation and then in woody vegetation. The heath vegetative biomass quickly increases and attains a maximum at around 6 years, followed by declines (McFarland, 1988). While the woodland species vegetative biomass increases at a slower rate and reaches maximum biomass at around 30 years (McFarland, 1988). The study area contained limited spatial variability in elevation, and thus prevented omission errors caused by aspect shadowing due to topographic reflectance variations (Hammill & Bradstock, 2006).

2.2. Burnt area data

The Department of Queensland Parks and Wildlife Service (QPWS) maintain fire perimeter maps and fire reports for the study area. These perimeter maps were used to identify Landsat images