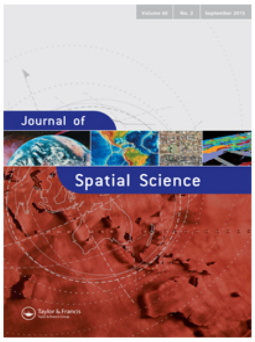

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Using MODIS data to analyse post-fire vegetation recovery in Australian eucalypt forests

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Remote sensing observations provide useful spatially explicit and temporally dense information for monitoring post-fire vegetation recovery patterns over large areas. Although large fires are common in Australian eucalypt forests, research on remote sensing of post-fire vegetation recovery in this ecosystem has been limited. In this study, time series (2000–2012) of Normalised Difference Vegetation Index, Enhanced Vegetation Index and Normalised Differenced Infrared Index derived from Moderate Resolution Imaging Spectroradiometer (MODIS) were used to analyse post-fire vegetation recovery in eucalypt forests in Australia. The analysis focused on 11 sites which burned during 2001/02 and 2002/03 fire seasons. Results indicated that spectral recovery in Australian eucalypt forests is particularly rapid after fire as spectral indices values returned to pre-fire levels three to six years after fire. Spectral recovery was particularly rapid during the first year following fire and the influence of severity was limited to the first two years after fire.

Keywords: forest recovery; Eucalypt forests; MODIS; fire

1. Introduction

Fire is a global phenomenon that affects most terrestrial biomes (Bond & Keeley 2005; Krawchuk *et al.* 2009). The reestablishment or redevelopment of biomass following fire events is traditionally referred to as vegetation recovery (e.g., Frolking *et al.* 2009). During the vegetation recovery process, both structural (e.g., fuel cover, biomass and species composition) and functional (e.g., plant productivity) characteristics of fire-affected systems evolve (Cochrane & Schulze 1999; Hicke *et al.* 2003; Reilly *et al.* 2006; Jacobson 2010) following trajectories influenced by several environmental factors including fire severity (Wilkinson & Jennings 1993; Jin *et al.* 2012) and vegetation type (van Leeuwen *et al.* 2010). Developing techniques for reliable assessment of post-fire vegetation recovery patterns is critical for better understanding fire-induced effects on key vegetation properties (Frolking *et al.* 2009) and planning fire management practices (e.g., fuel treatment, fuel hazard assessment and prescribed burning) (e.g., Gould *et al.* 2011).

Monitoring vegetation recovery at broad spatial and temporal scales through field sampling can be challenging due to time and resource constraints (e.g., Jacobson 2010; Lhermitte *et al.* 2011). Satellite sensors,

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acquiring data over large areas at regular time intervals, provide the potential for cost-effective spatially explicit monitoring of post-fire vegetation recovery (e.g., van Leeuwen *et al.* 2010; Veraverbeke *et al.* 2010; Lhermite *et al.* 2011). A number of vegetation properties, which are altered by fire, can be remotely sensed and their dynamics monitored using time-series of spectral data (Lentile *et al.* 2006; Frolking *et al.* 2009). In particular, information in the near-infrared (NIR: 0.7–1 μm) and shortwave infrared (SWIR: 1–2.5 μm) channels can be linked to temporal changes in fuel load (e.g., Brandis & Jacobson 2003; Chafer *et al.* 2004), leaf area index (e.g., Coops *et al.* 1997), vegetation regrowth rates (Jacobson 2010) and productivity (e.g., Hicke *et al.* 2003).

Data from a wide range of satellite platforms (e.g., Advanced Very High Resolution Radiometer, AVHRR; Moderate Resolution Imaging Spectroradiometer, MODIS; Landsat TM/ETM + and Satellites Pour l'Observation de la Terre, SPOT) have been used as a proxy to monitor post-fire vegetation recovery patterns in different regions and biomes of the world including tropical grassland in South Africa (e.g., Lhermitte *et al.* 2011), shrubland in Spain (e.g., Díaz-Delgado *et al.* 2003), chaparral in California (e.g., Hope *et al.* 2007), fynbos in South Africa (e.g., Hope *et al.* 2012), pine forest in Spain (e.g., Vicente-Serrano *et al.* 2011), tropical forest in Brazil (e.g., Numata *et al.* 2011) and boreal forest in Siberia (e.g., Cuevas-González *et al.* 2009) and North America (e.g., Hicke *et al.* 2003; Jin *et al.* 2012). Research on remote sensing of post-fire vegetation recovery in Australian eucalypt forests has received considerably less attention. Previous published remote sensing-based studies focused on vegetation recovery patterns in the early stages after fire. Walz *et al.* (2007) analysed the temporal development of MODIS-derived Normalised Burn Ratio (NBR; Key & Benson 2002) in the first two months after fire in western Australian eucalypt forests. Jacobson (2010) compared SPOT-derived Normalised Difference Vegetation Index (NDVI; Rouse *et al.* 1974) and Normalised Difference Infrared Index (NDII, Hunt Jr & Rock 1989) data to vegetation regrowth rates in south-eastern Australian eucalypt formations at 6 and 9 months after fire. Finally, Sever *et al.* (2012) used Landsat-derived data to analyse NDVI values of a mixed-species eucalypt forest in North-East Victoria at approximately 1, 12 and 24 months post fire.

The application of remote sensing time-series to analyse longer-term (i.e., multi-year) post-fire vegetation recovery patterns in Australian eucalypt forest remains therefore largely unexplored. Additionally, the potential influence of fire severity on those patterns has not been investigated in previous studies. Analysis of remotely sensed vegetation recovery patterns in Australia is important because most eucalypt species are resprouters which can survive fires (e.g., Wilkinson & Jennings 1993; Burrows 2002) and regenerate by means of fire resistant structures located beneath the bark (i.e., epicormic buds; Burrows 2002; Clarke *et al.* 2010). Recovery patterns in Australian eucalypt forests could, therefore, differ from those previously analysed in other forested ecosystems of the world. In particular, fundamental differences could exist between eucalypt forests and boreal forests in North America (e.g., Hicke *et al.* 2003; Epting & Verbyla 2005; Goetz *et al.* 2006; Jin *et al.* 2012) where most tree species are obligate seeders. In these forests, fires cause widespread mortality of trees (e.g., Rowe & Scotter 1973; Vierek 1983; Weber & Stocks 1998) and trees regenerate from seeds resulting in stand-replacement. Further research is, therefore, required to better understand the potential of remote sensing data for monitoring long-term post-fire recovery patterns and fire-induced changes in vegetation properties in Australian eucalypt forests.

The main objectives of this study were: (a) to analyse inter-annual post-fire vegetation recovery in Australian eucalypt forests using MODIS-derived spectral indices; and (b) to investigate the potential influence of fire severity on remotely sensed vegetation recovery patterns; and (c) to compare post-fire spectral recovery in Australian eucalypt forests to boreal forests.

2. Study area

This study was conducted in the Sydney Basin Bioregion in south-eastern Australia (Figure 1). The basin covers an area of approximately 3.6 million hectares and contains a diverse range of highly flammable vegetation communities with eucalypt dry sclerophyll forest accounting for over 70 percent of natural vegetation (Keith 2004; Tindall *et al.* 2004). These forests are characterised by an overstorey of evergreen eucalypt trees with canopy cover ranging from 30 percent to 50 percent and height ranging from 10 to 30 metres, an abundant sclerophyll and evergreen shrubby understorey and an open ground cover dominated by sclerophyll sedges (Keith 2004).

Fires have burnt over 1 million hectares of the study region in the last 15 years (New South Wales Office of Environment and Heritage, unpublished data, 2010). This study examined vegetation recovery patterns at eucalypt forest sites which burnt during the 2001/02 and 2002/03 fire seasons (Figure 1). Those fire seasons were selected because (i) fire severity maps (Hammill & Bradstock 2006; Hammill *et al.* 2010) were available, and (ii) those fires occurred after the beginning of the MODIS mission (i.e., 2000).

3. Data and methods

Fire severity data and study site selection

Fire severity maps (Hammill *et al.* 2010) were used to select the study sites (Figure 1). These maps were generated using NDVI and NBR derived from Landsat and SPOT images and validated using field data collected in the study area (Chafer *et al.* 2004; Hammill & Bradstock 2006; Hammill *et al.* 2010). The mapped fires are classified into three fire severity classes (i.e., Low, High and Extreme) representing different level of vegetation loss (Hammill *et al.* 2010 and Table 1).

Eleven study sites were selected within national parks across the Sydney Basin Bioregion (Figure 1 and Table 2) using the fire severity maps (Hammill *et al.* 2010) and available fire history records (New South Wales Office of Environment and Heritage, unpubl. data). Seven sites were in areas which burnt during the 2001/02 fire season and four sites were in areas which burnt during the 2002/03 fire season. Each study site contained two fire-affected areas which burnt at contrasting severity to represent two broadly different levels of vegetation loss, and one control area which did not burn during the study period (i.e., 2000–2012). All fire-affected areas burnt only once during the study period. At each study site, an area containing multiple MODIS pixels (i.e., larger than 25 ha) was selected for each of the fire-affected areas and the unburnt control. A vegetation layer (Keith 2004) was used to ensure both fire-affected and control areas at each study site were predominantly covered by native eucalypt dry sclerophyll forest (Table 2).

Control areas were included in the analysis to compare spectral values of fire-affected and unburnt areas (e.g., Cuevas-González *et al.* 2009; van Leeuwen *et al.* 2010) and to assess the time required for spectral signals of fire-affected areas to return to pre-fire condition (i.e., spectral signals of control areas). In this type of analysis, it is important to minimise the distance between areas in order to ensure that burnt and unburnt locations experience similar climatic conditions (e.g., Cuevas-González *et al.* 2009). Control areas were selected within 7.4 km of fire-affected areas.

The terms Elevated Severity and Moderate Severity were used to describe the two fire-affected areas at each study site. Since the spatial pattern of the fire severity classes (Table 1) was highly variable at local scale, Elevated and Moderate Severity areas were not

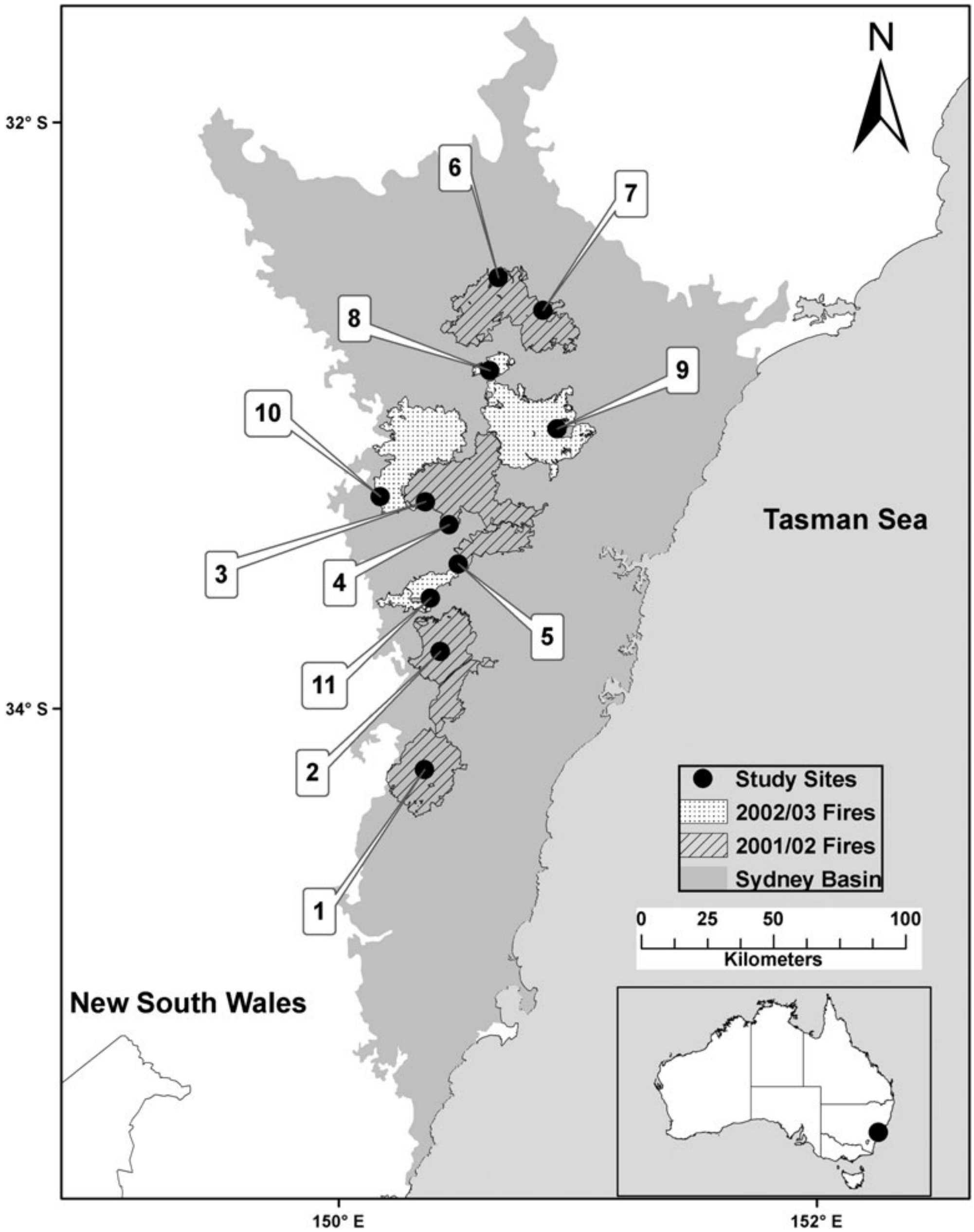

Figure 1. Map of the Sydney Basin Bioregion showing the location of the 11 study sites and fires which occurred during the 2001/02 and 2002/03 fire seasons

homogeneous in terms of severity and contained a mixture of the three severity classes (Table 1). In Elevated Severity areas, 76 ± 5.30(SE) percent, 23 ± 2.38(SE) percent and 1 ± 1.34(SE) percent of the surface (average values for all 11 Elevated Severity

Table 1. Name and description of the fire severity classes mapped by Hammill *et al.* (2010)

Class	Name	Description
1	Low	Understorey scorched and tree canopy unburnt
2	High	Understorey mostly consumed and tree canopy scorched
3	Extreme	Understorey and tree canopy completely consumed

areas) were covered by Extreme, High and Low severity classes, respectively (Table 1). Therefore, Elevated Severity areas represented locations where both understorey and overstorey were significantly affected by fire. In Moderate Severity areas, 4 ± 1.27(SE) percent, 25 ± 0.17(SE) percent and 70 ± 8.87(SE) percent of the surface (average values for all 11 Moderate Severity areas) were covered by Extreme, High and Low severity classes, respectively. Therefore, fire mainly affected the understorey in Moderate Severity areas.

Remote sensing data

We used 500-meter resolution 8-day composite surface reflectance MODIS data (MOD09A1, collection 5) from 2000 to 2012. MODIS data were used because this sensor provides temporally dense multispectral acquisitions at moderate spatial resolution which are suitable for long-term monitoring of vegetation patterns over extended areas (Cuevas-González *et al.* 2009; Jin *et al.* 2012). Data anomalies (e.g., cloud, cloud shadow and cirrus) were masked using MODIS quality assurance (QA) metadata (after Caccamo *et al.* 2011, 2012a). Time-series of NDVI (Rouse *et al.* 1974), NDII (Hunt Jr & Rock 1989) centred on 1640 nm (i.e., NDIIb6) and Enhanced Vegetation Index (i.e., EVI; Huete *et al.* 2002) were calculated from MODIS Band1 (620–670 nm), Band2 (841–876 nm), Band3 (459–479 nm) and Band6 (1628–1652 nm) using the following formulae:

$$NDVI = \frac{Band2 - Band1}{Band2 + Band1} \tag{1}$$

$$NDIIb6 = \frac{Band2 - Band6}{Band2 + Band6} \tag{2}$$

$$EVI = 2.5 \times \left(\frac{Band2 - Band1}{Band2 + 6 \times Band1 - 7.5 \times Band3 + 1}\right) \tag{3}$$

Table 2. Area (Ha), eucalypt dry sclerophyll forest cover (percent) and fire date of the eleven study sites. Area (Ha) and eucalypt dry sclerophyll forest cover (percent) are average values for the control and two fire-affected areas at each site

Study site	Study site area (Ha)	Eucalypt dry sclerophyll forest cover (percent)	Fire date
1	180 + 20.6(SE)	81 ± 4.3(SE)	December 2001
2	222 ± 61.7(SE)	90 ± 4.1(SE)	December 2001
3	283 ± 53.7(SE)	94 ± 2.5(SE)	December 2001
4	138 ± 25.4(SE)	86 + 3(SE)	December 2001
5	193 + 48.8(SE)	90 ± 1.4(SE)	December 2001
6	119 ± 21.4(SE)	89 ± 6.2(SE)	December 2001
7	265 ± 31.8(SE)	84 ± 7.8(SE)	December 2001
8	323 ± 76.8(SE)	82 ± 2.7(SE)	October 2002
9	260 + 59(SE)	69 ± 11.6(SE)	October 2002
10	334 ± 95.4(SE)	84 ± 10.3(SE)	January 2003
11	343 ± 78(SE)	77 ± 2.4(SE)	October 2002

NDVI, NDIIb6 and EVI were selected because they have been successfully used in this context in previous studies (e.g., Cuevas-González *et al.* 2009; Jin *et al.* 2012), and have been found to relate to a range of vegetation properties in this forest type such as leaf area index (e.g., Coops *et al.* 1997), biomass (e.g., Chafer *et al.* 2004), fuel moisture condition (Caccamo *et al.* 2012b) and vegetation regrowth rate (e.g., Jacobson 2010).

At each study site and for all fires analysed (Table 2), the first four NDVI, NDIIb6 and EVI 8-day composites following the fire date were averaged for all pixels contained within control, Moderate Severity and Elevated Severity areas. Using the same 8-day composites period, NDVI, NDIIb6 and EVI averages were also calculated for all the other years between 2000 and 2012. Thus time-series of pre- and post-fire NDVI, NDIIb6 and EVI values were generated for each fire-affected and control area of the eleven study sites at 1 year time steps. The use of this time window (i.e., four 8-day composites) allowed for the comparison of vegetation spectral properties immediately after fire (i.e., before the onset of potential confounding factors such as ground vegetation regrowth; Jacobson 2010) for the period 2000 to 2012. Moreover, this time window was large enough to ensure the availability of suitable (e.g., cloud-free) NDVI, NDIIb6 and EVI observations.

The difference between NDVI, NDIIb6 and EVI values of control areas and fire-affected areas (ΔNDVI, ΔNDIIb6 and ΔEVI) was calculated for both Moderate and Elevated Severity areas at all sites and each year of analysis using the following equation:

$$\Delta \mathrm{NDVI} = \mathrm{NDVI}_{\mathrm{Con}} - \mathrm{NDVI}_{\mathrm{Ele\ or\ Mod}} \quad (4)$$

$$\Delta \mathrm{NDIIb6} = \mathrm{NDIIb6}_{\mathrm{Con}} - \mathrm{NDIIb6}_{\mathrm{Ele\ or\ Mod}} \quad (5)$$

$$\Delta \mathrm{EVI} = \mathrm{EVI}_{\mathrm{Con}} - \mathrm{EVI}_{\mathrm{Ele\ or\ Mod}} \quad (6)$$

where Ele, Mod and Con are Elevated Severity, Moderate Severity and control areas, respectively. ΔNDVI, ΔNDIIb6 and ΔEVI data were used to investigate the recovery rate of vegetation spectral response and the number of years required for spectral signals of fire-affected areas (i.e., Moderate and Elevated Severity areas) to return to pre-fire conditions (i.e., number of years required for ΔNDVI, ΔNDIIb6 and ΔEVI values to be statistically not different from their values at time since fire $= -1$).

Using previously published data (Table 3), recovery rates of Australian eucalypt forests and North American boreal forests (i.e., Amiro *et al.* 2000; Hicke *et al.* 2003; Epting & Verbyla 2005; Goetz *et al.* 2006; Jin *et al.* 2012) were compared to analyse potential differences between forest types dominated by resprouter and obligate seeder species, respectively. Although the spectral bandwidths used to compute NDVI, NDII and EVI differ for MODIS, Landsat TM/ETM + and AVHRR, previous research has shown a good consistency

Table 3. Summary of remote sensing studies on post-fire recovery in North American boreal forests. Satellite: Advanced Very High Resolution Radiometer (AVHRR), Landsat Thematic Mapper and Enhanced Thematic Mapper (Landsat TM and ETM +) and Moderate Resolution Imaging Spectroradiometer (MODIS). Spectral Index: Normalised Difference Vegetation Index (NDVI), Normalised Difference Infrared Index (NDII), Enhanced Vegetation Index (EVI) and Net Primary Productivity (NPP)

Satellite	Spectral index	Recovery time (year)	Source
AVHRR	NPP (NDVI-driven)	>15	Amiro *et al.* 2000
AVHRR	NPP (NDVI-driven)	9	Hicke *et al.* 2003
Landsat TM and ETM +	NDVI and NDII	8 to 14	Epting & Verbyla 2005
AVHRR	NDVI	5 to 10	Goetz *et al.* 2006
MODIS	EVI	5 to 8	Jin *et al.* 2012

between the spectral response associated with their Red, NIR and SWIR channels (e.g., Gallo *et al.* 2005; Brown *et al.* 2006; Thome *et al.* 2006). Therefore, the comparison of recovery times derived from MODIS, Landsat TM/ETM + and AVHRR time series is scientifically valid.

4. Results

Post-fire ΔNDVI, ΔNDIIb6 and ΔEVI values showed a similar pattern (Figure 2a–c). Immediately after fire (i.e., time since fire = 0), ΔNDVI, ΔNDIIb6 and ΔEVI of Elevated Severity areas were higher than for Moderate Severity areas and the non-overlapping 95 percent confidence intervals indicated their averaged values were significantly different ($p < 0.05$). In the years following fire (i.e., time since fire > 0), ΔNDVI, ΔNDIIb6 and ΔEVI values of Moderate and Elevated Severity areas started decreasing. The decrease was particularly rapid within the first year after fire and more gradual in the following years. ΔNDVI, ΔNDIIb6 and ΔEVI values of Moderate and Elevated Severity remained significantly ($p < 0.05$) different for the first two years following fire.

ΔNDVI of Elevated and Moderate Severity areas returned to pre-fire levels after six and five years, respectively (matched-pairs *t*-test, df = 10, $p > 0.05$, H_0: $\Delta NDVI_{TimeSinceFire6and5} = \Delta NDVI_{TimeSinceFire-1}$), indicating their NDVI values closely matched the values of control areas (Figure 2a). Five years after fire ΔNDIIb6 of both Moderate and Elevated Severity areas had returned to pre-fire levels (matched-pairs *t*-test, df = 10, $p > 0.05$, H_0: $\Delta NDIIb6_{TimeSinceFire5} = \Delta NDIIb6_{TimeSinceFire-1}$). EVI showed a quicker recovery pattern (Figure 2b–c), ΔEVI of Elevated Severity areas returned to pre-fire levels after four years (matched-pairs *t*-test, df = 10, $p > 0.05$, H_0: $\Delta EVI_{\ TimeSinceFire4} = \Delta EVI_{\ TimeSinceFire-1}$), whilst ΔEVI of Moderate Severity returned to pre-fire levels after only three years (matched-pairs *t*-test, df = 10, $p > 0.05$, H_0: $\Delta EVI_{\ TimeSinceFire3} = \Delta EVI_{\ TimeSinceFire-1}$). The recovery time of NDVI, NDII and EVI in Australian eucalypt forests (i.e., 5 to 6-year, 5-year and 3 to 4-year, respectively) was therefore shorter than in North American boreal forests (i.e., 5 to 15 + -year, 8 to 14-year and 5 to 8-year, respectively) (Figure 2a–c and Table 3).

5. Discussion

The analysis of ΔNDVI, ΔNDIIb6 and ΔEVI values (Figure 2a–c) showed that fire had a significant influence on vegetation spectral response at the 11 study sites considered during the time period of analysis (i.e., 2000–2012). Immediately after fire, ΔNDVI, ΔNDIIb6 and ΔEVI increased and reached their highest value because fire scorched and/or consumed the forest layers (Table 1) and increased soil exposure, altering the spectral properties of the fire-affected areas (i.e., decrease in NIR and increase in SWIR reflectance; Walz *et al.* 2007). During the years following fire, ΔNDVI, ΔNDIIb6 and ΔEVI values of Moderate and Elevated Severity areas decreased towards pre-fire levels as a result of understorey and overstorey regrowth. Jacobson (2010) field-monitored post-fire vegetation regrowth in eucalypt formations within the Sydney basin, finding that ground, shrub and canopy cover returned to 82 percent, 66 percent and 41 percent of their pre-fire levels, respectively, one year after fire. It is possible that MODIS observations could capture the rapid recovery of the lower forest layers in both Elevated and Moderate Severity areas because the former fire largely consumed (i.e., removed) the overstorey, exposing the background, and in the latter the understorey still had a significant influence on vegetation spectral response (e.g., Pereira *et al.* 2004) due to the moderate canopy cover (i.e., 30–50 percent; Keith 2004) typical of eucalypt forests in the study area.

EVI showed a shorter recovery time than NDVI and NDIIb6 (Figure 2a–c). A possible explanation is that, since EVI is less sensitive to background noise (e.g., mixing of soil/

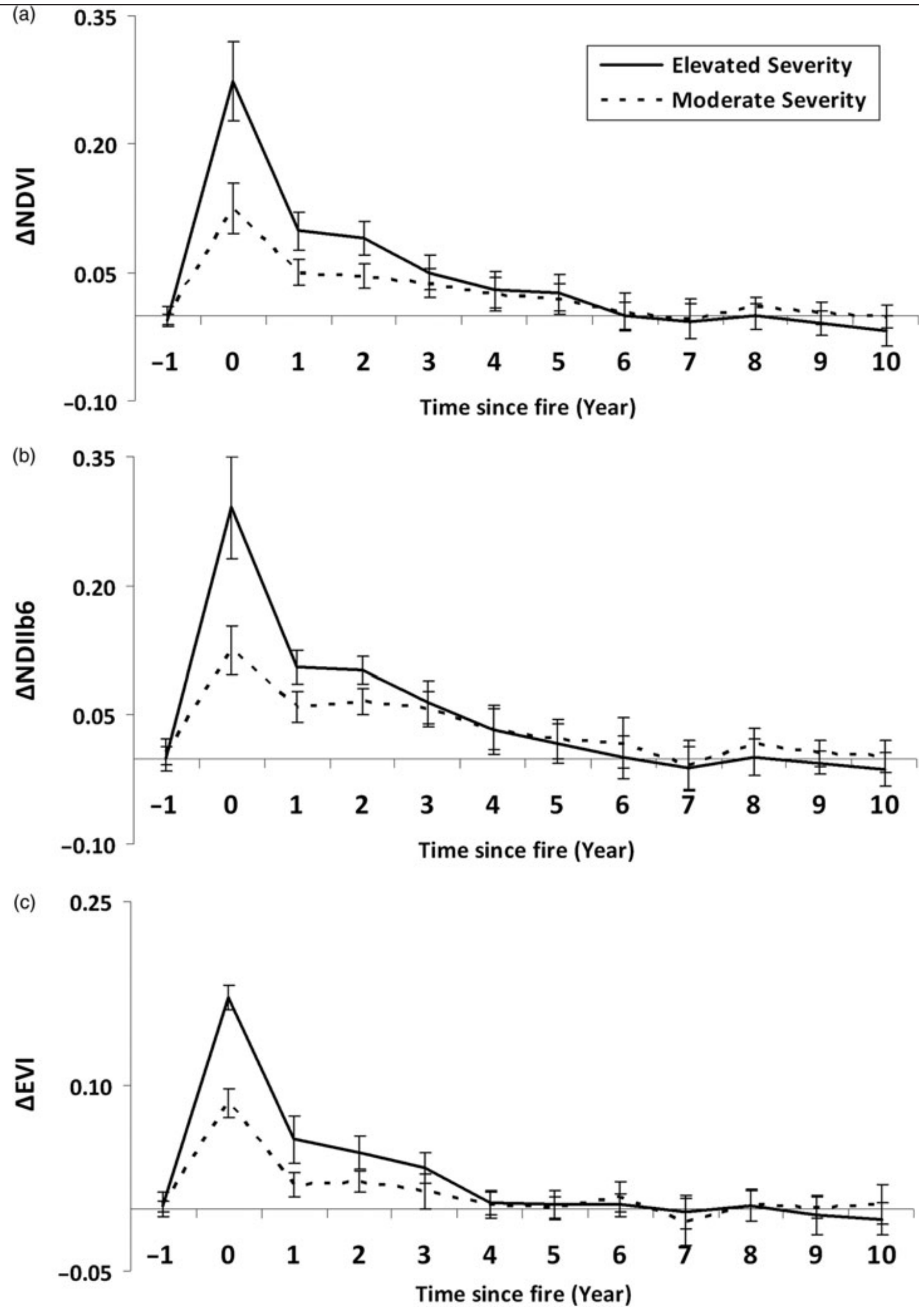

Figure 2. Average difference between control and fire-affected areas at all study sites as a function of time since fire for (a) Normalised Difference Vegetation Index (ΔNDVI), (b) Normalised Difference Infrared Index – Band6 (ΔNDIIb6) and (c) Enhanced Vegetation Index (EVI). Error bars indicate 95 percent confidence interval. The legend in (a) applies to (b) and (c)

vegetation signal) and it is more responsive to canopy structural variations including LAI and canopy architecture (e.g., Gao *et al.* 2000; Huete *et al.* 2002; Cunha *et al.* 2010), its signal might respond more quickly to post-fire reestablishment of understorey and overstorey vegetation and return more rapidly to pre-fire levels.

The relatively short recovery time of NDVI (i.e., 5 to 6-year), NDIIb6 (i.e., 5-year) and EVI (i.e., 3 to 4-year) is consistent with the fuel load accumulation pattern of eucalypt forests. Previous research in this region (e.g., Maggs & Pearson 1977; van Loon 1977; Conroy 1993; Jacobson 2010; Penman & York 2010) has shown that fuels tend to accumulate rapidly in the initial post-fire years (i.e., 0 to 10 years). The recovery rate of NDVI, NDIIb6 and EVI in eucalypt forests was faster than in North American boreal forests (Table 3 and Figure 2a–c). This could be explained by the different response to fire of the two forest types (e.g., Rowe & Scotter 1973; Burrows 2002). Fires in boreal forests are predominantly stand-replacement events (i.e., crown fire) leading to widespread tree mortality (e.g., Rowe & Scotter 1973; Weber & Stocks 1998). Most of the overstorey and understorey species in the eucalypt forests considered in this study (e.g., *Corymbia gummifera*, *Eucalyptus piperita*, *Eucalyptus sieberi*, *Banksia serrata* and *Bursaria spinosa*) can survive fire (e.g., Wilkinson & Jennings 1993; Benson & McDougall 1998; Atwell *et al.* 1999) and regenerate branches and leaves by resprouting from heat-resistant buds (e.g., Burrows 2002). The higher survival rate and resilience to fire of resprouter species (e.g., Burrows 2002) could facilitate a more rapid accumulation of aboveground biomass in eucalypt forests and, consequently, a shorter post-fire spectral recovery time (Figure 2a–c).

As previously reported in other studies (e.g., Díaz-Delgado *et al.* 2003; Jin *et al.* 2012), fire severity influenced post-fire NDVI, NDIIb6 and EVI profiles (Figure 2a–c). Immediately after fire (i.e., time since fire = 0), NDVI, NDIIb6 and EVI values decreased more in Elevated Severity areas than in Moderate Severity areas (Figure 2a–c). However, ΔNDVI, ΔNDIIb6 and ΔEVI values of Moderate and Elevated Severity areas remained significantly ($p < 0.05$) different only for the first two years following fire (Figure 2a–c). In the following years (i.e., time since fire > 2), the trajectories of Moderate and Elevated Severity areas converged (Figure 2a–c), suggesting that either (i) vegetation in both areas had recovered to pre-fire levels or (ii) MODIS data could not capture the differences in vegetation characteristics (e.g., species composition, fuel load, fuel cover and fuel height) between the two areas. The latter option is highly likely because post-fire remotely sensed signals are not always an exact representation of the recovery processes occurring at vegetation level (e.g., Buma 2012). When spectral values of fire-affected areas return to pre-fire levels, vegetation on the ground might not be in the same condition as it was before the wildfire (e.g., Cuevas-González *et al.* 2009). The rapid reestablishment of greenness (e.g., foliage, grasses, forbs, ground cover) could dominate the spectral signal and obscure potential differences in vegetation properties (e.g., height, biomass, species composition) (e.g., Buma 2012).

6. Conclusion

NDVI, NDIIb6 and EVI values of fire-affected areas returned to pre-fire levels within three to six years following fire. The limited influence of severity on post-fire recovery (i.e. effects of severity were mainly limited to the first two years following fire) indicates that spectral recovery in eucalypt forests is particularly rapid. The recovery time of remotely-sensed indices in *Eucalyptus* dominated forests in south-eastern Australia was shorter than in obligate seeder dominated forests (i.e., North American boreal forests), indicating that their contrasting fire-response strategy has a strong influence on the reestablishment of vegetation spectral properties.

Although this study has shown that the spectral recovery of NDVI, NDIIb6 and EVI in eucalypt forests was consistent with general patterns of vegetation regrowth in the study area it has also highlighted the need to further investigate the relationship between spectral and vegetation properties in this forest type. In particular, in order to ensure proper interpretation of the remotely sensed signals, further research will be required to relate the values of spectral indices to field-measured fuel characteristics (e.g., fuel cover, height and load) of different forest layers across a range of post-fire ages (Frolking *et al.* 2009). This type of analysis could explore the sensitivity of remotely sensed signals to the different dynamic components of forests and improve our understanding of the potential of satellite observations for monitoring fire-induced effects on vegetation properties.

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