RESEARCH ARTICLE

POST-FIRE RECOVERY OF EUCALYPT-DOMINATED VEGETATION COMMUNITIES IN THE SYDNEY BASIN, AUSTRALIA

Jessica T. Heath[1*], Chris J. Chafer[2], Thomas F.A. Bishop[1], and Floris F. Van Ogtrop[1]

[1] The University of Sydney, Department of Environmental Sciences,
Faculty of Agriculture and Environment,
C81-Biomedical Building, Sydney, New South Wales, 2006, Australia

[2] WaterNSW, Level 4, 2-6 Station Street, Penrith, New South Wales, 2750, Australia

[*] Corresponding author: Tel.: +61-2-99955632; e-mail: Jessica.Heath@sydney.edu.au

ABSTRACT

Monitoring landscape-scale vegetation responses of resprouter species to wildfire is helpful in explaining post-wildfire recovery. Several previous Australian studies have investigated the temporal recovery of eucalypt obligate-seeder communities (which have a significantly delayed revegetation response), but little research has been conducted for resprouter communities. In this study, we found that eucalypt dominated resprouter communities in Sydney's drinking water supply catchments (SDWC) have a rapid post-wildfire response and recovery rate. This study was designed to detect inter-annual landscape-scale changes in vegetation response using a 22 yr pre- and post-wildfire time series of Landsat satellite-derived Australian summer images (1990/91 to 2011/12). Four burned subcatchments and three unburned subcatchments were analyzed. The temporal change in eucalypt forest and woodland vegetation communities was examined within the subcatchments using the Normalized Differenced Vegetation Index (NDVI) to assess their health. A new spectral index, differenced Recovery Index (dRI), was

RESUMEN

El monitoreo a nivel de paisaje sobre las respuestas de la vegetación de especies rebrotantes a los incendios es útil para explicar su recuperación post-fuego. Diversos estudios previos en Australia han investigado la recuperación temporal de comunidades de eucaliptus que se reproducen por semilla (y que presentan una respuesta de revegetación diferida en el tiempo), aunque muy poca investigación ha sido realizada para comunidades rebrotantes. En este estudio, encontramos que las comunidades dominadas por eucaliptus rebrotantes en las cuencas de provisión de agua dulce para Sydney (SDWC), tienen una rápida respuesta y altas tasas de recuperación post-fuego. Este estudio fue diseñado para detectar cambios interanuales a nivel de paisaje en la respuesta de la vegetación a incendios usando series de tiempo de imágenes Landsat tomadas en Australia durante el verano 22 años antes y después (1990/91 y 2011/12) de esos eventos de fuego. Se analizaron cuatro sub-cuencas quemadas y tres no quemadas. Los cambios temporales en el bosque de eucaliptus y otras comunidades boscosas fueron analizados dentro de las sub-cuencas mediante el Índice de Vegetación de Diferencia Normalizado (NDVI), para determinar su sanidad. Un nuevo índice espectral, el índice diferenciado de recuperación (dRI), fue desarrollado para cuantificar developed to quantify the difference between the pre- and post-wildfire NDVI values. We found that, spectrally, at the landscape scale, vegetation communities recovered to near pre-wildfire conditions within five to seven years post wildfire. These results demonstrate the resilience of resprouter vegetation communities in the Sydney Basin to large-area disturbance events at the landscape scale.

las diferencias entre los valores de NDVI previos y posteriores al incendio. Encontramos que espectralmente y a nivel de paisaje, las comunidades vegetales recuperan las condiciones pre-fuego dentro de cinco a siete años después de ocurrido el evento de fuego. Estos resultados muestran la resiliencia de las comunidades vegetales rebrotantes en la cuenca de Sydney a los eventos de disturbios que ocurren en grandes áreas a escala de paisaje.

Keywords: eucalypt, Landsat, NDVI, resprouter, vegetation, wildfire

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INTRODUCTION

Wildfire can cause significant modifications in Australian vegetation communities (Florence 1996; Bradstock *et al.* 2002, 2012), yet many sclerophyllous vegetation communities (dominated by *Eucalyptus* spp. L'Héritier) are well adapted to recover from the periodic impact of wildfire via two facultative processes (Gill 1981, Bradstock *et al.* 1998, Waters *et al.* 2010):

1. the mass release and germination of seed from plants (seeding); or
2. via vegetative epicormic buds or lignotubers that facilitate resprouting from the stem, trunk, or branches of plants (resprouting).

Either or both of these processes can be employed, although obligate seeder species have limited resprouting ability and, therefore, rely on seed germination and growth to recover.

Within the drinking water supply catchments of southeastern Australia, post-wildfire hydrological response, vegetation response, erosion, and soil and water quantity have been well studied over the past two decades (White *et al.* 2006, Shakesby *et al.* 2007, Smith *et al.* 2011, Heath *et al.* 2014, Heath *et al.* 2015). Vegetation recovery after wildfire is dependent on many factors such as pre-fire vegetative fuel load, fire intensity, burn severity, climatic conditions, light, nutrient availability, and species composition (Williams 1995, Oii *et al.* 2004, Wright and Clarke 2007, Keeley 2009). Like many forested areas in southeastern Australia, Sydney's drinking water supply catchments (SDWC) are dominated by resprouter communities (Keith 2004). These floristic communities recover rapidly from wildfire and vegetative fuels can accumulate rapidly after wildfire (5 yr to 15 yr) to an asymptote in which the fuel biomass approaches a near-steady state (van Loon 1977, McCarthy *et al.* 2001, Raison 2005, Clarke *et al.* 2009, Gilroy and Tran 2009, Bradstock *et al.* 2010). Importantly, catchments with these rapidly recovering resprouter-dominated communities have a substantially different post-wildfire hydrological response than other water supply catchments in southeastern Australia (e.g., Vertessy *et al.* 1998 and Feikema *et al.* 2013), with only minor erosional events and short-term water yield deficits being recorded after extreme wildfire (Shakesby *et al.* 2007, Tomkins *et al.*

2008, Heath *et al.* 2014). Conversely, the obligate seeder communities that have been extensively studied in Australia's drinking water supply catchments can have serious post-wildfire erosion and significant multi-decadal water yield deficits (Vertessy *et al.* 1998, Lane *et al.* 2010, Nyman *et al.* 2011, Sever *et al.* 2012, Bell *et al.* 2014).

Although it has been well reported that forests and woodlands dominated by resprouter communities recover quickly from wildfire (Morrison *et al.* 1995, Clarke *et al.* 2009, Enright *et al.* 2012, Gill 2012), little spatial and temporal analysis at the landscape scale has been undertaken in Australian forests, as highlighted by Bradstock *et al.* (2010) and Enright *et al*. (2012). In this study, we used satellite image interpretation to investigate the inter-annual spatial and temporal impact and recovery of a very severe wildfire that occurred in the SDWC during December 2001 to January 2002 (Chafer *et al*. 2004; henceforth, references to summer seasons will be written with a slash between the consecutive years, such that this wildfire will be denoted as the 2001/02 wildfire). Using a 22 yr pre- and post- wildfire data set, we hypothesized that, at the landscape scale, forested catchments in SDWC recover to pre-wildfire conditions (fuel biomass) much faster than has been previously reported (Brown 1972). Additionally, we hypothesized that the impact of even the most severe burn has minimal medium-term (decadal) effect on the recovery on eucalypt forests and woodlands dominated by resprouter vegetation communities in the Sydney Basin (Shakesby *et al.* 2007).

Many recent studies have attempted to quantify the impact of wildfire on vegetation regrowth through the use of remote sensing by analyzing various vegetation indices including Fractional Vegetation Cover (FVC; Hernandez-Clemente *et al.* 2009), Normalized Burn Ratio (NBR; Fox *et al.* 2008, Lhermitte *et al.* 2011), Differenced Normalized Burn Ratio (dNBR; Fox *et al.* 2008), and the Normalized Difference Vegetation Index (NDVI; Díaz-Delgado *et al.* 2002, Fox *et al.* 2008, Hernandez-Clemente *et al.* 2009, Jacobson 2010). The NDVI was selected to compare pre- and post-wildfire healthiness of forested catchments in our study area because that index has a strong relationship with aboveground biomass and is widely used to detect vegetation change and investigate post-fire vegetation recovery (Fox *et al.* 2008, Gouveia *et al.* 2010, van Leeuwen *et al.* 2010, Lhermitte *et al.* 2011, Gitas *et al.* 2012). It is a ratio-based index using the red band of the spectral region, which strongly absorbs visible red light for use in photosynthesis and transpiration. Conversely, the leaf structure of most plants strongly reflects near-infrared light and that reflectance is related to canopy biomass, showing changes in vegetation growth (Sellers 1985, Grove and Navarro 2013). Combined, these bands incorporated into the NDVI measure the greenness of vegetation species. In the study area (Figure 1), most woodland and forested communities were dominated by eucalypts, which hold their leaves perpendicular to the ground (Keith 2004). This allows more light energy to penetrate through the canopy to the understory and ground layers, making NDVI an ideal spectral index to examine vegetal changes through the communities' vertical structure.

Research focusing on temperate vegetation recovery of forests and woodlands within Australia after wildfire using NDVI is limited. One study was conducted in Western Australia (Boer *et al.* 2008), two in Victoria (Dilley *et al.* 2004, Levin *et al.* 2012), and two in New South Wales (Jacobson 2010, Sever *et al.* 2012). All of those studies were limited to a 1 yr to 2 yr time frame, only examining vegetation recovery immediately post wildfire or for a short period post wildfire. For instance, Sever *et al.* (2012) undertook a study in southeastern Australia using Landsat 5 TM imagery and NDVI to analyze post-fire vegetation recovery. The wildfire took place in December 2006 and

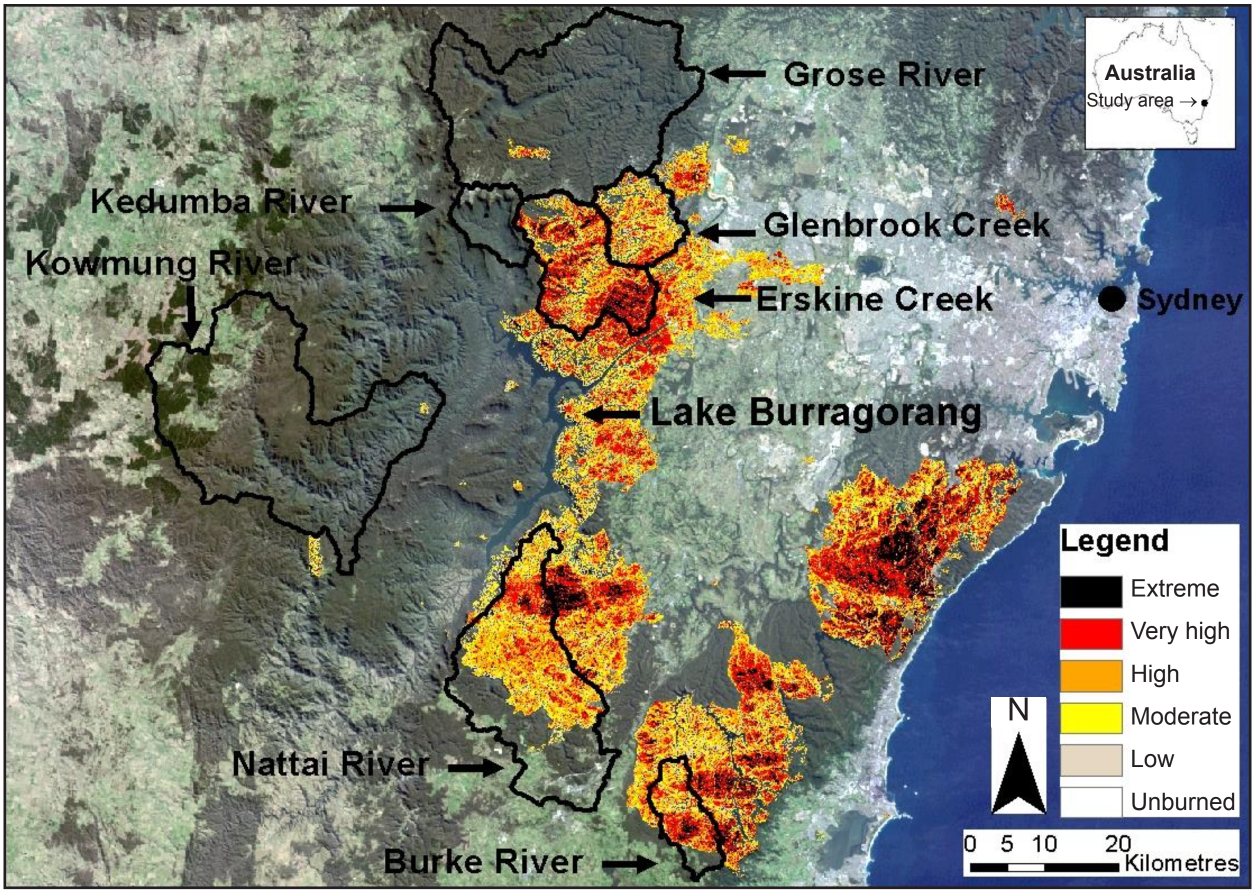

Figure 1. Location, area burned, and severity of the 2001/02 wildfire for each subcatchment (based on Chafer *et al.* 2004, 2008).

data was analyzed two years before and after the wildfire. Data was standardized against a controlled unburned site. Across both sites, it was found that topo-climatic factors affected the amount of stress that vegetation underwent pre and post wildfire. However, due to the short recovery period analyzed after the wildfire, no substantial information about medium-term recovery could be assessed in these studies.

Therefore, this study improves on the previous works conducted in Australia by assessing the response of vegetation over a longer period post wildfire. The aims of this study are to evaluate the inter-annual differences in the spectral properties for the vegetated area, stratified by:

1. subcatchment,
2. burn severity class within each subcatchment,
3. the dominant vegetation communities within each subcatchment, and
4. combinations of burn severity class and vegetation communities.

METHODS

Study Area

The study area was located in the Greater Blue Mountains area of the Hawkesbury-Nepean catchment in southeastern New South Wales, Australia (Figure 1). Four subcatchments extensively burned by the 2001/02 wildfire (Chafer *et al.* 2004) were selected to be examined for the spatial and temporal impact of wildfire, while three unburned subcatchments were used for comparison (Heath *et al.* 2014). The burned subcatchments were the Burke River, Nattai River, Glenbrook Creek, and Erskine Creek. The unburned subcatchments were the Grose River, Kedumba River, and Kowmung River (Figure 1).

Using the native vegetation maps of Gellie (2005) and Tozer *et al.* (2010), three sclerophyll-based communities, a rainforest community, a heathland community, and wetland communities were identified in the study area (Figure 2). Vegetation was structurally similar across all sites, with dry sclerophyll forests and shrubby woodlands being dominant on ridges and plateaus (Tozer *et al.* 2010). Moist sclerophyll forest and rainforest communities were present within the valleys (Keith 2004). Smaller communities of heathlands were also present throughout the subcatchments. Vegetation communities were dominated by resprouting *Eucalyptus* spp. in the canopy and a dense shrubby understory dominated by resprouting species with few obligate reseeders. Shrubby vegetation include *Banksia* spp. Carl von Linné, *Acacia* spp. Miller, *Leptospermum* spp. Forster, *Hakea* spp. Schrader, and *Allocasuarina* spp. Johnson. The vegetation communities described herein are by necessity simpli-

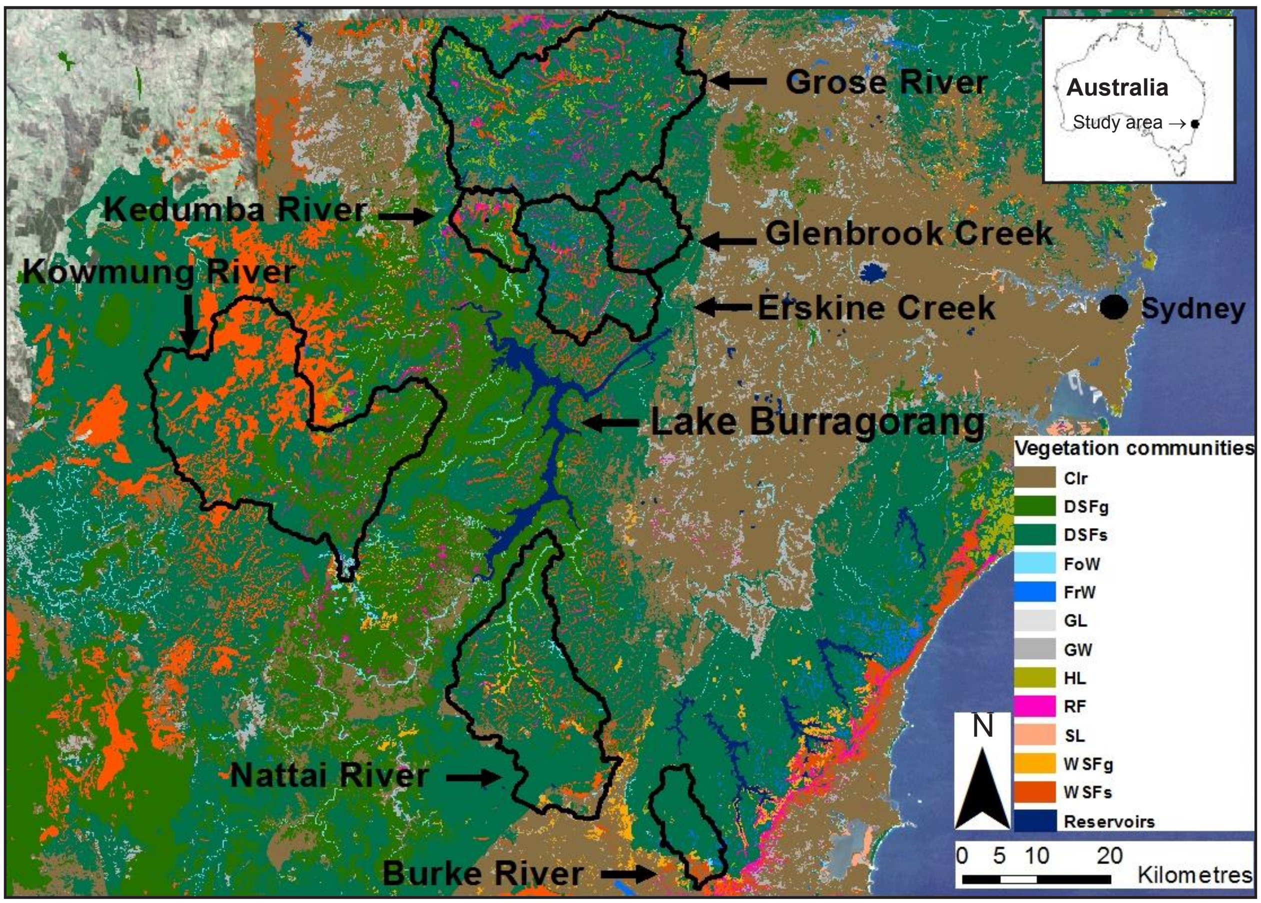

Figure 2. Vegetation communities found in each of the subcatchments (based on Gellie 2005 and Tozer e*t al.* 2010). Abbreviations: Clr = Cleared; DSFg = Dry Sclerophyll Forest—grassy subformation; DSFs = Dry Sclerophyll Forest—shrubby subformation; FoW = Forested Wetlands; FrW = Freshwater Wetlands; GL = Grasslands; GW = Grassy Woodlands; HL = Heathlands; RF = Rainforest; SL = Saline Wetlands; WSFg = Wet Sclerophyll Forests—grassy subformation; WSFs = Wet Sclerophyll Forests—shrubby subformation.

fied as there are more than 2500 plant species found within the study area (Fairley and Moore 1989). Four vegetation communities were chosen for their structure and dominance in the study region and are described below, from driest to wettest (Keith 2004).

Dry sclerophyll forest—shrubby understory (DSFs). DSFs is characterized by open eucalypt forest and woodlands 10 m to 30 m tall, and occurs across 85 % of the Blue Mountains area (Hammill and Tasker 2010). DSFs are generally found on sandstone plateaus, slopes, and ridges at low to mid elevations (Hammill and Tasker 2010).

Dry sclerophyll forest—grassy understory (DSFg). DSFg is characterized by open eucalypt forest and woodlands 10 m to 30 m tall (Hammill and Tasker 2010), with the understory consisting of perennial tussock grasses (Poaceae), sedges, and scattered shrubs that include a mixture of sclerophyllous and non-sclerophyllous plants (Keith 2004). These forests are present on nutrient-deficient soils.

Wet sclerophyll forest—shrubby understory (WSFs). WSFs consists of tall eucalypt species reaching up to 70 m or more, occurring on moderately fertile soils in areas with high rainfall (Keith 2004). WSFs covers just over 6 % of the Blue Mountains area (Hammill and Tasker 2010).

Rainforest (RF). Rainforest is characterized by a closed and continuous canopy composed of relatively soft, horizontally held leaves; are reliably moist; and are mostly free of fire. It has soils of moderate to high fertility (Keith 2004). Rainforest is found to only cover 1 % of the Blue Mountains area. It is found in relatively high rainfall areas situated in valleys and along rivers that are generally protected from fire (Hammill and Tasker 2010).

The study area has a warm temperate climate with maximum temperatures sporadically exceeding 30 °C to 35 °C over the summer months. Summer is generally moister than winter; however, there is no distinct dry season. As a result, the sclerophyllous vegetation has no unique growing season and grows almost continuously all year, although it responds to seasonal rains during September through April. At the time of the 2001/02 wildfire, the study region was declared in drought, strongly associated with the influence of an El Niño Southern Oscillation event (ENSO; Tomkins *et al.* 2008). The post-wildfire period endured back-to-back El Niño events, first in 2002, then in 2006, and last in 2009. The El Niño event of 2002 resulted in a decline in rainfall and an increase in temperature, causing eastern Australia to experience near-record drought conditions (Wang and Hendon 2007). These extreme conditions (Caccamo *et al.* 2011) caused significant increases in sclerophyllous vegetation water stress (Datt 1999).

Wildfire Severity within Each Subcatchment

The published fire severity map of Chafer *et al*. (2004) was used to delineate areas impacted by the 2001/02 wildfire. The six published severity classes established by Chafer *et al.* (2004) were derived from dNDVI using SPOT 2 satellite imagery and field data from 342 stratified sample sites covering a range of vegetation types and severities within area impacted by the 2001/02 wildfire event. It should be noted that NBR and dNBR had not yet been developed when Chafer *et al*. (2004) was published, and that Landsat imagery was costly and not readily available in Australia at that time. Hammill and Bradstock (2006) and Chafer (2008) later demonstrated that, within the present study area, there was little statistical difference in discriminating burn severity classes using dNDVI or dNBR. Furthermore, Bradstock *et al*. (2010) noted that the superior resolution of the SPOT 2 data allowed for a more robust classification than they could achieve in a part of the present study area that they had examined in detail from available Landsat imagery. Further details on the original methods used to derive the burn severity classes, with illustrated examples, can be found in Chafer *et al*. (2004) and Chafer (2008). The six burn severity classes used herein (unburned, low, moderate, high, very high, extreme) were clipped within ArcGIS to the subcatchment boundaries to calculate the area covered by each wildfire severity class (Figure 1, Table 1).

Image Processing

Landsat (30 m^2 pixels) is readily available satellite imagery and has been providing coverage of the Earth's surfaces since 1972. Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) have been extensively used to investigate vegetation change by using various vegetation indices (Vescovo and Gianelle 2008; Lhermitte *et al.* 2011). At the time of this study, both Landsat 5 and Landsat 7 crossed the study area every 16 days. In order to assess the recovery of vegetation following the 2001/02 summer wildfire, one Landsat image for each Australian summer (December to February) between 1990/91 to 2011/12 was selected to reduce the effect of seasonal phenological differences (Fox *et al*. 2008). As noted earlier, sclerophyllous plants (including eucalypts) grow almost continuously from spring through to autumn when conditions are suitable as a result of increased rainfall (Keith 2004). The images were radiometrically corrected to create Top of Atmosphere (ToA) reflectance images using the radiometric calibration coefficients of Chander *et al.* (2009). This correction helps account for anomalous atmospheric factors such as aerosols and haze that may affect the analysis of the satellite image (Hernández-Clemente *et al.* 2009, Vicente-Serrano *et al.* 2011). It also removes the cosine effect of different solar zenith angles due to their time difference between data acquisition, and the ToA reflectance corrects the variation in the Earth-to-Sun distance between different data acquisition dates (Chander *et al*. 2009). Imagery was processed using ERDAS Imagine (ERDAS Inc. 2010).

Processing of Spectral Indices

NDVI is calculated as the difference between the reflectance of the red and near-infrared (NIR) portions of the spectrum (Chen *et al*. 2011; Equation 1, Equation 2):

$$NDVI = \frac{NIR - red}{NIR + red} , \quad (1)$$

and

$$dNDVI = NDVI_{prefire} - NDVI_{postfire} . \quad (2)$$

Table 1. Wildfire behavior according to each wildfire severity class.

Class	Wildfire severity class	Wildfire behavior
1	Unburned	No obvious burned vegetation in any strata
2	Low	Ground layer burned, shrub layer scorched, canopy not burned
3	Moderate	All ground and most shrubby vegetation burned, canopy not burned
4	High	All ground and shrub layer vegetation incinerated, canopy scorched
5	Very high	All vegetation incinerated, except stems <10mm, which survive
6	Extreme	All vegetation and stems <10 mm totally incinerated

The NDVI values range from −1 to 1, with areas occupied by large, healthy, completely closed vegetation canopies having higher positive values closer to 0.8 (Sever *et al.* 2012).

Random Point Selection

Random site selection was conducted using a random point selection tool (ESRI 2011) with a minimum inter-point distance of 50 m so that sampling points did not occur in the same pixel.

For burned subcatchments, 50 random sample points were selected for each of the seven burn severity class (350 sites per subcatchment).

Additionally, a separate 50 random sample points were selected independently of burn severity for each vegetation class (200 sites per subcatchment) to determine the response of vegetation classes; and for unburned subcatchments, 50 random sample points were selected for each vegetation class (200 sites per subcatchment).

NDVI for each point was then extracted for each of the 22 Landsat images from 1990/91 to 2011/12 in order to examine the vegetation response to wildfire.

Spectral Profiles

Using NDVI, spectral profiles were created from all of the sample points within the spatial area based on the following groupings:

1. vegetative area of the entire subcatchment;
2. burn severity class;
3. vegetation communities; and
4. combination of vegetation communities within each burn severity class.

Before any analysis could be conducted, the spectral indices of these sample points were examined in order to exclude any outliers (e.g., points with extremely low NDVI values as a result of cloud coverage, shadow, or man-made structures such as roads). The mean NDVI value for each year was calculated for all vegetation within each subcatchment over the 22-year Landsat period. The mean NDVI was then calculated according to burn severity class within each subcatchment. This distinguished the impact that the wildfire had on the subcatchments as a whole from areas affected by greater burn severities. Vegetation was then incorporated into the analysis (Table 2) by calculating the mean NDVI in the four most dominant vegetation communities across all subcatchments.

NDVI were then calculated for each burn severity class within the dry sclerophyll forest—shrubby understory (DSFs). The DSFs was chosen as it was the most dominant vegetation class found throughout the study region and occurred in each of the subcatchments. DSFs is at greater risk of wildfire due to its occurrence on upper slopes of valleys and plateaus and its enhanced structural flammability (Hammill and Tasker 2010).

Lastly, to analyze the change in NDVI, the differenced Recovery Index (dRI) was computed for each sample point (Equation 3):

$$dRI = -0.02 + \frac{(NDVI_{post\,n} - meanNDVI_{pre})}{(meanNDVI_{pre} + NDVI_{post\,n})}, \quad (3)$$

where −0.02 is a constant to account for inter-annual differences, $NDVI_{post\ n}$ is the NDVI post-wildfire value for a particular date, and mean $NDVI_{pre}$ is the mean NDVI of the entire pre-wildfire period (1990/91 to 2000/01).

The −0.02 had been added to the formulae primarily due to the recalibration of radiometric calibration coefficients used to convert the raw Landsat digital number (DN) data to reflectance data during the computation of the top of atmosphere models (Chander *et al*. 2007, 2009; Finn *et al*. 2012). The changes in radiometric calibration led to a small change in the reflectance values of the two bands used in the computation of NDVI, with the differ-

Table 2. Vegetation community, total area, total area burned, and area burned for each burn severity class against the four dominant vegetation communities, in each of the burned subcatchments (Burke River, Erskine Creek, Glenbrook Creek, and Nattai River).

Sub-catchment	Vegetation community	±95% pre-NDVI values	Total area (ha)	Total area burned (%)	Area burned ha (%)					
					Extreme	Very high	High	Moderate	Low	Unburned
Burke	DSFg	0.65								
	DSFs	0.62	7256	91	611 (8)	2058 (28)	2129 (29)	1240 (17)	561 (8)	657 (9)
	WSFs	0.66	506	1	0 (0)	0 (0)	0.3 (0.1)	1 (0.2)	2 (0.4)	502 (99)
	RF	0.69	33	2	0 (0)	0 (0)	0 (0)	0.3 (1)	0.4 (1)	32 (98)
Erskine	DSFg									
	DSFs	0.62	17076	89	2715 (16)	5804 (34)	3992 (23)	1916 (11)	785 (5)	186 (11)
	WSFs	0.67	2398	78	112 (5)	576 (24)	536 (22)	395 (16)	249 (10)	529 (22)
	RF	0.68	1015	60	23 (2)	173 (17)	172 (17)	144 (14)	96 (9)	407 (40)
Glenbrook	DSFg									
	DSFs	0.60	8957	83	189 (2)	1505 (17)	2650 (30)	2011 (22)	1073 (12)	1528 (17)
	WSFs	0.63	828	54	0.9 (0.1)	47 (6)	135 (16)	140 (16)	123 (15)	383 (46)
	RF	0.63	576	48	2 (0.3)	37 (6)	87 (15)	88 (15)	62 (11)	300 (52)
Nattai	DSFg	0.59	6282	84	81 (1)	1122 (18)	2254 (36)	1319 (21)	4848)	1022 (16)
	DSFs	0.59	24202	59	763 (3)	2843 (12)	5634 (23)	3764 (16)	1176(5)	10022 (41)
	WSFs	0.62	3414	58	65 (2)	266 (8)	709(21)	671 (20)	264 (8)	1439 (42)
	RF	0.65	277	45	4 (2)	18 (6)	30 (11)	44 (16)	28 (10)	153 (55)

ence being about 0.02 higher than if the pre-2001 coefficients were used. So the constant is an estimated correction factor that maintains post-2001 NDVI values and corrects the dRI to retain values around zero when the post-2001 values are not significantly different from the pre-2001 NDVI values.

The dRI was based on the Normalized Regeneration Index proposed by Riano *et al.* (2002). However, instead of adjacent control sites, we compared the post-wildfire pixel values of each sample point to the pre-wildfire 10-year mean of the same pixel throughout the fireground (total area burned minus the internal areas that are not burned) for each sample point. It can be assumed that the pre-fire NDVI values represent mature steady-state communities that have not been severely impacted by wildfire for at least 11 yr prior to the 2001/02 wildfire event. Values of dRI can hypothetically range from −1 to 0 ±95% CI of the pre-wildfire 10-year NDVI mean. Sites that have been severely impacted by wildfire will have a large negative value at the first post-wildfire capture date (i.e., March 2002). This value should theoretically increase to values approximating zero when the vegetation community has returned to near-pre-fire cover, biomass, and structural diversity. To further illustrate the usefulness of dRI in monitoring recovery of the fireground, we illustrated the recovery process for the six severity classes of Chafer *et al.* (2004) and Chafer (2008), as mentioned earlier, in each of the burned subcatchments. We also compared the dRI of the burned catchments to show that, in unburned environments, the index remains stable around zero. The 5^{th} and 95^{th} percentiles were used in the plots to illustrate precision in the estimate of the mean dRI data for each time point in the recovery period for a catchment, severity, and community, and combinations of each. We suggest that a catchment, burn severity class, or vegetation community can be considered to have returned to pre-fire condition once it is within the 5^{th} and 95^{th} percentile, with a dRI of about 0.

RESULTS

Total Vegetation Area

The entire vegetated area within each of the seven subcatchments was analyzed to examine the change in NDVI across the study period. In all seven subcatchments, NDVI values were comparatively stable for the 11 pre-wildfire years (Figure 3). However, as expected, all four burned subcatchments demonstrated a significant decline in NDVI around 2001/02 when the wildfire event occurred (Figure 3), as previously mapped by Chafer *et al.* (2004). NDVI trends indicate that there was a relatively rapid recovery in burned subcatchments despite two drought events that occurred in 2002 and in 2006/07 (refer to Appendix 1 and 2). All burned subcatchments returned to pre-wildfire conditions by the summer of 2006/07 (Figure 3).

The dRI is used to display vegetation recovery post wildfire (Figure 4). All four burned subcatchments had negative values in the post-wildfire period, returning to approximately zero between 2005 and 2006 (Figure 5). The unburned subcatchments, in comparison, had dRI values consistently fluctuating around 0 and generally within the 5^{th} and 95^{th} percentile of the pre-wildfire mean NDVI value, and had minimal variation through time (Figure 5).

Burn Severity Class

The next component of the analysis examined the effect of burn severity on the vegetation within each of the burned subcatchments. The spatial distribution of burn severity in each of the burned catchments was considerably heterogeneous (Figure 1), and this had a significant effect on the catchments' overall recovery to pre-wildfire levels (Figure 4). Furthermore, an overall decrease in the dRI occurred as burn severity class increased from unburned to extreme (Figure 6). There was large variation between the unburned and extreme burn severity classes immediately post wildfire, as evidenced by the non-overlapping 95% confidence intervals (Figure 6). However, all burn severity classes in the burned subcatchments recovered rapidly to pre-wildfire conditions within six years (Figure 6). Lower burn severity classes (negligible, low, and moderate) recovered to pre-wildfire NDVI conditions within two years post wildfire. Higher burn severities (high, very high, and extreme) have little spectral difference between the pre- and post-wildfire data by six years post fire (2006/07) in all four subcatchments.

Vegetation Communities

The impact of wildfire on individual vegetation communities was examined by focusing on the four dominant communities found across the seven subcatchments. The drier the vegetation community, the lower the dRI value immediately post fire, with DSFs communities having the lowest dRI values post fire (Figure 7). Drier vegetation communities also had a larger proportion of areas burned, while wetter communities had a larger proportion of unburned areas (Table 2).

Interaction of Burn Severity Class and Vegetation Community

The final component of the research analyzed the impact of different levels of wildfire on vegetation community (Table 2). Drier vegetation communities were affected more significantly by the wildfire—not only did they have larger proportions of area burned, but

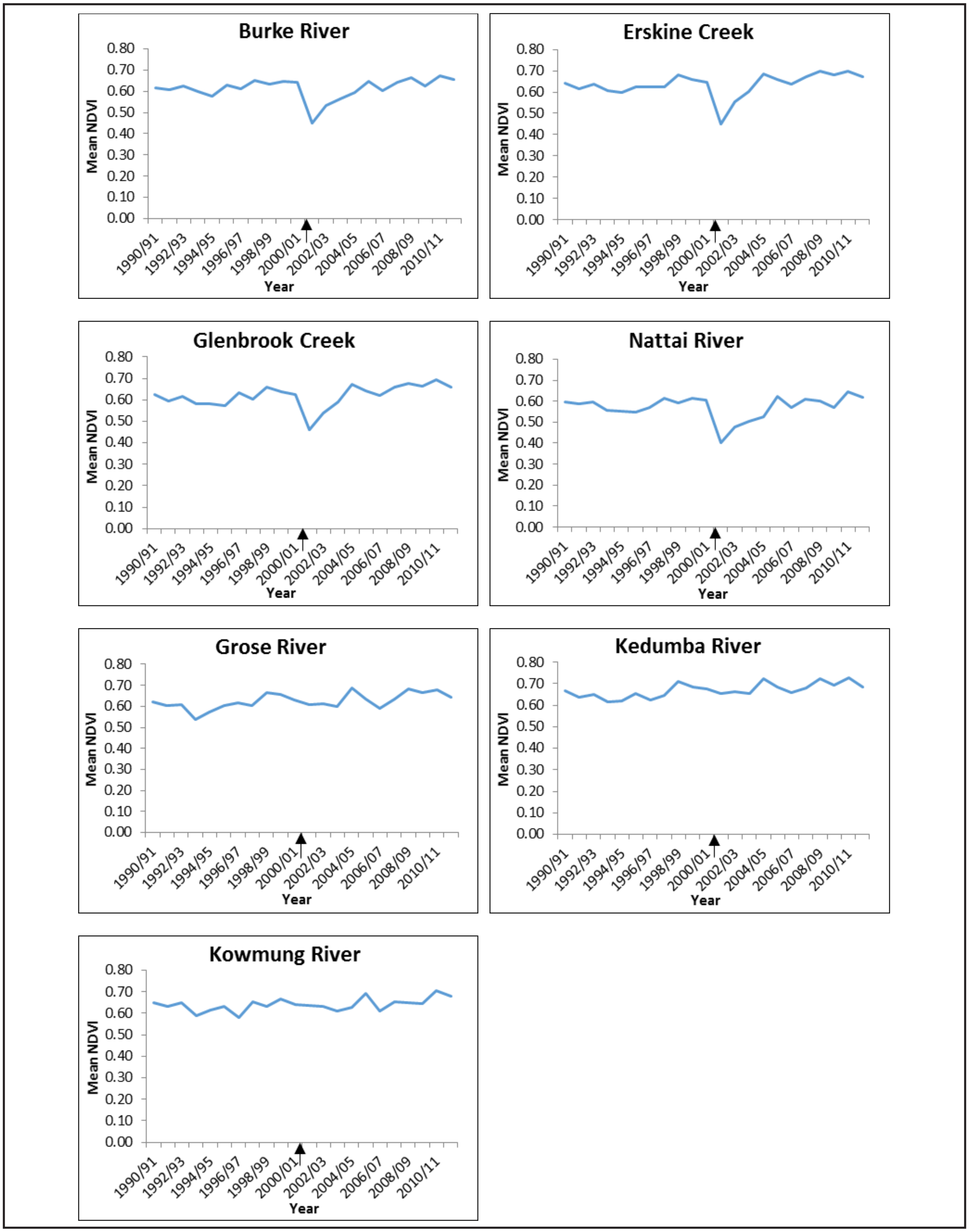

Figure 3. The inter-annual mean NDVI for the total vegetation area in each burned subcatchment (Burke River, Erskine Creek, Glenbrook Creek, and Nattai River) and unburned subcatchment (Grose River, Kedumba River, and Kowmung River). Black arrows indicate the 2001/02 wildfire.

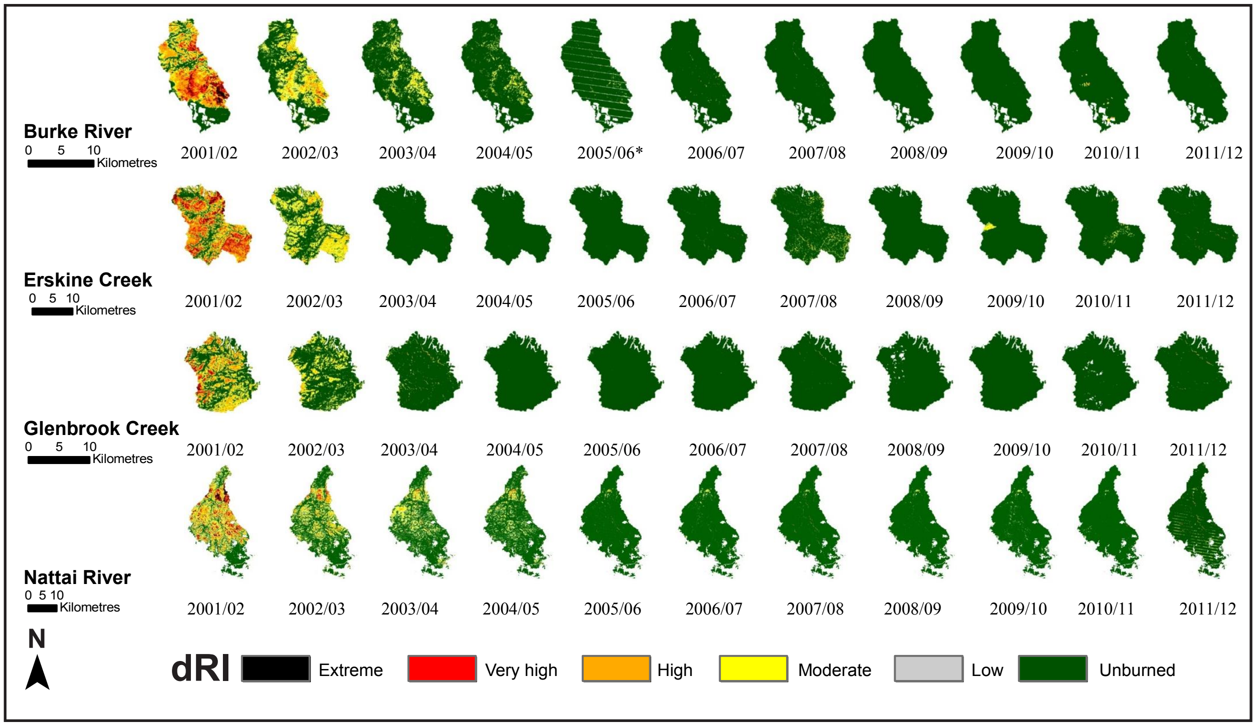

Figure 4. Spatial distribution of vegetation recovery from the 2001/02 wildfire using dRI values for each year post wildfire for Burke River, Erskine Creek, Glenbrook Creek, and Nattai River subcatchments. The rapid change in colors from red to orange to yellow to green indicates quick vegetation recovery. *Landsat 7 missing data gaps due to Scan Line Corrector (SLC) fail post May 2003.

they also had larger proportions of areas in higher burn severity classes. For instance, areas affected by extreme burn severity occurred mainly in DSFs vegetation while, in some instances, no RF or WSFs was affected by extreme burn. This is demonstrated in the Burke River subcatchment, where 611 ha (8%) of DSFs was extremely burned, while RF and WSFs had 0 ha (0%) of area extremely burned (Table 2).

DISCUSSION

Spatial Response of Vegetation Growth across a Landscape

Areas affected by the 2001/02 wildfire event had a noticeable decline in vegetation cover, as indicated by NDVI values (Figure 3). The degree of impact varied spatially across the landscape for the burned subcatchments as higher intensity fire occurred on upper gully slopes, plateaus, and along ridge lines where drier vegetation with higher fuel loads occurred (i.e., DSF; Figure 2; Chafer *et al*. 2004, Hammill and Bradstock 2006). This is noticeable in both the Erskine Creek and Nattai River subcatchments as unburned and low severity areas generally followed riparian corridors and burned areas covered most of the remaining landscape.

The response of the vegetation regrowth within the burned subcatchments was rapid as the region is dominated by resprouting species. Resprouting species favor areas of disturbances (Russell-Smith *et al.* 2010) and maximize fitness by allocating more resources to root reserves and structures that will increase their chances of surviving the next fire (Bond and Van Wilgen 1996). Knox and Morrison (2005) also demonstrated the quick response of resprouting sclerophyll vegetation,

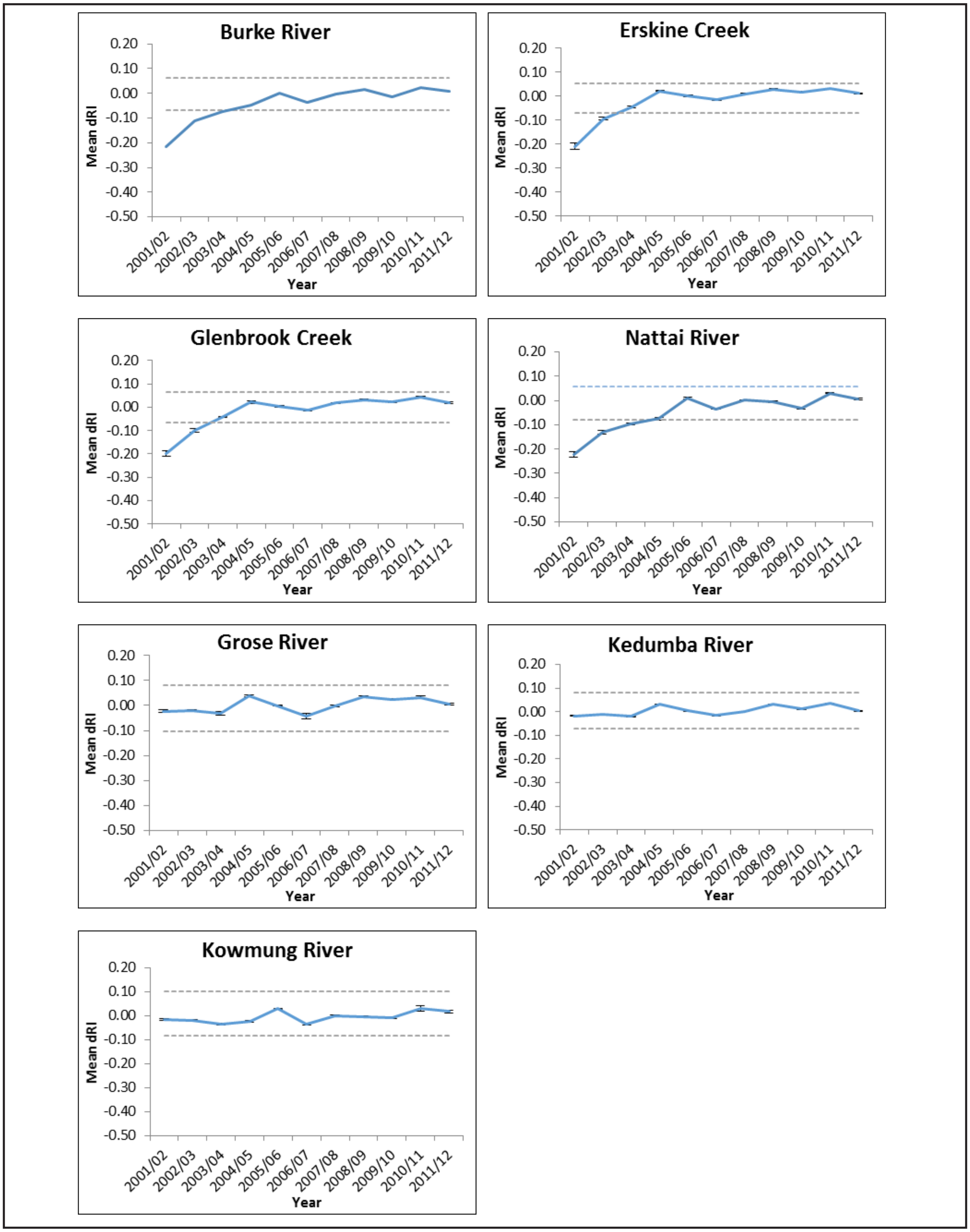

Figure 5. The inter-annual mean dRI for all sclerophyll vegetation in each burned subcatchment (Burke River, Erskine Creek, Glenbrook Creek, and Nattai River) and unburned subcatchment (Grose River, Kedumba River, and Kowmung River). The dashed horizontal bands represent pre-fire 95th and 5th percentiles.

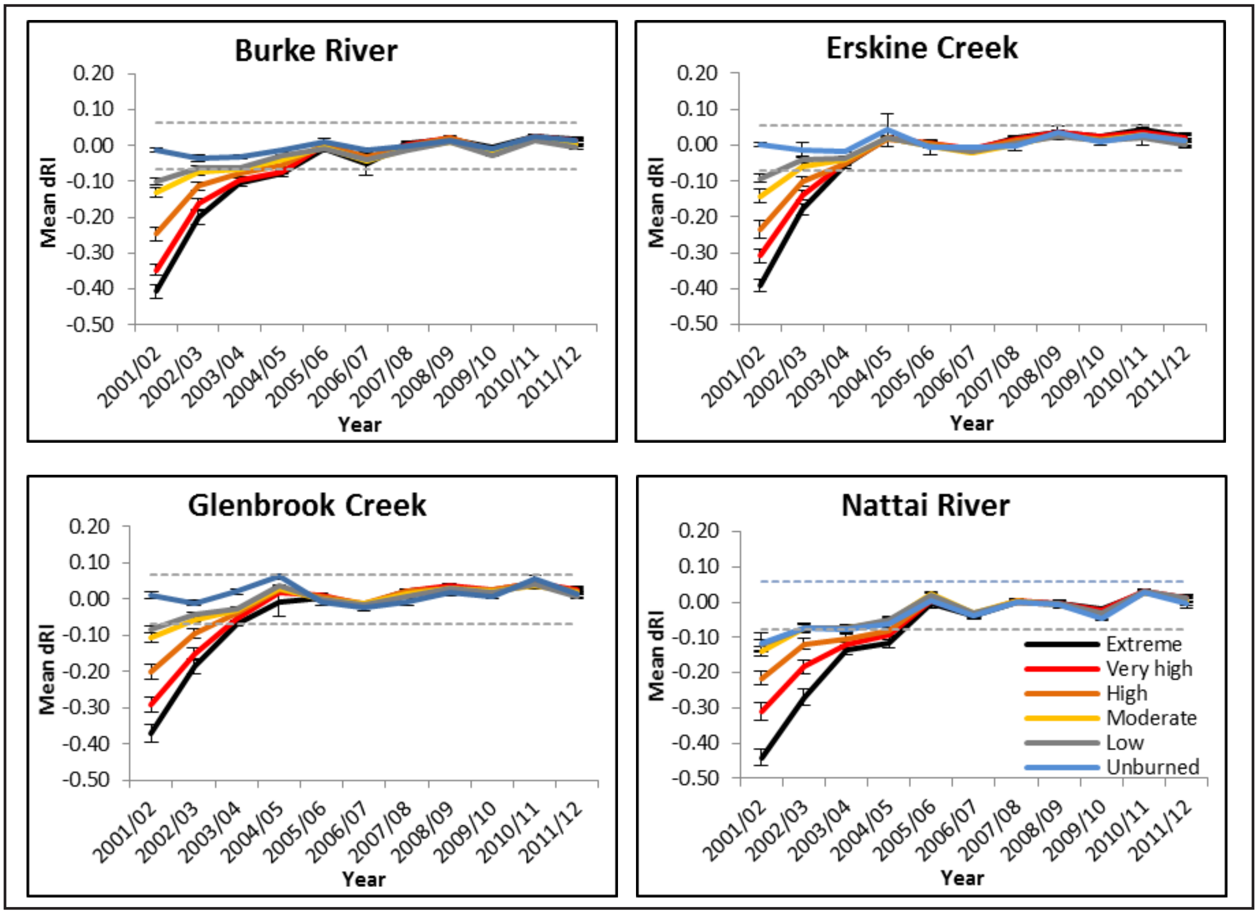

Figure 6. The inter-annual mean dRI comparison of each burn severity class for the four burned catchments. The dashed horizontal bands (pre-fire 95th and 5th percentiles) illustrate relatively rapid recovery of burned subcatchments to within the pre-fire parameters after the 2001/02 wildfire. The 95% confidence intervals around each point in time account for the variability in data.

finding that shrubs resprouting from lignotubers had greater reproductive output at sites with longer rather than shorter inter-fire intervals. Resprouting species do not lose all of their aboveground biomass and the canopy is not always 100% scorched (Morrison and Renwick 2000). In comparison, obligate seeders are often killed by wildfire and require a fire-free period after germination and adequate post-fire rainfall to ensure seedling growth and development (Lamont and Markey 1995), which slows down the overall vegetation response process.

Although post-fire drought events occurred as illustrated by the strong negative values of Southern Oscillation Index (SOI) and Standardized Precipitation Index (SPI) (Appendix 2; see also Caccamo *et al.* 2011), the initial recovery response (production of epicormic growth) was quick (Figure 8). The severity of drought shows considerable variation within the study region during 2001/02, 2002/03, and 2006/07 (Caccamo *et al.* 2011). The period in between 2003 and 2005 experienced vigorous regrowth. The regrowth was in response to above average rainfall that occurred in eastern Australia (Reid 2003) and, in particular, the study region (Appendix 2), is evident in the NDVI and dRI graphs as the mean values recover towards pre-wildfire conditions (Figures 3 and 4). Bradstock (2008) undertook an assessment of wildfire response

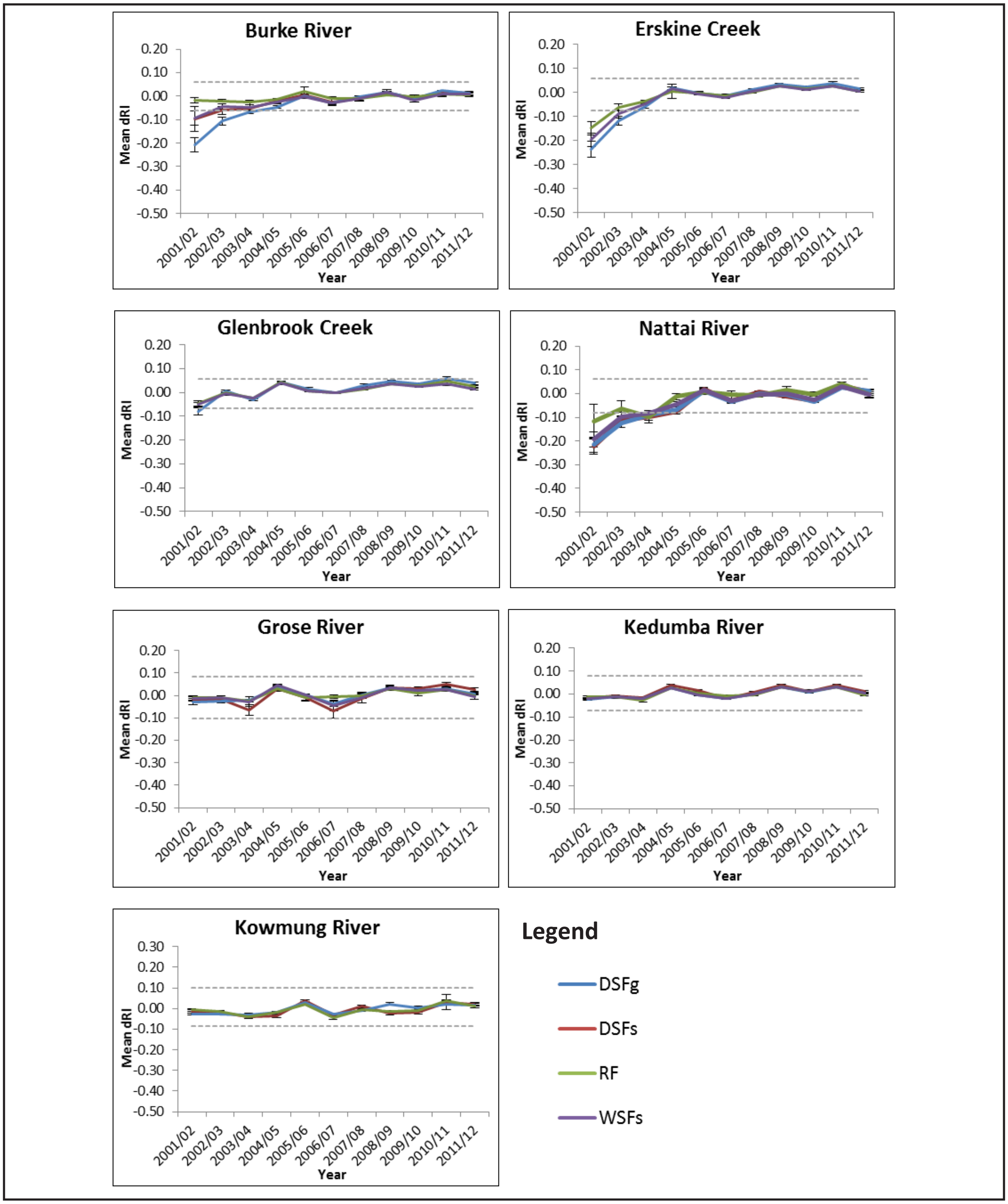

Figure 7. The inter-annual mean dRI for the four vegetation classes used (DSFg [driest], DSFs, WSFs, and RF [wettest]) for each burned subcatchment (Burke River, Erskine Creek, Glenbrook Creek, and Nattai River) and unburned subcatchment (Grose River, Kedumba River, and Kowmung River). The dashed horizontal bands (pre-fire 95th and 5th percentiles) illustrate the stability of the index through time in the unburned subcatchments and the relatively rapid recovery of burned subcatchments to within the pre-fire parameters after the 2001/02 wildfire. The 95 % confidence intervals around each point in time account for the variability in data.

Figure 8. Vegetation recovery from very high fire severity in dry sclerophyll forest (DSFs) from a sample site in Erskine Creek subcatchment displaying a quick response of epicormic resprouting. From top to bottom: four months after the fire (top), 4 years post wildfire (middle), 6 years post wildfire (bottom).

traits on species in southern Australia and found that resprouter species respond very quickly to increased rainfall.

Vegetation recovery was slowed by another drought event occurring in 2006/07 (Caccamo *et al.* 2011). El Niño reached its maturity during spring 2006, causing widespread drought conditions across eastern Australia (Qi 2007). This is visually demonstrated in the dRI maps for Erskine Creek and Glenbrook Creek subcatchments as stress caused a decline in vegetation coverage (Figure 4). These two subcatchments showed this response because severe drought conditions were present in the northern-central areas of the Sydney region, while southern areas showed less severe drought according to the SPI values generated by Caccamo *et al.* (2011). Topo-climatic factors would have had an impact on the vegetation response, potentially influencing the amount of vegetation coverage in each subcatchment (Sever *et al.* 2012). Despite the severity of drought, all subcatchments appeared to have spectrally reached pre-wildfire conditions by 2007.

Burn Severity Influence on Post-Wildfire Recovery Rates

The fire behavior of the 2001/02 wildfire event was more severe on ridges and steeper slopes; crown fire affected 30% of ridges and <15-degree slopes where drier vegetation communities are located (Figure 2). Gullies, which consist of wetter vegetation communities, had a greater proportion of low-intensity and patchy understory fire (~0.20; see Chafer *et al.* 2004, Hammill and Bradstock 2006, and Bradstock *et al.* 2010 for detailed discussion on the role of topography in fire severity in the study area). This behavior is also evident in the dRI maps, demonstrating that the largest differences in pre- and post-wildfire vegetation coverage occurred on the ridges, while lower severity areas occurred along the riparian corridors (i.e., rainforest: Figure 4). The southern subcatchments (Burke River and Nattai River) and Erskine Creek subcatchment had a larger area affected by more severe wildfire. These areas are dominated by open forest and woodland with a dense shrubby understory up to five meters high and were subjected to crown fire (Hammill and Bradstock 2006).

All burned subcatchments experienced some level of very high to extreme burn severity. The dRI values ranges between −0.35 to −0.45 for all locations affected by extreme burn severity. However, all areas responded rapidly post wildfire, returning to pre-fire dRI values within five years post wildfire (Figure 5). The dRI values in the northern subcatchments (Erskine Creek and Glenbrook Creek) returned to pre-wildfire conditions by 2005 for all burn severity classes. These subcatchments are located in the lower Blue Mountains and therefore generally receive higher rainfall and cooler temperatures. The southern catchments (Burke River and Nattai River), in comparison, had a slightly slower response, although they still recovered towards pre-wildfire conditions by 2006/07. The slight delay in recovery could be a result of the slightly drier landscape and lower annual rainfall, but resprouting subcatchments have a very quick response to wildfire (Clarke *et al.* 2009, Bradstock *et al.* 2012). In comparison, studies in Victoria, Australia, show that the obligate seeder *Eucalyptus regnans* F.Muell. is in strong competition with other vegetation for at least the first five years of growth (Langford 1976). In effect, it can take these species 75 yr to 150 yr to reach maturity and, hence, recovery towards pre-wildfire conditions is much longer than these seen in resprouter communities (McCarthy *et al.* 1999).

As discussed by Gill (2012) and Enright *et al.* (2012), there are few medium to long-term studies with unequivocal data on recovery time of vegetation communities within Australia. Within the study area, Jacobson (2010) showed that after only 12 months post fire in a DSFs study site, ground vegetation had recovered to 73% pre-fire means, shrubby vegetation had revered to 50% pre-fire cover, and canopy had returned to 35% pre-fire cover. These results are consistent with the generally reported recovery period of 5 yr to 7 yr in the dry sclerophyll forests, woodlands, and heathlands in the Sydney Basin (van Loon 1977, Conroy 1993, Penman and York 2010). More recently, Caccamo *et al.* (2015) have also demonstrated a rapid 5 yr to 7 yr recovery of dry sclerophyll forests in the Sydney Basin using MODIS imagery.

In this study, we have shown that, by using existing vegetation mapping and satellite imagery interpretation, it is feasible to reconstruct vegetation patterns and recovery regimes across large areas of forested landscape at a relatively fine spatial scale. The results from this study, coupled with the broader-scale findings of Caccamo *et al.* (2015), clearly demonstrate that, within the greater Sydney Basin, sclerophyllous vegetation communities dominated by resprouter species recover rapidly (5 yr to 7 yr) to pre-fire biomass conditions.

Variability in Vegetation Community Response

Wildfire opens up the canopy and many species of eucalypts are able to resprout quickly after wildfire from the living tissues beneath the soil (lignotuber) or within trunk and branches (epicormic buds) (Keith 2004). This quick response is clearly demonstrated within the dRI graphs (Figure 7). The DSF communities (both dry sclerophyll forest grassy understory, DSFg, and dry sclerophyll forest shrubby understory, DSFs) are the most dominant vegetation communities within the subcatchments (Figure 2). In the burned subcatchments, the DSFs experienced the greatest amount of extreme and very high burn severity, which was influenced by their topographic position in the landscape and the presence of a shrubby understory as opposed to a grassy one (Chafer *et al.* 2004, Hammill and Bradstock 2006). The study region is dominated by DSF, which are generally present on plateaus, ridge lines, and rugged terrain (Keith 2004). With a highly flammable structure, rapid accumulation of ground fuels, and exposure to harsh environmental conditions, they are very prone to extreme wildfire conditions (Hammill and Tasker 2010). Even with these high degrees of burn severity, the DSFs recovered within five years post wildfire, demonstrating the quick response of the Sydney resprouting vegetation communities to a wildfire event.

Wet sclerophyll forests (WSFs) were not as impacted by the 2001/02 wildfire due to their location in moist areas, resulting in smaller areas being affected by extreme burn severity (Table 2). There was an initial drop in dRI immediately post wildfire (Figure 7) and, although WSFs are highly combustible, most communities have the ability to develop lignotubers under the soil (Keith 2004), allowing for a quick response of the wet sclerophyll forest post wildfire. Rainforests (RF), in comparison, experienced minimal impact by the wildfire due to their location in the gullies along riparian zones. Similar results were established by Knox and Clarke (2012), who examined vegetation flammability in eastern Australia and found that 53% of the rainforest remained unburned in their study area. In this study, rainforest communities experienced low burn severity and were similar to unburned subcatchment within approximately three years (Figure 7).

Detecting Vegetation Response with NDVI and dRI

The inter-annual response of four vegetation communities was compared following the recovery from a severe wildfire in 2001/02 against an 11-year pre-fire time series of summer Landsat images. It was found that NDVI and dRI are very useful spectral indices for studying the response of vegetation post wildfire at the landscape scale. These indices can be incorporated into future catchment management strategies due to their sensitivity to spectral changes across the landscape. Recovery response of the vegetation within the study area was relatively quick and varied spatially in response to the level of burn severity that impacted a given area. Nevertheless, all burned subcatchments recovered towards pre-wildfire conditions by 2006/07 (five years post wildfire).

Gitas *et al*. (2012) provide a comprehensive review of using remotely sensed data and spectral indices in monitoring post-fire vegetation communities, predominantly in the northern hemisphere. Within that review, it is clear that NDVI is the dominant and preferred vegetation index used by many researchers. Previous studies have incorporated other vegetation indices in order to establish the severity of wildfire on vegetation of both resprouting and seeding mechanisms. The Normalized Burn Ratio (NBR) is often used to determine post-wildfire burn severity, but has only been used for a few studies to determine annual vegetation regrowth (van Leeuwen *et al.* 2010). The Enhanced Vegetation Index (EVI) has also been used in a small number of studies such as one conducted by Wittenberg *et al.* (2007) in the Mediterranean landscape of Mt. Carmel, Israel. Like the findings in our study, the results from the EVI values showed a quick response to pre-fire states of vegetation cover. However, EVI takes into account the canopy background and effects of aerosol resistance, making this index overly sensitive to vegetation at high biomass levels due to its sensitivity to canopy structure (Matsushita *et al*. 2007). The Normalized Differenced Vegetation Index (NDVI) has been more commonly used to determine post-wildfire vegetation response (see Gitas *et al.* 2012 for a review). For instance, Díaz-Delgado *et al*. (2003) studied the 1994 wildfire in the province of Barcelona, Spain, using NDVI. Similar to our study, they found that there was an immediate response by shrubland and oak tree woodland due to their resprouting capabilities. Aleppo pine forests, in comparison, were found to have a slow recovery due to the limited availability of a seedbank. Bastos *et al*. (2011) reviewed post-fire vegetation recovery throughout Portugal using NDVI. They found recovery patterns in resprouter communities similar to that found in the present study. Within the Sydney Basin, Caccamo *et al*. (2015) used the much coarser resolution MODIS imagery to analyze post-fire vegetation recovery. Their study partially overlaps the area reported in the present study. Like the results reported herein, recovery of vegetation ranged from four to seven years; however, no attempt was made to discriminate between vegetation communities.

Vegetation spectral indices are important in assessing the spatially heterogeneous impact of wildfire on vegetation at the landscape scale in rugged terrain that makes physical access very difficult. Resprouter communities within the Sydney region have a comparatively rapid response and recovery rate to wildfire (5 yr to 8 yr). The techniques used here can also aid in the understanding of the hydrological impact of wildfire on forested water supply catchments, especially in relation to water yield deficit (Heath *et al.* 2014) and post-fire erosion events (Tomkins *et al*. 2008, Shakesby *et al.* 2007), which is crucial for improving the management of water quantity and quality within these catchments.

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Appendix 1. Climatic variables. Drought classification of Standardized Precipitation Index (SPI) values (source: Lloyd-Hughes and Saunders 2002).

SPI value	Category
2.00 or greater	Extremely wet
1.50 to 1.99	Severely wet
1.00 to 1.49	Moderately wet
0.00 to 0.99	Mildly wet
0.00 to −0.99	Mild drought
−1.00 to −1.49	Moderate drought
−1.50 to −1.99	Severe drought
−2.00 or less	Extreme drought

Appendix 2. a) The monthly Southern Oscillation Index (SOI; BoM 2015) for the study period. A 12-month periodic Standardized Precipitation Index (SPI) for 1991 to 2012, representing the local climate for b) Burke River and Nattai River subcatchments based on data from a rainfall station located in Mittagong (Southern Highlands), New South Wales (NSW), Australia; and c) the Grose River, Kedumba River, and Kowmung River subcatchments based on data from a rainfall station located in Blackheath (Blue Mountains), NSW, Australia. The black arrows indicate control date for the 2001/02 wildfire.