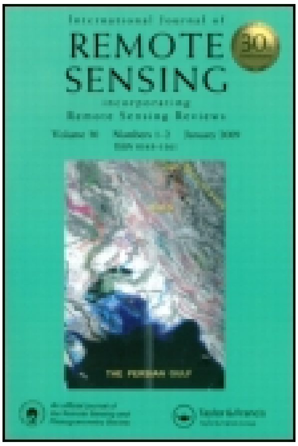

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Characterizing post-fire recovery of fynbos vegetation in the Western Cape Region of South Africa using MODIS data

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Characterizing post-fire recovery of fynbos vegetation in the Western Cape Region of South Africa using MODIS data

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Post-fire recovery trajectories of five fynbos vegetation stands in the Western Cape Region of South Africa were characterized using moderate-resolution imaging spectroradiometer (MODIS) normalized difference vegetation index (NDVI) 250 m data. Indices of NDVI recovery relative to pre-fire values or values from unburnt control plots indicated full recovery within 7 years and particularly rapid recovery in the first two post-fire years. Intra-stand variability of pixel NDVIs generally increased after fires and also exhibited a rapid recovery to pre-fire conditions. While stand age was the dominant determinant of NDVI recovery, drought interrupted the recovery pathways and this effect was amplified on drier, equator-facing slopes. Post-fire recovery characteristics of fynbos NDVI were found to be similar to those documented for chaparral vegetation in California despite contrasting rainfall and soil nutrient conditions in the two regions.

1. Introduction

Mediterranean-climate regions (MCRs) of the world are characterized by cool, wet winters and hot, dry summers and are dominated by sclerophyll shrubland ecosystems (Miller and Hajek 1981). These regions are located in areas of the Mediterranean Basin, Chile, Australia, South Africa and western North America. The long summer droughts produce a well-defined fire season and shrub communities have evolved to be resilient to burning (Keeley 1986, Keeley and Bond 1997). While MCRs comprise only 2% of the world's land area, they have been more heavily impacted by human activities than almost any other ecosystem (Rundel 2004).

Wildland fires in MCR shrubland ecosystems are episodic events that dramatically alter land-cover conditions, initiating a well-defined vegetation recovery sequence (pyric succession). This sequence starts with the landscape being dominated by herbaceous or geophytic plant species which give way over time to an increasing proportion of shrubs, until eventually the shrub cover is complete (Trabaud and Prodon 1993, Viedma *et al*. 1997). Fires play an important role in the maintenance of shrubland community structure and function (Christensen 1985). Although different fire frequencies and intensities can cause the succession process to follow different recovery trajectories and may result in permanent changes to vegetation species composition, post-fire composition in most shrublands closely resembles that of the pre-fire community (Christensen 1985, Viedma *et al*. 1997).

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Monitoring post-fire vegetation recovery is important for land management applications such as the scheduling of prescribed burns, post-fire resource management and soil erosion control (Riaño *et al*. 2002, Malak and Pausas 2006, Chafer 2008, Corona *et al*. 2008). Full recovery of MCR shrublands may take many years and have a prolonged effect on water, energy and carbon fluxes in these ecosystems. Models to predict these fluxes at landscape and regional scales have used post-fire vegetation recovery characteristics derived from satellite data (e.g. McMichael *et al.* 2004, Malak and Pausas 2006, Hope *et al*. 2007). The normalized difference vegetation index (NDVI) has become one of the most widely used tools for assessing vegetation post-fire recovery rates at landscape scales since it is a reasonable proxy for green biomass (Lentile *et al*. 2006, Malak and Pausas 2006).

Post-fire recovery rates of California chaparral ecosystems have been characterized using the NDVI by McMichael *et al.* (2004) and Hope *et al.* (2007). In both studies, time series of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) data were used to derive the NDVI on fire anniversary dates. While McMichael *et al.* (2004) employed a chronosequence approach to derive the relationship between vegetation recovery and post-fire stand age, Hope *et al.* (2007) tracked the recovery of five different chaparral vegetation types after a single large fire. Regardless of the vegetation type or the approach used to relate recovery to stand age, chaparral ecosystems were shown to approach pre-fire conditions 7–10 years after the fire (McMichael *et al.* 2004, Hope *et al*. 2007). Individual vegetation types did not exhibit different rates of recovery and the recovery trajectories were only distinguished by the maximum post-fire NDVI observed after 10 years (Hope *et al*. 2007). Spatial patterns of pixel NDVIs within stands also showed a systematic return to pre-fire conditions in chaparral vegetation stands examined by Hope *et al*. (2007).

Water availability is the primary limit on vegetation growth in arid and semi-arid ecosystems (Zhang *et al*. 2005). Hope *et al*. (2007) found that the recovery of stand average NDVI in chaparral ecosystems slowed during drought periods while the variability in patch-scale (pixel) NDVIs increased. This increase in intra-stand NDVI variability was affected more by drought than the reduced rate of recovery of the stand average NDVIs (Hope *et al*. 2007).

Ecosystems in the five MCRs of the world are widely recognized as classic examples of convergence in ecosystem structure and functioning, attributable to the similarity in climate conditions (Cody and Mooney 1978, Cowling *et al*. 2004). There is a long history of comparative ecological studies in these regions and over the past half century, there has been renewed interest in these comparative studies (Rundel 2004). A goal of MCR ecosystem comparisons has been the expectation of using information regarding ecosystem function that has been derived in one ecosystem to help make predictions in other MCR systems (Keeley 1992).

Keeley (1992) has noted that the fynbos ecosystems in the Cape Floristic Region of South Africa (Western Cape Region) demonstrate a considerable degree of convergence with chaparral ecosystems of California in some aspects of post-fire vegetation regeneration and marked differences in other aspects. Although the initial post-fire flora of fynbos is dominated by geophytes and chaparral is dominated by annuals (Kruger 1983), shrub regeneration in fynbos and chaparral is very similar (Keeley 1992). Seasonal rainfall distribution is different in these two regions with the California MCR experiencing virtually no rain in the summer while the Western Cape MCR receives approximately 25% of the annual rain in this season (Cowling *et al*. 2004). On an inter-annual basis, rainfall is also less variable in the Western Cape than in California (Cowling *et al*. 2004, 2005). Consequently, fynbos ecosystems experience fewer and shorter episodes of water stress than the chaparral ecosystems. The nutrient-deficient nature of fynbos soils has been well documented and, together with the differences in water stress, may account for degrees of non-convergence between the two ecosystems (Keeley 1992). Vegetation patterns in the fynbos region are largely determined by soil nutrient levels rather than the customary moisture availability (Stock *et al*. 1992).

Given the convergence and divergence of chaparral and fynbos ecosystems discussed above and the contrasting environmental conditions in these two MCRs, an obvious question arises as to the similarity or dissimilarity in post-fire recovery pathways of vegetation stands in these two regions. Remote sensing studies have demonstrated a well-defined course of post-fire vegetation recovery in chaparral ecosystems (rapid recovery and sensitivity to variations in rainfall). Consequently, we initiated this study to characterize the post-fire recovery pathways of Western Cape fynbos stands and to determine whether these pathways are similar to those documented for chaparral vegetation in California.

2. Objectives

The goal of the study was to use moderate-resolution imaging spectroradiometer (MODIS) NDVI products to characterize the initial (first 7 years) post-fire recovery patterns of different fynbos vegetation stands in the Cape Floristic Region. More specifically, these recovery patterns were analysed in terms of (1) the rate of recovery of stand average NDVI, (2) the changes in intra-stand NDVI variability with post-fire stand age and relative to pre-fire variability and (3) sensitivity of recovery pathways to variations in moisture availability (rainfall). As mentioned above, the study also aimed to evaluate the extent to which these recovery characteristics were similar/dissimilar to those reported for California chaparral ecosystems.

MODIS data from the Terra and Aqua satellites have been collected since 2000 and 2002, respectively, and the record length is now adequate to examine the initial post-fire recovery phase (7–10 years) of vegetation in MCRs. MODIS-composited NDVI products are available at 16-day intervals and are similar to those that have been produced from advanced very high resolution radiometer (AVHRR) data. However, the availability of 250 m ground resolution MODIS NDVI compared to the 1 km^2 ground resolution of AVHRR products allows for a more precise location of fire boundaries in the MODIS images and an examination of spatial variability in NDVI values at a finer spatial resolution. Consequently, this study also provided an opportunity to evaluate the MODIS NDVI product for vegetation recovery studies in MCRs and other regions of the world.

3. Methodology

3.1 *Study sites*

Selection of fires for this study was restricted to events that occurred in the second and third years of the MODIS era. This was necessary to permit the analysis of at least 7 years of post-fire recovery and 1 or 2 years of pre-fire data to establish the pre-fire NDVI values. To avoid the effects of repeated fires on the vegetation recovery pathways, only fires that occurred in stands that were unburnt in the preceding 20 years were considered for the investigation. A digital fire history map (Western

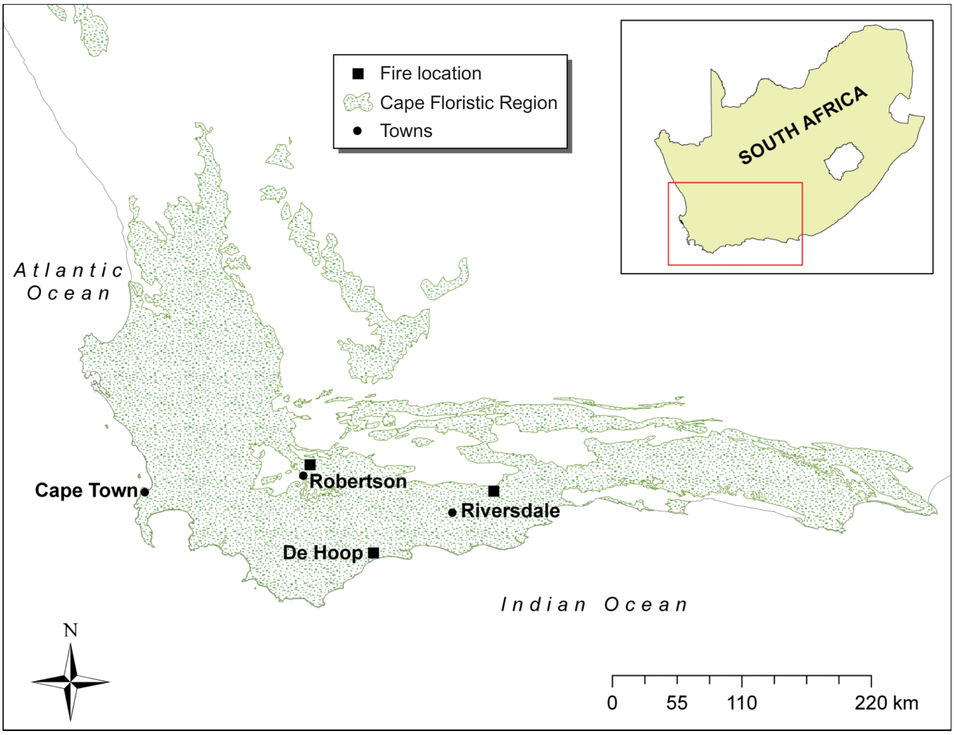


Figure 1. Location of the three fires in the Cape Floristic Region, South Africa.

Cape Nature Conservation Board, Scientific Services Division) was used to identify fires that satisfied these selection criteria. Fires in three locations representing different vegetation and environmental conditions were selected for the investigation (figure 1). The location of different vegetation types within these burnt areas were obtained by intersecting a digital vegetation map (Mucina and Rutherford 2006) with the fire history map. Characteristics of the three study locations and the fires are summarized in table 1.

Suitable fires for this study occurred early in 2002 and were located in the De Hoop Nature Reserve and near the towns of Riversdale and Robertson (figure 1). Four types of fynbos vegetation were impacted by these fires and their characteristics and associated environmental conditions are summarized in table 2.

3.2 *MODIS data preprocessing*

The 250 m MODIS 16-day composited NDVI data (MOD13Q1) were used for this study (https://lpdaac.usgs.gov/lpdaac/get_data/data_pool). While the compositing process is intended to establish NDVI values free of cloud cover effects, anomalous values occur in the data which are attributed to residual cloud cover effects, sensor errors and variations in atmospheric conditions (Viovy *et al*. 1992). The quality flags provided with the MODIS data did not identify all erroneous pixel values which necessitated a preprocessing step to remove large anomalous NDVI values. The best index slope extraction (BISE) algorithm (Viovy *et al*. 1992) is well suited for the removal of residual noise from NDVI time series data (Vancutsem *et al*. 2007). This algorithm

Table 1. Characteristics of the burnt fynbos stands at De Hoop, Riversdale and Robertson.

		Location					
Fire name	Fire date	Latitude	Longitude	Vegetation unit	Area (km^2)	Elevation (m)	MAR (mm)
De Hoop	March 2002	34° 26′ S	20° 31′ E	De Hoop Limestone fynbos	29.57	50–175	468.8
		34° 27′ S	20° 33′ E	Overberg Dune strandveld	3.29	50–80	
Riversdale	March 2002	33° 56′ S	21° 36′ E	North Langeberg Sandstone fynbos	5.58	200–500	453.4
		33° 57′ S	21° 36′ E	South Langeberg Sandstone fynbos	18.18	150–700	
Robertson	January 2002	33° 44′ S	19° 56′ E	South Langeberg Sandstone fynbos	5.09	350–1200	492.5

Note: MAR, mean annual rainfall.

Table 2. Characteristics of the four fynbos vegetation types.

	De Hoop Limestone fynbos	Overberg Dune strandveld	North Langeberg Sandstone fynbos	South Langeberg Sandstone fynbos
Mean annual precipitation (mm)	250–530	400–600	250–1200	320–1440
Soils	Decomposed limestone and sandstone	Calcareous sands, decomposed limestone and sandstone	Decomposed sandstone	Decomposed sandstone
Landscape features	Inland range of hills with plains on the seaward foreland	Flat or slightly undulating dune fields	Gentle to steep north-facing slopes	Gentle to very steep south-facing slopes
Vegetation characteristics	Asteraceous and proteoid fynbos	Evergreen, hard-leaved shrublands in moist dunes and wind-protected valleys (up to 4 m tall)	Proteoid and restoid fynbos with ericaceous fynbos at higher altitudes	Ericaceous and restoid fynbos at higher altitudes
	Restoid fynbos in sandy areas	Coastal thickets in wind-shorn and exposed littoral areas (up to 1 m tall)	Asteraceous fynbos on lower slopes	Moderately tall to tall proteoid fynbos on mid/lower slopes
	Karstic sinkholes and dry valleys in some areas			Scrub/restoid fynbos in habitats with much groundwater

Source: Mucina and Rutherford (2006).

removes and interpolates across sudden drops in NDVI time series. The algorithm searches forward and excludes points when the NDVI of subsequent points in a window exceed a specified threshold. We tested a range of NDVI thresholds and window sizes to establish a combination that removed obvious NDVI anomalies but did not result in excessive smoothing of the data. A change threshold of 0.15 NDVI and moving window of one composite period was found to be suitable for our study. This NDVI threshold was consistent with a value suggested by Vancutsem *et al.* (2007) and also used by Knight *et al.* (2006) in a similar filtering approach to remove gross errors in MODIS 250 m data while retaining seasonal and local variations in the NDVI.

3.3 *Characterizing post-fire recovery*

To ascertain how long it takes burnt vegetation stands to return to their pre-fire average NDVI condition, it is necessary to relate the post-fire NDVIs to pre-fire values or values from a control plot. We define the stand regeneration index (SRI) at time t after the fire as

$$\mathrm{SRI}_t = \frac{(\mathrm{NDVI})_{\mathrm{post},t}}{(\mathrm{NDVI})_{\mathrm{pre}}}, \tag{1}$$

where $(\mathrm{NDVI})_{\mathrm{post},\,t}$ is the stand average NDVI at time t after the fire and $(\mathrm{NDVI})_{\mathrm{pre}}$ is the stand average NDVI before the fire. A similar index using a control stand NDVI instead of the pre-fire NDVI has been used in a number of fire recovery studies (e.g. Riaño *et al*. 2002, Díaz-Delgado *et al*. 2003, Lhermitte *et al*. 2007). This relative regeneration index (RRI) at time t is

$$\mathrm{RRI}_t = \frac{(\mathrm{NDVI})_{\mathrm{post},\,t}}{(\mathrm{NDVI})_{\mathrm{con},\,t}}, \tag{2}$$

where $(\mathrm{NDVI})_{\mathrm{con},t}$ is the average of the NDVI control stand at time t. The advantage of using SRI to evaluate post-fire recovery is that it relates all post-fire NDVI values to the actual situation in the stand before the fire. However, pre-fire NDVIs are specific to antecedent environmental conditions affecting vegetation growth (e.g. rainfall). By utilizing a nearby control stand NDVI to derive RRI, changes in environmental conditions are potentially captured by the NDVI of this unburnt stand throughout the period of analysis.

Selection of the control stands that are similar to the burnt stands is critical for the calculation of the RRI. Digital fire history and vegetation type maps described earlier were used to identify areas with the same vegetation and in close proximity (<15 km) to the burnt stands. The control stands were also required to have a long history (>20 years) without fire to ensure they were not undergoing change associated with vegetation recovery. We attempted to select control sites with similar elevation ranges to those of the burnt areas to minimize differences in temperature and rainfall characteristics. We also examined level slice images for the maximum NDVI in the two pre-fire years (2000 and 2001) to help identify control sites with similar properties to the burnt areas. Once potential control sites had been identified, the final selection was based on the degree of alignment between NDVI time series for control and test stands in 2000 and 2001 (i.e. before test stands were burnt).

Both the SRI and RRI were calculated for two phenologically important periods each year, at the time of maximum and minimum NDVI. The maximum NDVI in MCRs is likely to be affected by green biomass from both the herbaceous annual plant species and the shrub species, while the minimum NDVI is more likely to be associated with only the shrub species (Riaño *et al*. 2002). The two recovery indices (equations (1) and (2)) were calculated for both phenological periods and plotted against post-fire stand age.

The variability of pixel-scale NDVI was quantified for each burnt stand by calculating the coefficient of variation (CV) of NDVI values using imagery on fire anniversary dates (before and after the fires). These CV values were plotted against post-fire stand age to determine how intra-stand NDVI variability responded to fires and recovered after the fires. Since Hope *et al.* (2007) had shown that NDVI variability was more sensitive to drought stress than changes in the recovery rates of stand average NDVI, variations in the CV were also related to inter-annual differences in annual rainfall totals.

3.4 *Fire severity*

Regeneration rates of burnt vegetation could be affected by the amount of vegetation that remained unburnt after a fire (i.e. the fire severity). Vegetation in wet, riparian areas and in protected enclaves or depressions may be untouched by a fire or only partially burnt. To quantify the severity of fires in each vegetation stand, we introduced a fire severity index (FSI) based on the relationship between pixel pre- and post-fire NDVI values. An example of the relationship between pre- and post-fire NDVIs is illustrated in figure 2 for the De Hoop Limestone fynbos stand. These scatter plots were all characterized by a cluster of pixels with similar, small post-fire NDVI values that were spread across the range of pre-fire NDVI values (e.g. figure 2). The NDVI of these pixels, indicated by $NDVI_b$ in figure 2, was taken to define the value for completely burnt pixels. The FSI was calculated for each pixel as

$$\mathrm{FSI} = \frac{\left((\mathrm{NDVI})_p - (\mathrm{NDVI})_f\right)}{\left((\mathrm{NDVI})_p - (\mathrm{NDVI})_b\right)} \quad (3)$$

where $(\mathrm{NDVI})_p$ and $(\mathrm{NDVI})_f$ are, respectively, the pre- and post-fire NDVIs for individual pixels and $(\mathrm{NDVI})_b$ is the value for completely burnt pixels derived from the NDVI scatter plots (e.g. figure 2). A FSI of 0 represents no change in vegetation after a fire while a value of 1 indicates complete vegetation removal. The fire severity for each stand was taken as the median FSI value.

3.5 *Rainfall data*

While rain gauge data are collected throughout the Western Cape Region, these data were not available for the last 9 months of the study period. Zhang *et al.* (2005) concluded that data from Tropical Rainfall Measuring Mission (TRMM) are useful in MODIS-based analyses of vegetation response to precipitation. We used the TRMM 3B43 monthly rainfall product (http://daac.gsfc.nasa.gov/data/datapool/TRMM) to derive an annual rainfall time series for each study location. Annual rainfall totals were compiled for each year starting 1 April and ending 31 March so that these ‘water

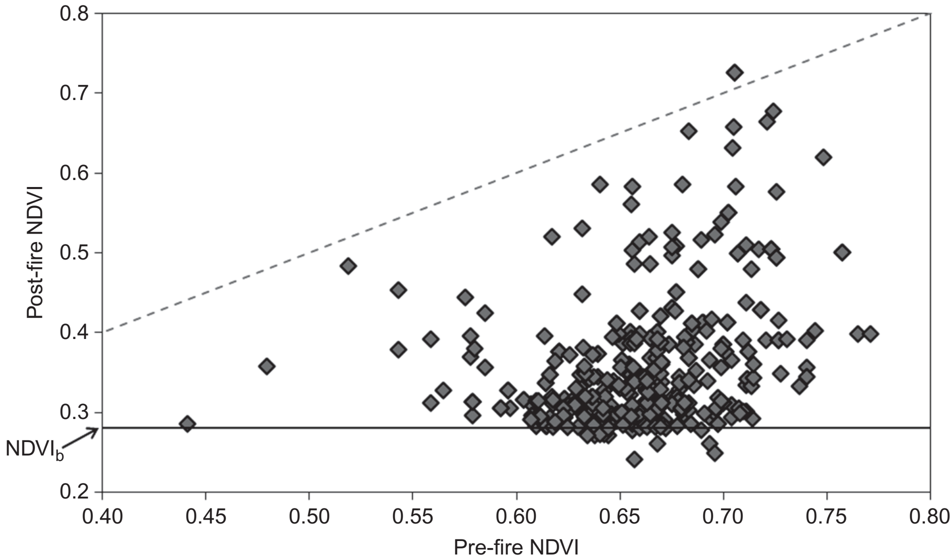


Figure 2. Scatterplot of pre- and post-fire normalized difference vegetation index (NDVI) values for De Hoop Limestone fynbos. The horizontal line indicates the NDVI associated with completely burnt pixels ($NDVI_b$) and the broken line indicates equal pre- and post-fire NDVI values.

years' were synchronized with the fire dates and water availability for re-growth of the vegetation. Annual rainfall totals for the three study locations are given in figure 3.

4. Results and discussion

4.1 *Post-fire recovery rates*

Examples of the NDVI time series for burnt and control stands are given in figure 4 for the De Hoop Limestone fynbos and Robertson South Langeberg Sandstone fynbos stands. The pre- and post-fire NDVI characteristics depicted in these time series were typical of the five vegetation stands. There was good alignment between the pre-fire NDVIs of the control and burnt stands. The control stand for Robertson South Langeberg Sandstone fynbos (figure 4(*b*)) showed evidence of a fire in 2006 which was not reported in the digital fire history map. Since we were unable to find a suitable replacement for this control stand (poor pre-fire alignment of NDVIs) and the unreported fire was late in the study period, we retained the site as a control up to the unreported fire date. The NDVI time series for each burnt and control stand revealed distinct seasonality, similar to the examples shown in figure 4. This feature of fynbos vegetation has also been noted by Hoare and Frost (2004) based on the analysis of a burnt fynbos landscape using AVHRR data.

Recovery trajectories for the maximum and minimum NDVIs of the five fynbos stands based on the SRI and RRI indices (equations (1) and (2)) are given in figures 5 and 6, respectively. The general patterns of post-fire recovery were similar for the two indices and despite differences in vegetation type and the location of the fires, the five fynbos stands had similar recovery patterns (figures 5 and 6). Vegetation recovery

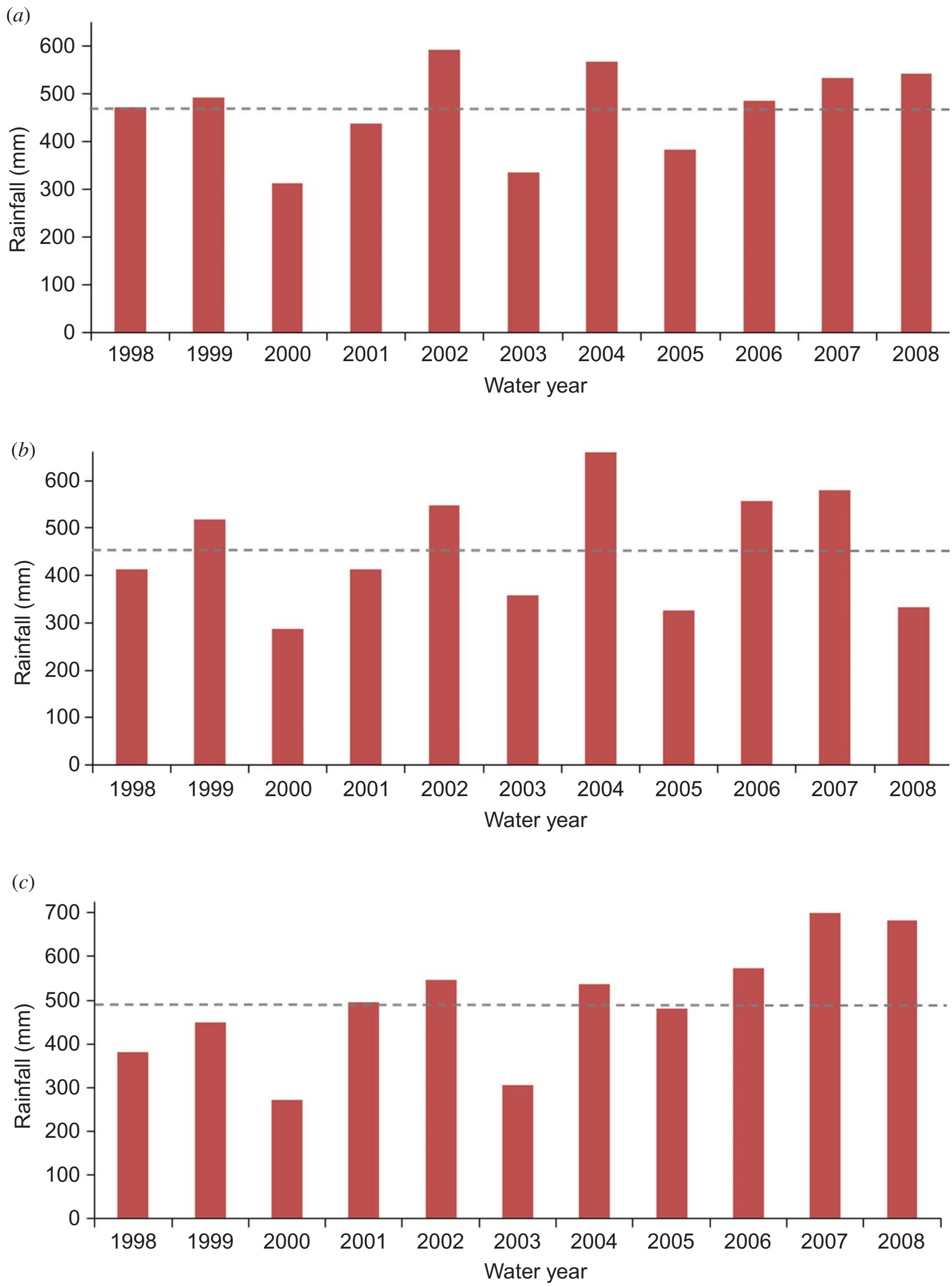


Figure 3. Annual rainfall totals for water years (1 April–30 March) between 1998 and 2008 at each fire location: (*a*) De Hoop, (*b*) Riversdale and (*c*) Robertson. Mean annual rainfall (MAR) is indicated by the broken line and the year indicates the start of the water year.

trajectories were characterized by rapid re-growth in the first two post-fire years (2002, 2003), followed by a pause in the rate of recovery for the next 2–3 years (2004–2006) and then a resumption of recovery to pre-fire/unburnt conditions by 2007 or 2008.

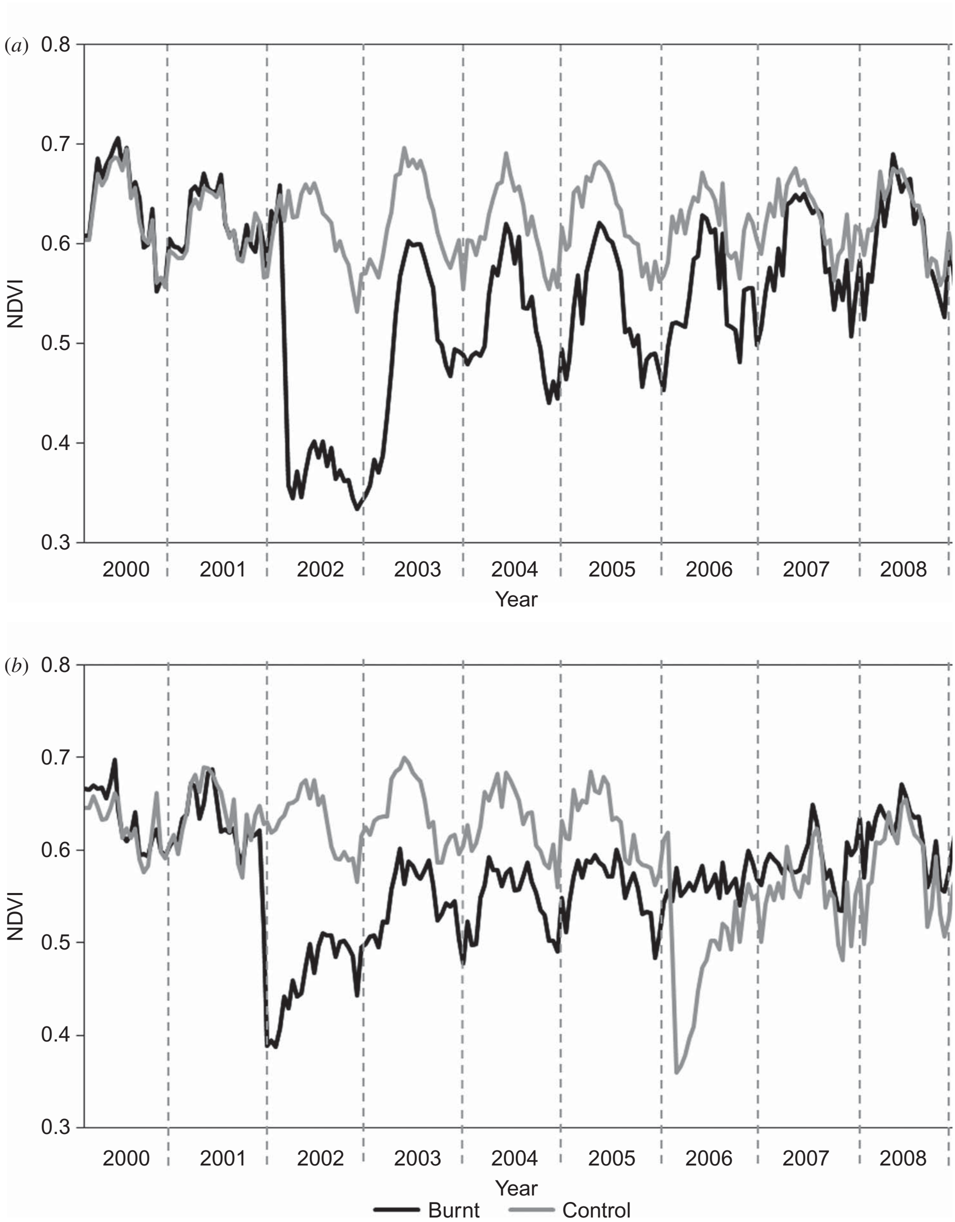


Figure 4. Examples of normalized difference vegetation index (NDVI) time series for burnt and unburnt fynbos stands. (*a*) De Hoop Limestone fynbos and (*b*) Robertson South Langeberg Sandstone fynbos.

The NDVI of two Riversdale fynbos stands (figures 5(*c*) and (*d*) and 6(*c*) and (*d*)) reached full recovery in the second year after the fire, before the drought stress could interrupt the post-fire recovery. It is not apparent why these stands recovered more rapidly and this feature could not be attributed to obvious differences in site conditions (table 1) or rainfall (figure 3). The maximum NDVI had a tendency to recover slightly

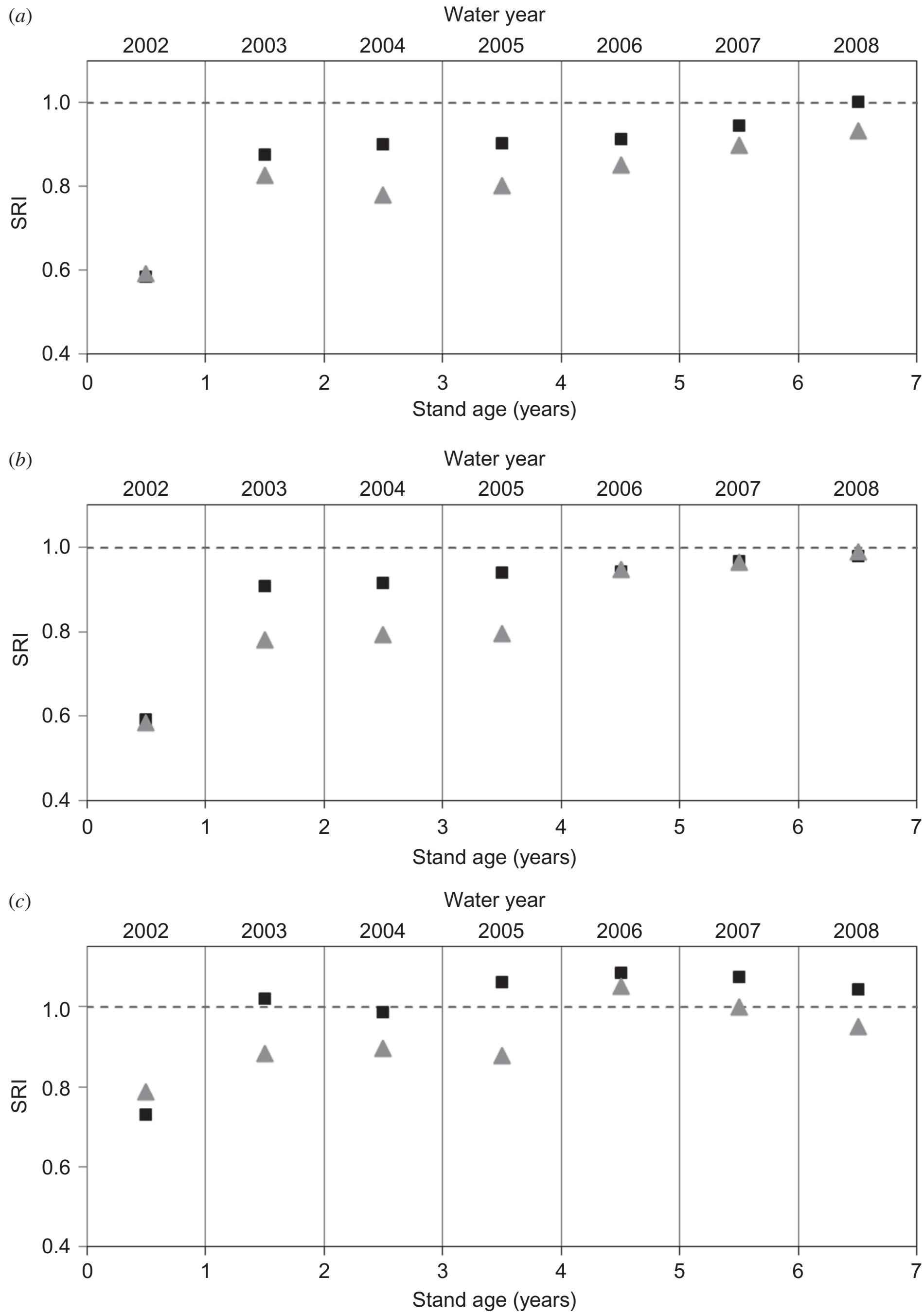
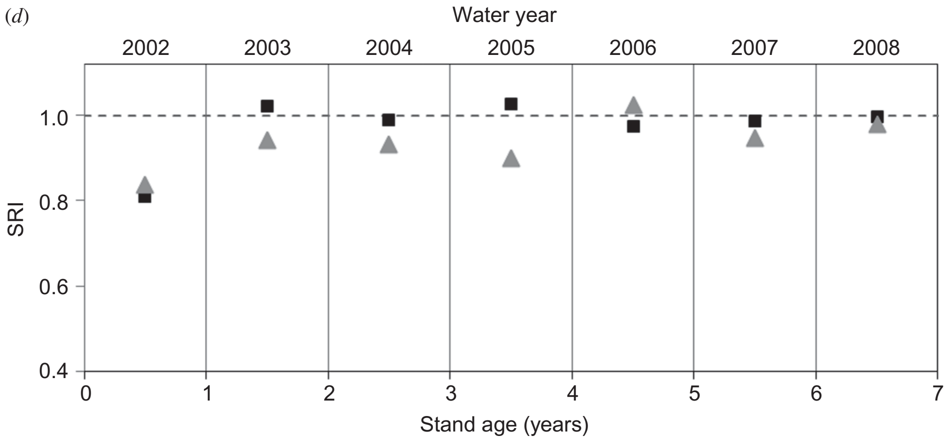


Figure 5. Post-fire recovery of stand average annual maximum normalized difference vegetation index (NDVI) (■) and annual minimum NDVI (▲) based on the stand regeneration index (SRI) for (*a*) De Hoop Limestone fynbos, (*b*) De Hoop Overberg Dune strandveld, (*c*) Riversdale North Langeberg Sandstone fynbos, (*d*) Riversdale South Langeberg Sandstone fynbos and (*e*) Robertson South Langeberg Sandstone fynbos. The horizontal line indicates recovery to pre-fire conditions (SRI = 1.0).

(*d*)



(*e*)

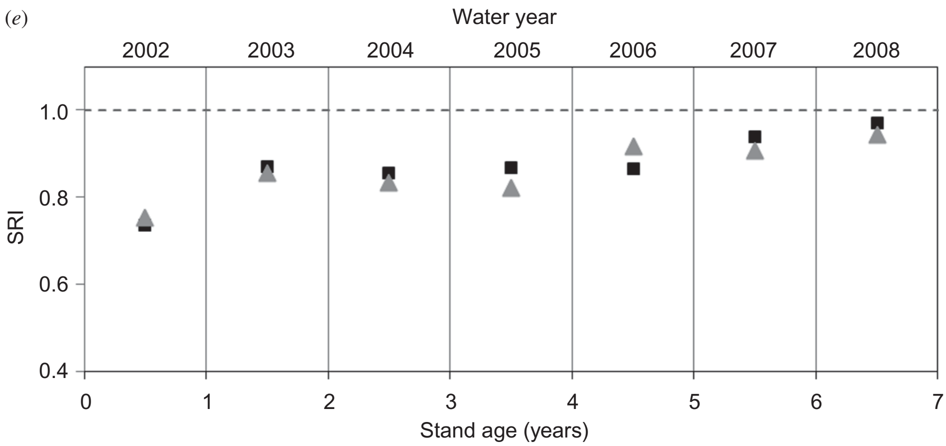


Figure 5. (*Continued.*)

faster than the minimum NDVI in all stands (figures 5 and 6). The greater recovery of the maximum NDVI compared to minimum NDVI may be associated with the contribution of annual plant species to maximum NDVI values.

The pause in post-fire vegetation recovery after 2 years was a regional phenomenon (i.e. evident in all the vegetation stands despite location). Each location had below-average rainfall in 2003 (figure 3) and the less than expected growth in 2004 may have been a consequence of the soil water deficits at the start of the growing season. All three locations had above-average rainfall in 2004 but there was no apparent response in vegetation re-growth in 2005 (figures 5 and 6). While reduced rainfall in the second year (2003) is a plausible explanation for the subsequent pause in vegetation re-growth rates, the lag in vegetation response to drought and the lack of response to water surpluses (i.e. above-average rainfall in 2004) points to likely complexities in the environmental controls over vegetation re-growth. These may include the timing of rainfall relative to the NDVI observation dates, variables besides rainfall affecting soil water availability, soil nutrients and the complex relationships between vegetation physiological processes and soil water.

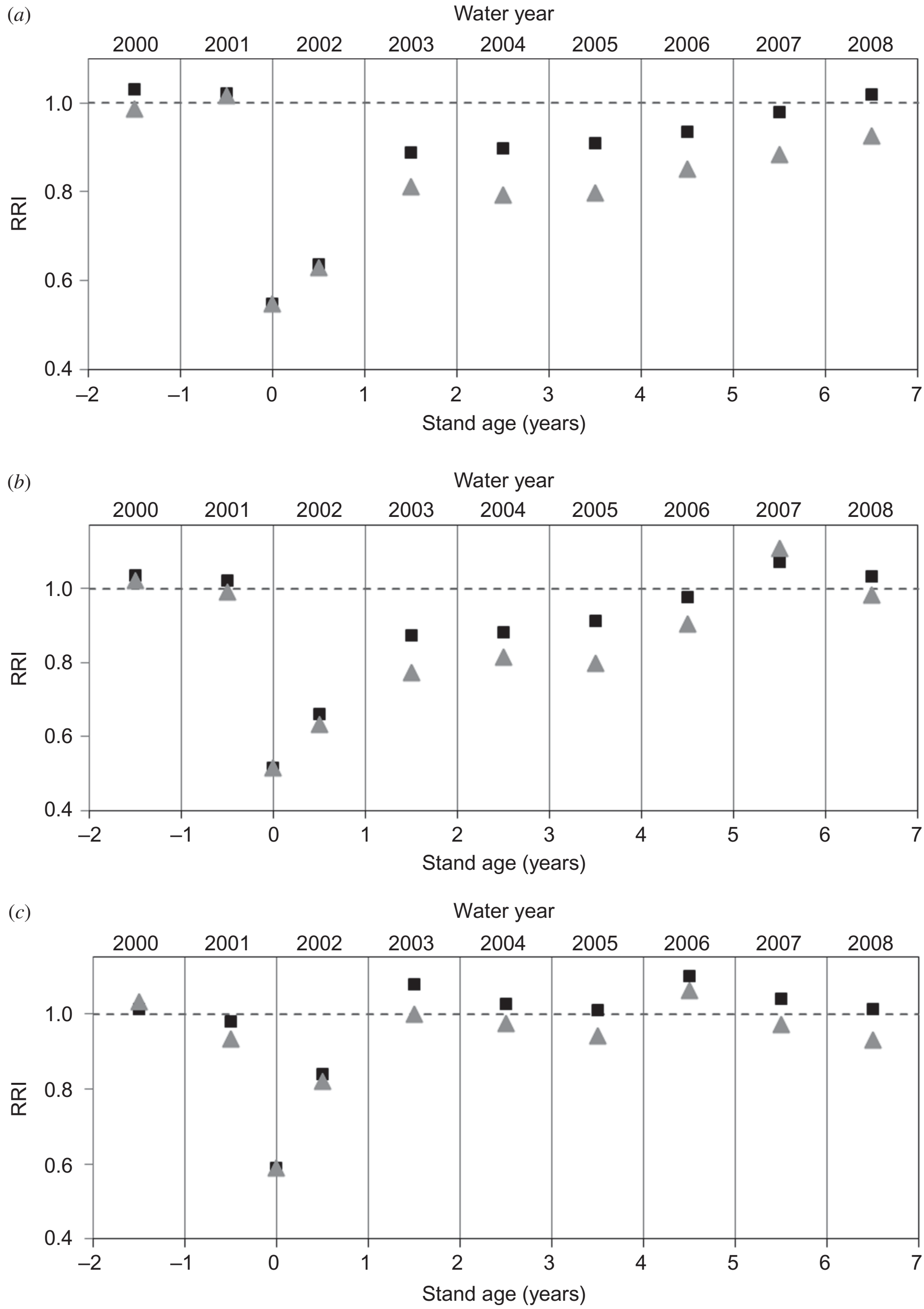


Figure 6. Post-fire recovery of stand average annual maximum normalized difference vegetation index (NDVI) (■), and annual minimum NDVI (▲) based on the relative regeneration index (RRI) for (*a*) De Hoop Limestone fynbos, (*b*) De Hoop Overberg Dune strandveld, (*c*) Riversdale North Langeberg Sandstone fynbos, (*d*) Riversdale South Langeberg Sandstone fynbos and (*e*) Robertson South Langeberg Sandstone fynbos. The horizontal line indicates recovery to pre-fire conditions (RRI = 1.0).

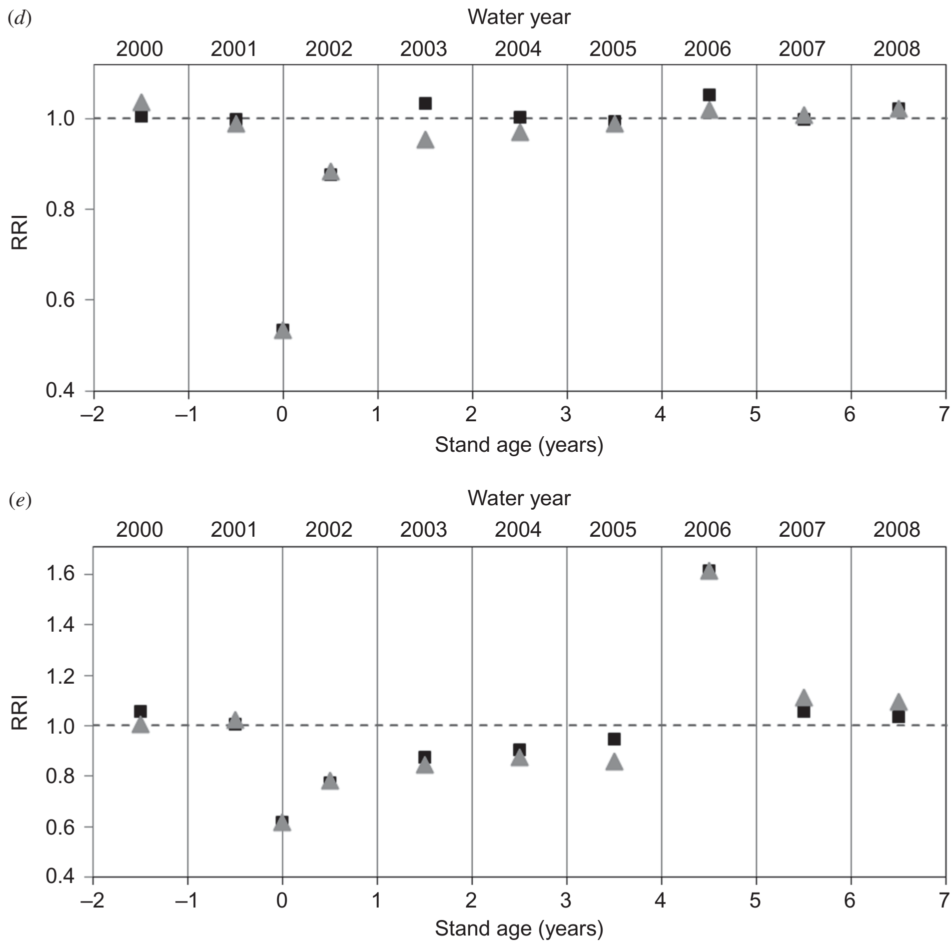


Figure 6. (*Continued.*)

Differences in fire severity and the amount of vegetation destroyed by fires did not appear to be a determinant of post-fire recovery rates in these fynbos stands. Median FSI values for each stand are given in table 3 and ranged between 0.673 for the Robertson South Langeberg Sandstone fynbos and 0.883 for the Riversdale North Langeberg Sandstone fynbos. Despite the greater amount of unburnt vegetation in the Robertson South Langeberg Sandstone fynbos stand (small median FSI), this stand only reached pre-fire NDVI values in 2008 (figure 5(*e*)). Other stands with more vegetation destruction and larger median FSI values, such as the Riversdale North and South Langeberg Sandstone fynbos, reached pre-fire NDVI levels by 2003 (figure 5(*c*) and (*d*)).

4.2 *Intra-stand NDVI variability*

The variability of pixel-scale NDVIs in chaparral vegetation stands was shown by Hope *et al.* (2007) to increase after fires and then recover to pre-fire conditions as the vegetation regenerated. Recovery rates of the NDVI variability in these chaparral stands were similar to those observed for the stand average NDVI but exhibited more

Table 3. Normalized difference vegetation index (NDVI) values for completely burnt pixels ($NDVI_b$) and the median fire severity index (FSI) for each fynbos stand.

Fire	Vegetation unit	$NDVI_b$	Median FSI
De Hoop	De Hoop Limestone fynbos	0.280	0.856
	Overberg Dune strandveld	0.250	0.878
Riversdale	North Langeberg Sandstone fynbos	0.200	0.883
	South Langeberg Sandstone fynbos	0.200	0.863
Robertson	South Langeberg Sandstone fynbos	0.250	0.673

sensitivity to drought than the average NDVI (Hope *et al*. 2007). The increase in NDVI variability due to drought stress was explained by Hope *et al.* (2007) in terms of local differences in plant access to stored soil/ground water associated with variations in variables such as soil depth, soil water holding capacity, depth to the water table and plant rooting depth.

The CV traces in figure 7 depict changes in intra-stand NDVI variability for each of the fynbos stands on fire anniversary dates. NDVI variability in all stands increased the year before the fires as indicated by an increase in CV values (figure 7). The fires were early in 2002 so the below-average cumulative rainfall in the two preceding years, 2000 and 2001 (figure 3), may have been associated with this greater heterogeneity in vegetation growth and NDVI. The Riversdale North Langeberg Sandstone fynbos exhibited the largest increase in NDVI variability the year before the fire (figure 7). The greater solar energy and evaporative losses on the equator-facing slopes of this vegetation stand may have exacerbated the impacts of water stress on differential growth within the stand.

Fires caused the CV to increase in all stands except the Riversdale North Langeberg Sandstone fynbos (figure 7). This stand had the largest median FSI value (table 3) and the greater destruction of vegetation may have resulted in a more homogenous landscape. However, while the Riversdale North Langeberg Sandstone fynbos had a median FSI of 0.883, it was only marginally larger than the FSI for other burnt stands which did show an increase in CV after the fires (table 3). Although fire severity may have played a role in reducing NDVI variability within the Riversdale North Langeberg Sandstone fynbos stand after the fire, other unexplained factors may have been more significant.

Overall, intra-stand NDVI variability approached pre-fire levels by the end of the study period. The reduction in NDVI variability was generally rapid in the first post-fire year, similar to the rapid recovery of that observed for stand average NDVI (figures 5 and 6). However, post-fire CV values fluctuated more than the stand average NDVI values. The CV increased notably in the Robertson South Langeberg Sandstone fynbos and Riversdale North Langeberg Sandstone fynbos in the second post-fire year and in the Riversdale North and South Langeberg fynbos in the fourth post-fire year. These CV values were associated with antecedent rainfall amounts that were below average (figure 3). The Riversdale North and South Langeberg Sandstone fynbos stands had increases in variability 7 years after the fire (figure 7), the only location to have below-average rainfall in the preceding year (figure 3). The North Langeberg Sandstone fynbos stand had a much greater increase in variability in this year compared to the South Langeberg Sandstone fynbos stand. Again, this points to drought effects on fire recovery being amplified on the drier, equator-facing slopes.

The general increase in NDVI variability in fynbos stands in response to drought stress is consistent with the findings for chaparral stands in California reported by

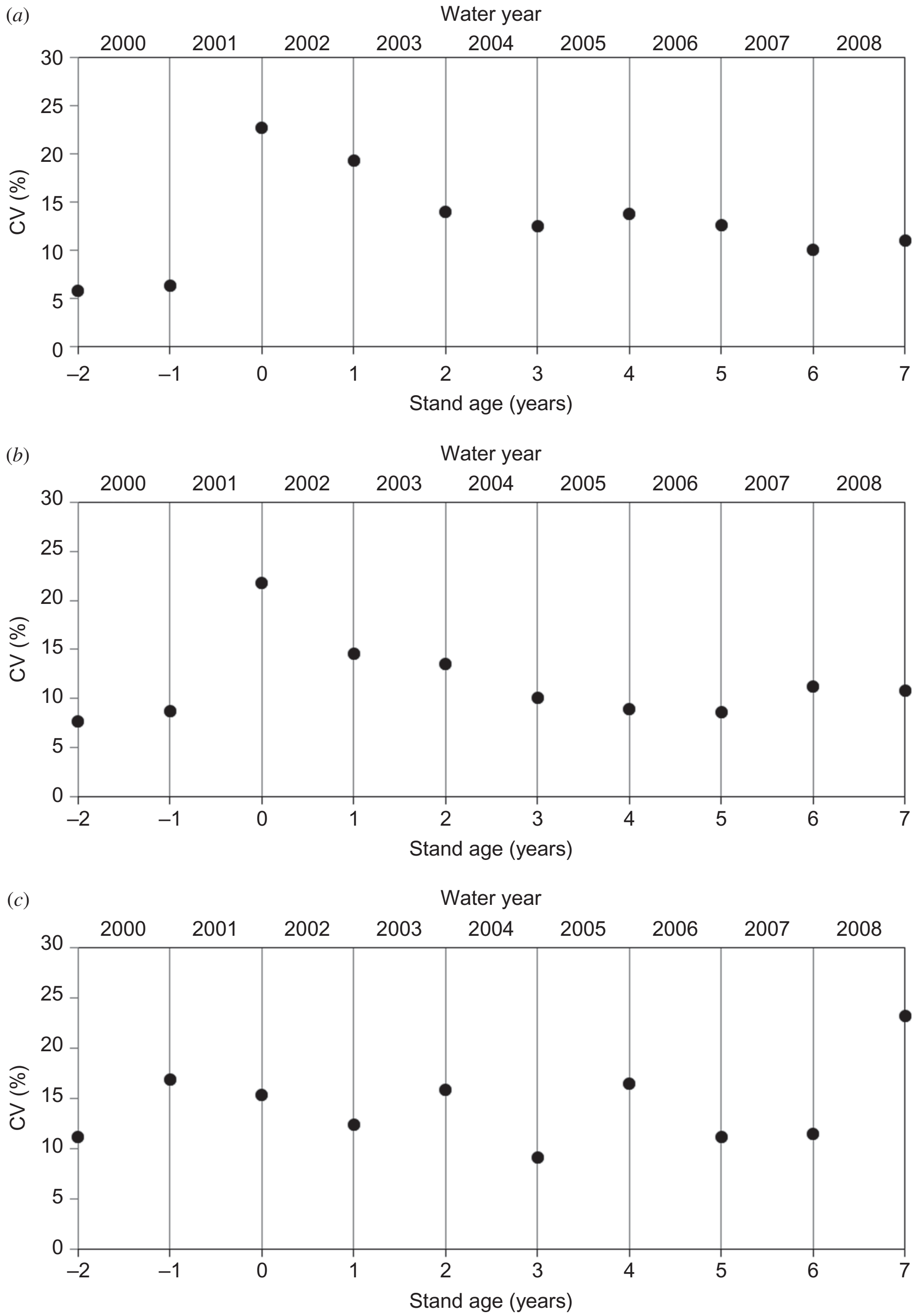
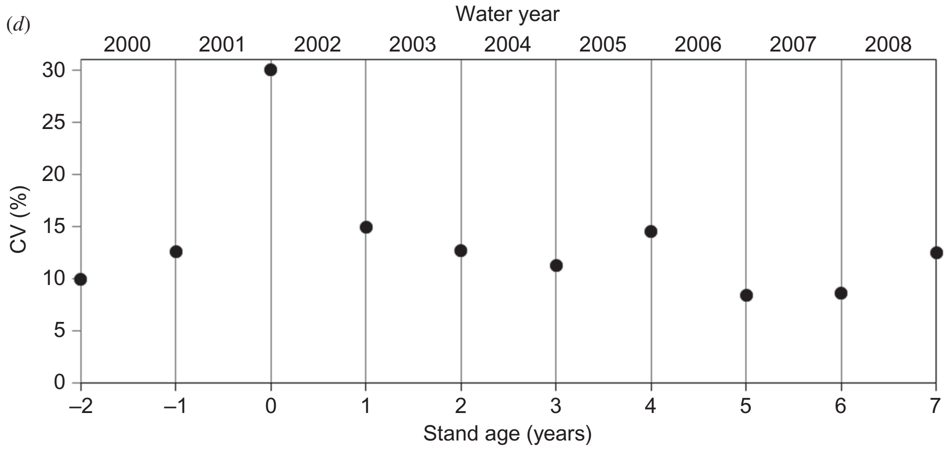


Figure 7. Coefficient of variation (CV) of pixel normalized difference vegetation index (NDVI) values (fire anniversary dates) for (*a*) De Hoop Limestone fynbos, (*b*) De Hoop Overberg Dune strandveld, (*c*) Riversdale North Langeberg Sandstone fynbos, (*d*) Riversdale South Langeberg Sandstone fynbos and (*e*) Robertson South Langeberg Sandstone fynbos.



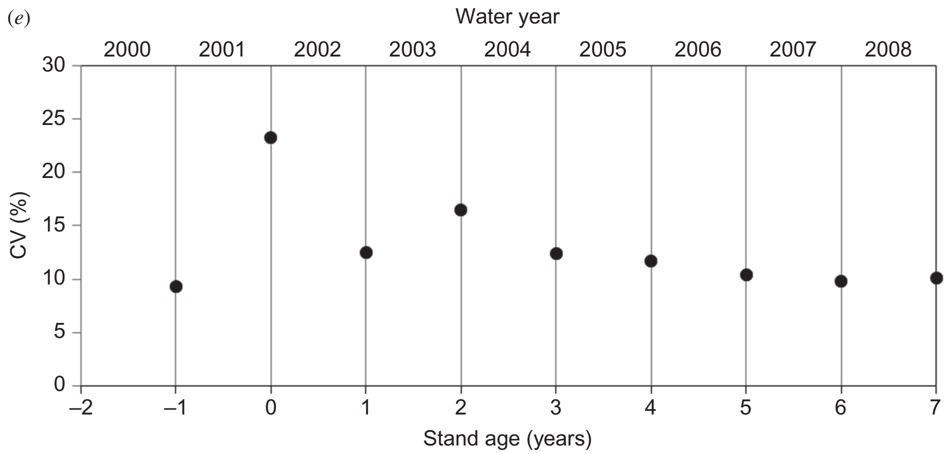


Figure 7. (*Continued.*)

Hope *et al*. (2007). However, sensitivity to reduced rainfall amounts was not consistent for all the fynbos stands and is probably indicative of the complex factors affecting vegetation growth at these patch scales.

5. Conclusions

Both chaparral and fynbos ecosystems are adapted to fires, and post-fire stand age has been shown to be the dominant determinant of NDVI recovery in these landscapes. Despite the contrasting rainfall and soil nutrient conditions of fynbos and chaparral ecosystems and the resulting differences in vegetation characteristics, this NDVI-based study confirmed the observation made by Keeley (1992) that the vegetation recovery characteristics are similar in both ecosystems. The post-fire recovery of fynbos vegetation was rapid and stands reached their pre-fire NDVI values within 7 years. There were some small differences in the rates of recovery for different fynbos vegetation types, as was the case for chaparral ecosystems reported by Hope *et al.* (2007).

Regressing post-fire NDVI values on the pre-fire values helped identify the NDVI for completely burnt pixels in vegetation stands and this value was subsequently used in an index to quantify stand differences in fire severity (vegetation destruction). The amount of vegetation removal by the fires did not have a consistent relationship with the rate of post-fire recovery. Other factors, such as topographic aspect and possibly vegetation species composition, appear to be the more likely controls over the small differences in recovery rates.

The post-fire recovery trajectories of fynbos vegetation stands were interrupted by drought stress. Drought effects on the NDVI recovery trajectories were amplified on the drier equator-facing slopes. Water stress in the fynbos stands increased patch-scale variations in vegetation growth as depicted by the CV of pixel NDVI values. The effect of drought on the recovery characteristics of fynbos was consistent with the findings reported for chaparral sites in California by Hope *et al.* (2007).

Although the focus of this study was on the recovery characteristics of fynbos vegetation and a comparison with post-fire recovery of California chaparral, the results showed some similarities and dissimilarities to those obtained in studies conducted in MCR shrubland ecosystems in Spain. Viedma *et al.* (1997) and Malak and Pausas (2006) found that most of the NDVI recovery in ecosystems they studied in Spain was completed in the first 5–7 years after fire, as had been observed in the chaparral and fynbos ecosystems. While chaparral and fynbos post-fire recovery characteristics were shown to be affected by drought, recovery rates of vegetation stands in Spain were found to be largely unaffected by variations in rainfall amounts (Viedma *et al*. 1997, Malak and Pausas 2006). The insensitivity of fynbos recovery rates to fire severity also contrasted with results from a study in northeast Spain by Díaz-Delgado *et al.* (2003), which demonstrated that the recovery of vegetation was impeded by fire severity. The apparent role of soil water stress and fire severity on fynbos and chaparral recovery characteristics may distinguish these shrubland ecosystems from comparable MCR ecosystems in Spain, and possibly other MCR locations. However, these contrasting findings may also be attributed to different methodologies and data sets employed in the studies.

The utility of MODIS 250 m NDVI products for characterizing the post-fire recovery trajectories of shrubland vegetation stands in a consistent manner has been demonstrated in this study. Adopting a consistent data set and methodology in future studies is likely to lead to more reliable conclusions regarding similarities or dissimilarities in post-fire recovery characteristics of different MCR ecosystems. As the MODIS record length increases, studies to examine post-fire vegetation response to variations in fire history will be possible. Results from a study conducted by Díaz-Delgado *et al.* (2002) in Spain using Landsat multispectral scanner (MSS) data have indicated that post-fire recovery of NDVI to pre-fire conditions is affected by fire recurrence in these ecosystems. A comparative study of the sensitivity of different MCR ecosystems to fire recurrence would be a logical extension of the study we have presented in this article.

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