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Title

Landscape-scale assessment of tree crown dieback following extreme drought and heat in a Mediterranean eucalypt forest ecosystem

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Abstract

Mediterranean regions are under increasing pressure from global climate changes. Many have experienced more frequent extreme weather events such as droughts and heatwaves, which have severe implications for the persistence of forest ecosystems. This study reports on a landscape-scale assessment investigating potential associated factors of crown dieback in dominant tree species following an extreme dry and hot year/summer of 2010/11 in the Northern Jarrah Forest of Western Australia. Analyses focussed on the influence of (i) geology, (ii) topography, (iii) climate, and (iv) fire history. The results showed that trees on specific soils were more likely to show canopy dieback. Generally, trees on rocky soils with low water holding capacity were found to be affected more frequently. Other explanatory factors identified that dieback occurred (i) on sites that were close to rock outcrops, (ii) in areas that received a slightly higher amount of annual rainfall compared to the surrounding landscape, (iii) on sites at high elevations and (vi) on steep slopes, and (v) in areas that were generally slightly warmer than their surroundings. These results expand our understanding of how landscape-scale factors contribute to the effects of an extreme drought and heating event in Mediterranean forest ecosystems, and give indications of where changes are likely to occur within the landscape in the future. The analogues with other Mediterranean climate regions make the results of this study transferable and a starting point for further investigations.

Keywords

climate change; drought effects; heat effects; warming; die-off; dieback; tree mortality; forest mortality; soils; topography; geology

Introduction

Climate changes are taking place in an increasing rate across the globe and are likely to continue into the future (IPCC 2007). Landscape-scale changes are happening in the wake of these significant global climate processes (IPCC 2007). Conservative estimates of a 2 - 4.5°C rise in temperature by 2100 and an increased likelihood of more extreme weather events such as droughts and heatwaves are projected worldwide (Chapter 10 in IPCC 2007). The increases in temperature and changes in rainfall patterns have been highlighted as two important factors contributing to the loss of natural biota and declines in ecosystems (Allen et al 2010; Mantyka-Pringle et al 2011). Extreme weather events, like droughts and heatwaves, are further increasingly held responsible for triggering dramatic dieback responses particularly in forested ecosystems around the world (Fensham and Holman 1999; Lloret et al 2004; Worrall et al 2008; Allen et al 2010; Carnicer et al 2011; Peng et al 2011).

Mediterranean climate regions maintain one of the highest levels of biodiversity, supporting five of the world's 35 biodiversity hotspots (Klausmeyer and Shaw 2009; Mittermeier et al 2011). The climate in Mediterranean regions is generally projected to undergo a process of warming and considerable drying also experiencing more frequent extreme weather events over the next century (Chapter 10 & 11 in IPCC 2007; Klausmeyer and Shaw 2009). This is likely to have a profound effect on the rich biodiversity these regions support, adding to the concerns surrounding global biodiversity conservation (Myers et al 2000; Klausmeyer and Shaw 2009; Mittermeier et al 2011). Forest ecosystems in the Mediterranean climate regions around the world are already showing the negative effects of these climate trends and extremes through severe dieback and mortality in some of the dominant tree species (e.g. Allen et al 2010; Carnicer et al 2011; Sarris et al 2011). This is particularly true when extreme weather events such as drought and heatwaves occur simultaneously (Suarez et al 2004; Thabeet et al 2009; Allen et al 2010; Carnicer et al 2011), likely negatively impacting on the biodiversity that Mediterranean forest ecosystems support.

The uncertainties of how forest ecosystems will respond to the projected changes in climate are an ongoing challenge (Medlyn et al 2011). Particularly factors and processes determining when and where dieback and mortality events will take place within the wider landscape are poorly understood (Allen et al 2010). This information is essential for assessing climate change vulnerability and developing sustainable forest management plans for adaptation (Lindner et al 2010), to ensure forest ecosystems services like carbon sequestration and biodiversity values are preserved into the future.

For Mediterranean climate regions, few studies exist investigating what factors at the landscape-scale were associated with the impacts of drought and heating events *per se*. In these few studies, relationships between tree crown dieback and topography, such as slope and landscape position, were found to be weak (Lloret et al 2004; Suarez et al 2004; Thabeet et al 2009). These studies did, however, consistently earmark the underlying geology as having a likely effect in relation to drought-induced (Lloret et al 2004) and drought/heat-induced canopy dieback (Suarez et al 2004; Thabeet et al 2009). In these studies, poor site conditions such as low water holding capacity of the soils was found to be a likely underlying cause for the dieback and mortality observed. All of these studies, however, focussed on tree level effects using relatively few study sites ($n = 4 – 52$) within the landscape. More detailed multi-site landscape-scale analyses of drought and heat-triggered impacts in Mediterranean forest ecosystems have generally been lacking.

The southwest of Western Australia (SWWA), is a Mediterranean climate region and one of the five globally recognised Mediterranean 'biodiversity hotspots' (Klausmeyer and Shaw 2009; Mittermeier et al 2011). Mediterranean ecosystems have been recognised as highly sensitive to climate driven ecosystem shifts (Klausmeyer and Shaw 2009), with SWWA being one of the regions most likely to be affected (Klausmeyer and Shaw 2009; Laurance et al 2011), making it a priority for biodiversity conservation (Klausmeyer and Shaw 2009). The SWWA experienced an extreme dry (driest on record) and warm (second hottest) year in 2010 (BOM 2011b), followed by multiple heatwaves (i.e. three or more consecutive days of 35+ °C) in the summer of 2010/11 (Dec, Jan, Feb) (BOM 2011a). Following a prolonged (7+ days) heatwave at the end of February (BOM 2011a), extensive rapid dieback in the dominant canopy species *Eucalyptus marginata* (jarrah) and *Corymbia calophylla* (marri) was observed in the Northern Jarrah Forest (NJF) (Matusick et al submitted). Similar events have been recorded around the world (Allen et al 2010), but none have been recorded and investigated across the NJF region previously. The objective of this study was to perform a landscape-scale assessment investigating the relationships between the canopy dieback observed and landscape related factors focussing on the (i) geology, (ii) topography, (iii) climate, and (iv) fire history of the NJF region.

Methods

Study area

The Northern Jarrah Forest (NJF) is situated in the SWWA (between Latitude 30° 45 - 33° 30'S and Longitude 115° 52 - 117° 5'E; Fig. 1), as defined by the Interim Biogeographic Regionalisation of Australia (IBRA) (Australian Government 2012). The region has a

Mediterranean climate and is characterised by warm to hot, dry summers and mild to cool, wet winters (Csa and Csb, following Peel et al 2007). Most (~80%) rainfall falls between April and October (Bates et al 2008) and a distinct seasonal dry period occurs between October and April lasting between 4 to 7 months (Gentilli 1989). There is a strong west-east rainfall gradient across the forest, ranging from ~1100 mm on its western edge (Darling Scarp) to ~700 mm in the east and north (Gentilli 1989). In terms of climate change, the SWWA has experienced an increase of 0.45 °C in mean temperature and a continuous reduction in annual rainfall of up to 14% since the mid-1970s (Bates et al 2008). The majority of current climate change models agree on a continuation of this trend, projecting a reduction in rainfall of up to 40% and an increase in temperature of up to 5 °C by 2070 (CSIRO and BOM 2007) . Similar trends have been observed and projected for other Mediterranean climate regions around the world (Chapter 11 in IPCC 2007; Klausmeyer and Shaw 2009).

Figure 1 approximately here##

Geology

The NJF is situated on the Darling Plateau that consists of parent materials made up of felsic rocks (i.e. granites) intersected by belts of older mafic rocks (Churchwood and Dimmock 1989). Intense and long-lasting weathering resulted in a nutrient poor, deep (up to 50 m to granite bedrock) lateritic profile (Dell and Havel 1989). The topography is undulating with uplands averaging in elevation between 280 and 320 m intersected by shallow and steep valleys up to 100 m below (Churchwood and Dimmock 1989). Uplands generally consist of shallow, sandy to gravely topsoil's (10-20 cm deep) overlying a rock lateritic duricrust (0.5-2

m) and underlying clays with a relatively high water storage capacity (Schofield et al 1989). Slopes consist of sandy gravels and loams (up to 1 m in depth) overlying a lateritic duricrust or rock and underlying clays. Valley floors predominantly hold loams and sandy loams overlying clays. Granite bedrock frequently intersects these profiles across the NJF forming distinct rock outcrops within the landscape (Churchwood and Dimmock 1989). The native vegetation of the NJF spans 472 different soil types based on the soil landscape mapping for southwest Australia (Table 1). The main soil types are the Dwellingup subsystem (16.1%) mainly occurring on undulating uplands and slopes, Yarragil subsystem (5.5%) in valleys, Murray subsystem (4.7%) in the valleys associated with the Murray river, Yalanbee subsystem (4.4%) on uplands, and the Dwellingup 2 phase (4.3%) on gently undulating uplands and slopes.

Table 1 approximately here##

Vegetation

The remaining native vegetation in the NJF covers an area of approximately 1,127,600 ha (Fig. 1). The NJF is dominated in the canopy by *Eucalyptus marginata* (jarrah) trees and commonly found in association with *Corymbia calophylla* (marri), *Eucalyptus wandoo* (wandoo) and *Eucalyptus patens* (blackbutt), with a mixed mid-story including *Banksia grandis, Allocasuarina fraserani, Persoonia* spp. and *Hakea* spp. (Heddle et al 1980). The dominant tree species are highly adapted to the climatic and soil conditions in the NJF, utilising water from the deeper clays during the summer drought using sinker roots penetrating the lateritic duricrust (Abbott et al 1989; Dell and Havel 1989; Schofield et al 1989). The remaining native vegetation of the NJF spans 49 different vegetation classes based on the vegetation complexes mapping for southwest Australia (DEC, 2006 in Table 1). This vegetation dataset corresponds with the soil type classification, using a similar naming protocol (see previous paragraph), but including more detailed information on soil hydrology and vegetation composition for each class. Information on soil hydrology was based on soil and vegetation surveys linking physical soil characteristics (e.g. proportion of gravel/stones, sand, loam, but also thickness of the soil profile and slope angle) to determine the level of water holding capacity, infiltration and drainage (for more information see metadata DEC, 2006 in Table 1).

Sample and data analyses

On the 26th of May 2011, a 508 km long aerial survey was undertaken using a Cessna 172 fixed-wing aircraft spanning the western-half of the NJF (Fig. 1). The survey was undertaken to detect sites where crown dieback had occurred, first observed in late February 2011. The flight path and locations of the affected sites were recorded using a Garmin GPS (GPSMAP ® 92s, Garmin International Inc., Missouri, USA). Accurate positioning and delineation of the affected sites was achieved using high-resolution vertical orthophotos and georeferenced oblique photos taken from the plane. The affected sites were found to be in distinct patches with sizes ranging between 0.3 and 85.7 ha (Matusick et al submitted). Initially 236 affected sites were recorded; however, two sites fell in less than 3-month-old burned areas and were omitted for the purpose of this study, resulting in 234 affected sites used in the analyses.

The sample area was estimated to be an approximately 2000 m wide strip representing the field of view from the plane running parallel to the recorded flight path (Matusick et al submitted). This strip was used to extract the area of remaining native vegetation (Fig. 1) using the clip function in ArcGIS Analysis tools (ArcGIS 10, ESRI, California, USA). For the purpose of this study, an equal random sample representing unaffected sites was generated within the boundaries of this area of native vegetation using ArcGIS Data Management tools. This was achieved after omitting the 234 delineated affected sites, and a 50 m internal buffer to correct for potential edge effects. Therefore, a total sample of $n = 468$ was used for the analyses. The coordinates of the centre points of both affected ($n = 234$) and unaffected ($n = 234$) sites were used in this study to extract values from datasets of interest (Table 1) using the bilinear interpolation option in ArcGIS Spatial Analyst tools.

To validate the accuracy of the size and position of the aerial delineations for the affected sites, 28 sites were randomly selected and delineated on the ground using a differential GPS (Pathfinder Pro XRS receiver, Trimble Navigation Ltd., California, USA). The aerial and ground delineations were compared statistically using ArcGIS. With the exception of one, all aerial delineations overlapped for at least 50% with the ground delineations. More importantly, for points that were used to extract values for the analyses, 86% either fell in or within a radius of <20m from the ground delineations. To minimise the effect of the 14% error, bilinear interpolation was applied using the values from adjacent cells of the various value raster datasets to calculate the average values for the affected and unaffected sites that were used in the analyses.

The full dataset ($n = 468$) was used as presence-absence (i.e. affected (A) vs. unaffected (U)) data, and related to a suite of landscape metrics computed from various relevant spatial datasets. Data layers and measurements used for the analyses were: topographic position, including slope position and Euclidean nearest neighbour distance measures (to account for potential spatial correlations); vegetation classes; geology; fire history; and climatology

(Table 1). The slope position classification was created with Land Facet Corridor Tools for ArcMap 10 (Jenness et al 2011) using the Digital Elevation Model (DEM). This tool creates a classification based on calculating an index using height and slope derived from the DEM. For instance, high positive index values are tops of ridges going down to upper slopes towards low negative index values indicating lower slopes and valleys (for more details see Jenness et al 2011). For climatology, climate-related variables were generated from the AWAP dataset, which includes gridded (5x5 km) rainfall and temperature data based on observations recorded by the Australian Bureau of Meteorology (Jones et al 2009; Raupach et al 2009, 2011). We calculated yearly and seasonal (i.e. summer (Dec, Jan, Feb), autumn (Mar, Apr, May), winter (Jun, Jul, Aug), spring (Sep, Oct, Nov)) averages for rainfall and temperature, for the period 1981-2010 representing the long-term 30-year average, and averages for the period March 2010 to February 2011 (2010/11) to capture the extreme weather events that occurred.

To investigate the configuration of the affected and unaffected sites within the sample area, a cluster analysis was performed using the Average nearest neighbor tool available in the ArcGIS Spatial statistics toolbox. All other statistical analyses were performed using R (2.12.0, www.r-project.org). Continuous variables (see Table 1) were found to be non-normally distributed and were analysed using independent 2-group Mann-Whitney-Wilcoxon tests. Categorical variables were analysed using Chi-square tests of independence. Continuous variables were further used to perform logistic regression analyses building predictive models following steps described in Logan (2010).

Results

Site configuration

The affected sites were found to be clustered within the sample area (Nearest Neighbor Ratio: 0.813, z = -5.484, P = <0.001), indicating a spatial correlation between these sites. The unaffected sites were found to display a dispersed pattern within the sample area (Nearest Neighbor Ratio: 1.425, z = 12.425, P = <0.001).

Geology

The sample area accurately represented the five major soil types of the NJF. Affected sites were found on 29 different soil types across the sample area. For the five major soil types of the NJF (see Methods, *Geology*), no differences were found between affected and unaffected sites (Table 2), indicating that these soil types did not predispose the observed crown dieback. The only soil type where more frequent canopy dieback was observed was the Helena subsystem, which is characterised by shallow to deep stony soils situated on steep slopes (>25%) with frequent rock outcrops. Affected sites were found more often on this soil type than unaffected sites (Chi-square: X^2 = 4.680, A = 14, U = 4, P = 0.031). The Helena subsystem was found to cover 1.2% of the sampled area (and 0.1% for the whole NJF), but 6.0% of all affected sites were found on this soil type. Altogether this suggests a higher than average likelihood of trees experiencing dieback on this particular soil type.

Table 2 approximately here##

Vegetation classes

Affected sites were found in 12 different vegetation classes across the NJF. Forest canopies of these classes were all dominated by *E. marginata* and *C. calophylla*, confirming observations made on the ground during the validation exercise. Again for all major classes (e.g. Dwellingup, see *Geology/Vegetation* in Methods), no differences were found between affected and unaffected sites (Chi-square: P = 0.213 - 0.476). In the vegetation dataset (Table 1), water holding capacity of the soils for the five major classes was classified as moderate to good. Considering all vegetation types, affected sites were more frequently found within the vegetation class designated to the Helena class (Chi-square: X^2 = 12.109, A = 26, U = 6, P <0.001), similar to the findings made for the soils (see previous section). This vegetation class is dominated in the canopy by *E. marginata* and *C. calophylla*, and underlying soils are further characterised by high incidence of rock outcrops, strongly water shedding, with poor infiltration and low water holding capacity. This together with the soils results indicates the likely association of the underlying geology in determining the occurrence of canopy dieback when combined drought and heatwaves occur.

Topographic position

Trees on sites situated higher in the landscape were found more likely to be affected than trees on sites at lower elevation (Table 3), and affected sites were found more frequently on upper slope positions (i.e. high within the landscape) (Chi-square: X^2 = 4.074, A = 30, U = 16, P = 0.044). Trees on sites on steep slopes were found more likely to be affected than trees on slopes with lower incline, supporting the soils results. For aspect, West facing slopes were found most frequently affected (Chi-square: X^2 = 5.901, A = 94, U = 68, P = 0.015), and East facing slopes the least (Chi-square: X^2 = 19.267, A = 37, U = 79, P <0.001). No differences were found for the number of affected and unaffected sites on North or South facing slopes (Chi-square: $P = 0.091 - 0.365$).

Table 3 approximately here##

Trees on sites closer to ridge tops were found more likely to be affected than trees on sites further away (Table 3), suggesting that together with elevation and slope position, trees on sites situated higher in the landscape seemed to be more sensitive to dieback. Additionally, trees on sites close to rock outcrops within the landscape were found more likely to be affected than trees on sites further away (Table 3), whereas distance to drainages and valleys were found to have no effect (Mann-Whitney-Wilcoxon: $P = 0.088 - 0.540$).

Rainfall

For the survey area (Fig. 1), average 30-year rainfall of 946-998 mm, dropped to 484-515 mm in 2010/11, which corresponds with a reduction of 48-49%. Both affected and unaffected sites experienced the same percentage reduction in rainfall in 2010/11. However, affected sites were found to be situated in areas that generally received slightly more rainfall based on the 30-year average than unaffected sites (Table 3).

Temperature

In 2010/11, the mean temperature was found to be 0.6 °C higher (+3.5%) ranging from 16.8-17.2 °C compared with the 30-year average temperature. This increase was mainly due to an increase of 1.1 °C (+4.6%) in the mean maximum temperature, ranging from 23.7-23.8°C in

2010/11 compared with the average. These increases in maximum temperatures were mainly prevalent in spring (Sep, Oct, Nov; 2010) +2.3 °C (+10.8%; range 22.5-24.9 °C) and summer (Dec, Jan, Feb; 2010/11) +1.5 °C (+5.0%; range 30.4-32.9 °C) compared to the seasonal average. Both affected and unaffected sites experienced the same percentages increase in temperature, however, affected sites were found in areas that were generally slightly warmer (+0.4°C) based on the 30-year average than unaffected sites (Table 3). Together, the results suggest that trees that were affected generally developed under slightly wetter and hotter conditions on average than unaffected trees in the surrounding landscape.

Fire history

The majority (65.0%) of sites that were affected were found in areas that were burnt in the last 10 years. This percentage was similar to the percentage area of native vegetation burnt in the last 10 years for the whole of the NJF (67.9%), suggesting no particular impact of fire history on the observed crown dieback. Another 15.0% of the affected sites fell in areas that were burned 10-15 years ago. Again the percentage affected sites in this category was no different from the whole of the NJF (15.5%). Together this suggests that the time since last fire did not have an influence on the incidence of canopy dieback in the NJF following the 2010/11 extreme weather events.

Logistic regression analyses

The logistic analysis revealed that the five most important continuous variables explaining the incidence of canopy dieback were, from most to least important: distance to rock outcrop, average annual rainfall, elevation above sea level, slope of the ground surface, and average temperature (Table 4). These five variables together were found to produce the model explaining the highest amount of variation within the dataset ($R^2 = 0.15$). Including interactions between the individual variables did not improve the models.

Table 4 approximately here##

Equation 1 Logistic regression equation.

$$y(x_i) = \frac{e^{\beta_0+\beta_1 x_1+\ \dots\ +\beta_i x_i}}{1+\ e^{\beta_0+\beta_1 x_1+\ \dots\ +\beta_i x_i}} \tag{1}$$

Values for the individual variables (x_i), β_i and *Intercept* (β_0) from Table 4 were used to calculate the probability of a site being affected after extreme weather events such as experienced in 2010/11 in the NJF, using Equation 1. The probabilities of crown dieback influenced by distance to a rock outcrop, and in combination with 30-year average rainfall are displayed in Fig. 2. These graphs show that trees are most likely affected on sites in close proximity of a rock outcrop that, compared to the surrounding landscape, receive a relatively high amount of annual rainfall. In addition to these two main explanatory variables, the models indicate that the likelihood of trees being affected increased on sites that were higher in elevation, steeper in slope, and that were found in areas that were on average slightly warmer compared to the surrounding landscape (Table 4).

Figure 2 a and b approximately here##

Discussion

The extreme drought and heating events of 2010/11 were the likely primary factors that caused the significant crown dieback response observed in the Mediterranean NJF of Western Australia (Matusick et al submitted), which is supported by global observations (Allen et al 2010). Reduced rainfall of up to 49% in combination with extreme high temperatures and multiple heatwaves during the annual dry season (spring and summer, Sep-Feb) were registered (This study; BOM 2011a, b). These conditions likely resulted in soil water deficits followed by the observed crown dieback response (Fensham and Holman 1999; Allen et al 2010).

This study revealed some of the likely associated factors at the landscape-scale that contributed to the observed crown dieback. Specific soils were found to be associated with the observed canopy dieback, which was likely related to variability in water holding capacity determined by the underlying geology. Further associated landscape factors for the occurrence of crown dieback were (i) proximity to rock outcrops, (ii) annual average rainfall, (iii) elevations in the landscape, (vi) slope angle and (v) annual average temperature. The recognition of these associations represents an important step towards the identification of areas within the Northern Jarrah Forest landscape that are likely to become increasingly sensitive to the projected drying and warming conditions.

Based on the Köppen-Geiger climate classification map (Csa and Csb, following Peel et al 2007 and see insert Fig. 1), a review by Allen et al (2010) identified 13 cases of drought and/or heat induced mortality for Mediterranean climate regions around the world. In only three of these cases an attempt was made to look at the landscape-scale and related factors that contributed to crown dieback observed following extreme weather events being either extreme drought (Lloret et al 2004) or drought combined with periods of extreme temperatures (Suarez et al 2004; Thabeet et al 2009).

Studies in Mediterranean regions focussing on relationships between extreme weather induced tree-crown dieback and landscape factors, found varying, mainly non-significant results with regard to topography and landscape position (Lloret et al 2004; Suarez et al 2004; Thabeet et al 2009). For example, in a study on the impacts of the extreme weather events (i.e. drought and heatwaves) that occurred in the period of 2003-2005 affecting Scots pine (*Pinus sylvestris* L.) in the French Mediterranean region, Thabeet et al (2009) could not derive a significant relationship for altitude, slope, and aspect likely because of the low number of sites that were used (n = 4). Lloret et al (2004) used two to eight upslope transects at six sites to look at the impacts on the dominant tree species *Quercus ilex* following a drought that occurred in 1994 in North East Spain. They showed that trees on upper slope positions were more severely damaged than trees on lower slopes. Suarez et al (2004) used a comparison of 26 sites with >50% tree mortality vs. 26 sites with <25% tree mortality in northern Patagonia. They looked at effects on the dominant tree species *Northofagus dombeyi* after a severe drought and heating event that occurred in 1998-99 across the landscape. They found no relationship between the severity of the effects with altitude, aspect, and proximity to water, but did find a weak relationship with slope, where affected sites were found more frequently on steeper slopes. The main concern with these studies was likely the relatively few sites (n = 4 - 52 compared to n = 468 in this study) that were used to derive possible relationships at the landscape-scale.

The relationships that were found in the previous studies (Lloret et al 2004; Suarez et al 2004; Thabeet et al 2009), however, match with our results. We found that sites situated higher in the landscape and on steeper slopes were more often affected than sites lower down. This could be the result of lower water availability on higher and steeper sites, where groundwater tables are deeper and recharge from rainfall is generally lower compared to low lying areas (Schofield et al 1989). Since 1993, groundwater levels have been shown to decline in response to the declining trend of annual rainfall in the NJF (Kinal and Stoneman 2011). The extreme drought might have resulted in a lack of recharge, causing the groundwater table to drop below the zone utilised by the root system of the trees, which resulted in the dieback response observed in the higher landscape positions.

Previous studies in Mediterranean regions consistently showed that the underlying geology had a significant influence on the level of damage to trees following extreme weather events (Lloret et al 2004; Suarez et al 2004; Thabeet et al 2009). In these studies, poor site conditions relating to factors such as shallowness (i.e. impenetrable (rock) layer close to surface), rockiness, and low water holding capacity of the soils were found to be likely predisposing factors for the canopy dieback observed. Our analyses support these observations, where the underlying geology in the NJF seemed to have had a significant influence in determining where dieback occurred after the extreme drought and heat of 2010/11. We found a higher incidence of crown dieback occurring clustered around rock outcrops on soils characterised by shallow to deep stony profiles with frequent rock outcrops situated on steep slopes, strongly water shedding, with poor infiltration and low water holding capacity. Combined with affected sites being generally close to rock outcrops, the characteristics of the soil profile determining the water holding capacity (e.g. percentage of rock) and the root morphology of the trees (Poot et al 2012) likely played a role in the incidence and extent of the dieback response observed at these locations.

To investigate relationships between the dieback observed and spatially-explicit climate data, we used coarse 5 km resolution datasets (Jones et al 2009; Raupach et al 2009, 2011) across the sample area (Fig. 1). Average 30-year rainfall and temperature estimates were both found to be related to the likelihood of dieback occurring following the extreme weather event. Trees were found more likely to have suffered crown dieback in areas receiving generally more rainfall and being warmer on average compared to the surrounding landscape. A higher physiological resilience of trees that established on drier locations, found for instance for *Eucalyptus microtheca* by Li et al (2000), and water deficits being reached more quickly on warmer sites might be possible explanations for this higher incidence of dieback in relation to the drought and heating events of 2010/11. However, caution should be used in interpreting these results particularly for temperature. Estimation errors for the AWAP dataset were calculated to be ranging between 0.7 - 1.0 °C for temperature and between 19.6-21.2 mm for rainfall (Jones et al 2009). The significant difference of only 0.4 °C found between affected and unaffected sites (Table 3) lies well within the error range, which might have influenced the direction of the relationship found. For rainfall, however, the relationship (difference 38.9 mm, Table 3) is likely to be more robust. We suggest that a remote-sensing approach using a larger sample and study area could be used to investigate these relationships further.

Forests of the NJF have established under a climatic regime with characteristic seasonal periods of prolonged drought (Gentilli 1989). The endemic trees are generally considered well adapted to these seasonal drought conditions, utilising water from the lower clays below the lateritic duricrust using sinker roots (Abbott et al 1989; Dell and Havel 1989; Schofield et al 1989). The extent and the severity of this dieback event might be an early warning sign for the changes that may take place in the NJF in the future. The observed and projected warming and declines in rainfall in SWWA (CSIRO and BOM 2007; Bates et al 2008), and the associated drop in groundwater levels for the NJF (Kinal and Stoneman 2011) could compromise the resilience of the vegetation in this forest ecosystem. Various tree species endemic to the southwest have increasingly shown phases of decline (Hooper and Sivasithamparam 2005; Cai et al 2010), which might have been, at least partly, the result of these climatic trends. The addition of a higher frequency in extreme weather events such as experienced in 2010/11 might be accelerating the negative effects of climate change and could result in significant vegetation shifts (Scheffer et al. 2001), which might already be happening in the NJF and in other Mediterranean regions (Allen et al 2010).

The climate trends, more frequent extreme weather events, and the dieback responses observed in SWWA are very similar to global trends (e.g. Allen et al. 2010, Carnicer et al. 2011). These analogues make the results of this study potentially transferable to other areas. This study has provided a first step in identifying areas where the forest has the highest probability of shifting under the current changing climate; although more detailed work needs to be undertaken (Matusick et al submitted). The qualitative soil and vegetation maps available for the southwest (Table 1) can be used in combination with the model and values derived from the quantitative maps (Equation 1, Table 4) as a starting point to further develop tools that can help identify or predict areas that are most likely to undergo changes in the future. In order to effectively target conservation actions and facilitate the development of adaptive management plans in the face of climate change (Lindner et al 2010), we suggest that more broad-scale landscape assessments are needed for identifying potential high-risk areas within the landscape for subsequent timely implementation of climate change adaptation strategies. The results of this study can be used as a starting point in doing so.

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Table 1 Data and variables that were used in the landscape-scale assessment of tree crown dieback following extreme weather conditions in the Northern Jarrah Forest (NJF), Western Australia.

Data description	Variable computed for the analyses	Values/Categories	Details of parent dataset used
Native vegetation	Native vegetation extent for the NJF	One category	Native vegetation current extent, 2010, DAF, WA
Topographic position	Elevation	Meters (m)	Digital Elevation Model, 10m res, South West basins, 2008, Landgate/CSIRO, WA
	Slope	Degrees (°)	Digital Elevation Model, 10m res, South West basins, 2008, Landgate/CSIRO, WA
	Aspect	North, East, South, West	Digital Elevation Model, 10m res, South West basins, 2008, Landgate/CSIRO, WA
	Slope position	six classes	Digital Elevation Model using Land Facet Corridor Tools (see Jenness et al 2011)
	Distance to valley	Meters (m)	Digital Elevation Model, 10m res, South West basins, 2008, Landgate/CSIRO, WA
	Distance to ridge	Meters (m)	Digital Elevation Model, 10m res, South West basins, 2008, Landgate/CSIRO, WA
	Distance to rock	Meters (m)	Rocky outcrop, 2002, DEC, WA
	Distance to drainage	Meters (m)	Hydrography, 2001, DEC, WA
Vegetation classes	Vegetation class	Multiple categories	RFA Vegetation Complexes, 2006, DEC, WA
Geology	Soil type	Multiple categories	Soil-landscape mapping South-Western Australia, 2008, DAF, WA
Fire history	Time since last fire	1- 5, 6-10, 11-15, 15-20, >20 years	Fire history, June 2011, DEC, WA
Climatology	Av rainfall (1981-2010)	Millimetres (mm)	Australian Water Availability Project, 5km res, CSIRO, http://www.csiro.au/awap
	Rainfall in 2010/11	Millimetres (mm)	Australian Water Availability Project, 5km res, CSIRO, http://www.csiro.au/awap
	Av temperature (1981-2010)	Degree Celsius (°C)	Australian Water Availability Project, 5km res, CSIRO, http://www.csiro.au/awap
	Av seasonal temp (1981-2010)	Degree Celsius (°C)	Australian Water Availability Project, 5km res, CSIRO, http://www.csiro.au/awap
	Av temperature in	Degree Celsius (°C)	Australian Water Availability Project, 5km res, CSIRO,

	2010/11		http://www.csiro.au/awap
	Av seasonal temp in 2010/11	Degree Celsius (°C)	Australian Water Availability Project, 5km res, CSIRO, http://www.csiro.au/awap

CSIRO: Commonwealth Scientific and Industrial Research Organisation, DAF: Department of Agriculture and Food, DEC: Department of Environment and Conservation, WA: Western Australia, Australia, Av: Average, Distance: Euclidean nearest neighbour distance.

Table 2 Chi-square test for the occurrence of affected and unaffected sites on the five main soil types of the NJF as represented in the sample area.

Chi-square test	A	U	X^2	P
Dwellingup subsystem	62	47	2.344	0.126
Yarragil subsystem	16	22	0.716	0.397
Murray subsystem	18	14	0.302	0.583
Yalanbee subsystem	0	6	na	na
Dwellingup 2 phase	26	19	0.885	0.347

2-sample test for equality of proportions with continuity correction using n = 234 for affected (A) and n = 234 for unaffected (U) sites. na = Sample size too small/unbalanced

Table 3 Factors associated with canopy dieback affected (A) and unaffected (U) sites following a drought and heating event in 2010/2011 in the NJF.

Mann-Whitney-Wilcoxon	Range A		Range U		Med A	Med U	W	*P*
Elevation (m)	104.2	472.6	135.1	437.9	299.7	288.7	23529	0.009
Slope (°)	0.8	25.2	0.0	21.2	5.0	4.3	23164	0.004
Distance to rock (m)	7.9	4199.8	28.8	11499.4	456.6	1076.1	36389	<0.001
Distance to ridge (m)	0.0	1890.3	0.0	2542.7	393.9	556.2	32249	0.001
Av rainfall (1981-2010) (mm)	739.8	1102.5	731.2	1102.1	997.8	958.9	20359	<0.001
Av temperature (1981-2010) (°C)	15.8	17.4	15.6	17.9	16.6	16.2	24084	0.024

Range/Med U/A: Range and Median values for the affected (A) and unaffected (U) sites, Distance: Euclidean nearest neighbour, Av: average based on 30-years of data, *n* = 468

Table 4 Logistic regression models including factors associated with the canopy dieback observed in the NJF.

Model $y(x_i)$	β_i	S.E. β_i	z	P	Odds	C.I.		AIC$_c$	R^2
Distance to rock (m)	-0.0005	0.0001	-4.576	<0.001	0.9995	0.9993	0.9997	565.1	0.15
Av rainfall (1981-2010) (mm)	0.0073	0.0012	6.049	<0.001	1.0073	1.0049	1.0097		
Elevation (m)	0.0097	0.0024	4.002	<0.001	1.0098	1.0050	1.0146		
Slope (°)	0.0855	0.0272	3.141	0.002	1.0893	1.0327	1.1490		
Av temperature (1981-2010) (°C)	0.7131	0.2419	2.948	0.003	2.0403	1.2700	3.2778		
Intercept (β_0)	-21.5700	4.6140	-4.675	<0.001					
Distance to rock (m)	-0.0005	0.0001	-4.833	<0.001	0.9995	0.9993	0.9997	572.0	0.13
Av rainfall (1981-2010) (mm)	0.0068	0.0012	5.691	<0.001	1.0068	1.0045	1.0092		
Elevation (m)	0.0084	0.0024	3.583	<0.001	1.0085	1.0038	1.0131		
Slope (°)	0.0681	0.0263	2.592	0.010	1.0705	1.0167	1.1271		
Intercept (β_0)	-8.8271	1.4590	-6.050	<0.001					
Distance to rock (m)	-0.0006	0.0001	-5.483	<0.001	0.9994	0.9992	0.9996	577.1	0.12
Av rainfall (1981-2010) (mm)	0.0072	0.0012	6.092	<0.001	1.0072	1.0049	1.0096		
Elevation (m)	0.0060	0.0021	2.878	0.004	1.0060	1.0019	1.0101		
Intercept (β_0)	-8.0371	1.4037	-5.726	<0.001					
Distance to rock (m)	-0.0006	0.0001	-5.631	<0.001	0.9994	0.9992	0.9996	583.6	0.11
Av rainfall (1981-2010) (mm)	0.0065	0.0011	5.753	<0.001	1.0065	1.0043	1.0087		
Intercept (β_0)	-5.5894	1.0717	-5.215	<0.001					
Distance to rock (m)	-0.0005	0.0001	-5.031	<0.001	0.9995	0.9993	0.9997	617.6	0.05
Intercept (β_0)	0.5416	0.1376	3.936	<0.001					

Model $y(x_i)$: shows the variables and intercept included in the logistic regression model. β_i: indicates the slope and direction of the relationship for the individual variables with canopy dieback. S.E. β_i: Standard Error for β_i. Odds: indicates the odds ratio for dieback to take place for every unit increase of the variable. C.I.: 95% confidence interval for the Odds ratio. AIC$_c$: corrected Akaike Information Criterion indicating the model explaining most of the variability (i.e. lowest value is best). R^2: quantifies the explained variation by the model (range 0-1). Models presented passed all goodness-of-fit tests and assumptions following Logan (2010). $n = 468$

Fig. 1 The inserted world map indicates regions (black highlights) across the globe with similar Mediterranean climate characteristics (Csa and Csb, following Peel et al 2007) as for the study area (black square). The thick black line indicates the extent of the area that was surveyed during the flight (i.e. survey area) over the remaining native vegetation in the Northern Jarrah Forest (NJF) (dark grey) and the surrounding regions (light grey) lying within the urban and agricultural matrix (white) of the southwest of Western Australia (SWWA).

Fig. 2 Predicted probability curve for canopy dieback following the 2010/11 extreme weather events in the NJF based on distance to the nearest rock outcrop alone (a) and with 30-year average rainfall (b) as landscape indicators (see also Table 4). In (a) solid dots on level 1 and 0 indicate the value distribution for affected and unaffected sites respectively, and dotted curves indicate the 95% confidence interval.

535 Fig. 1

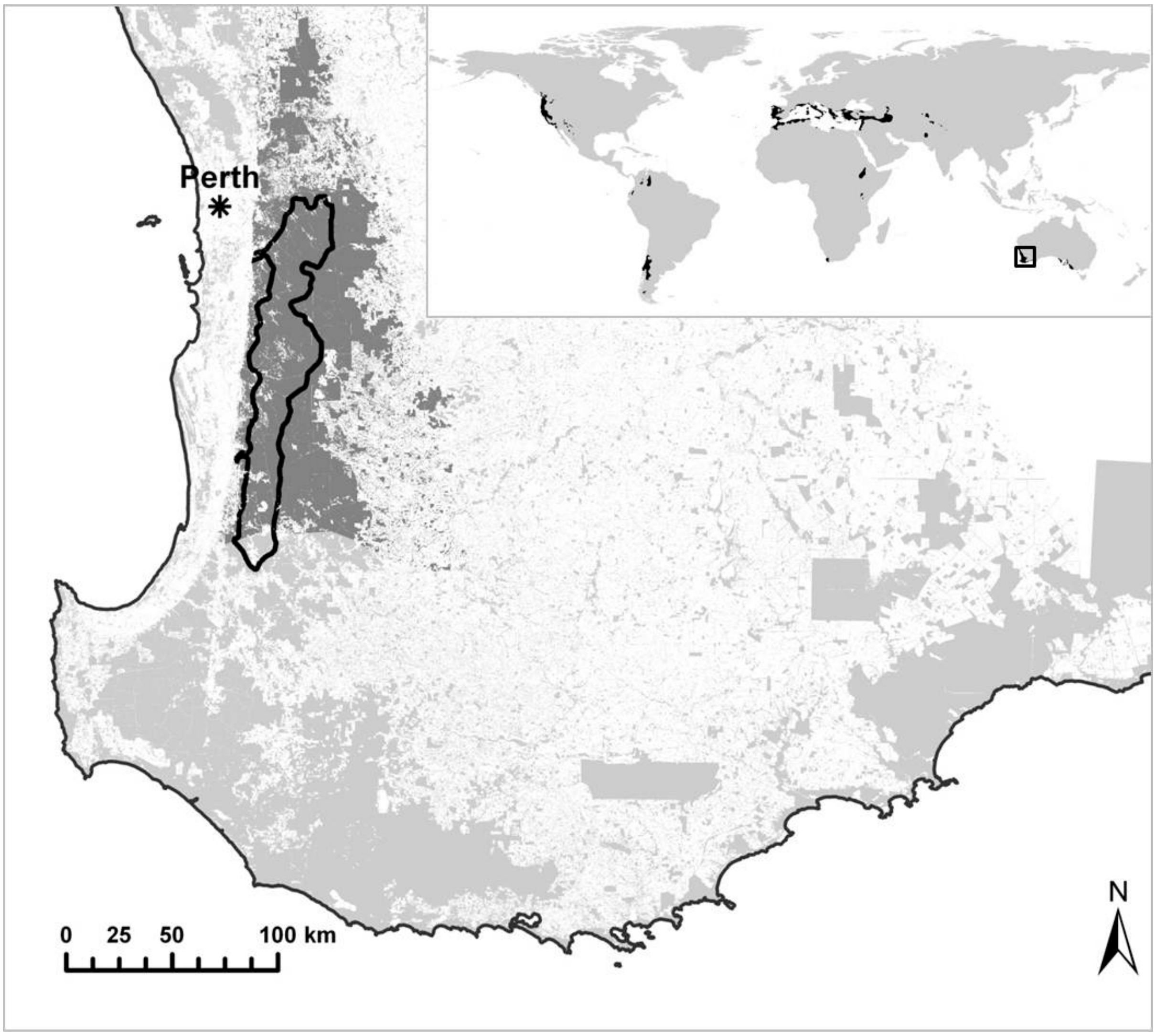
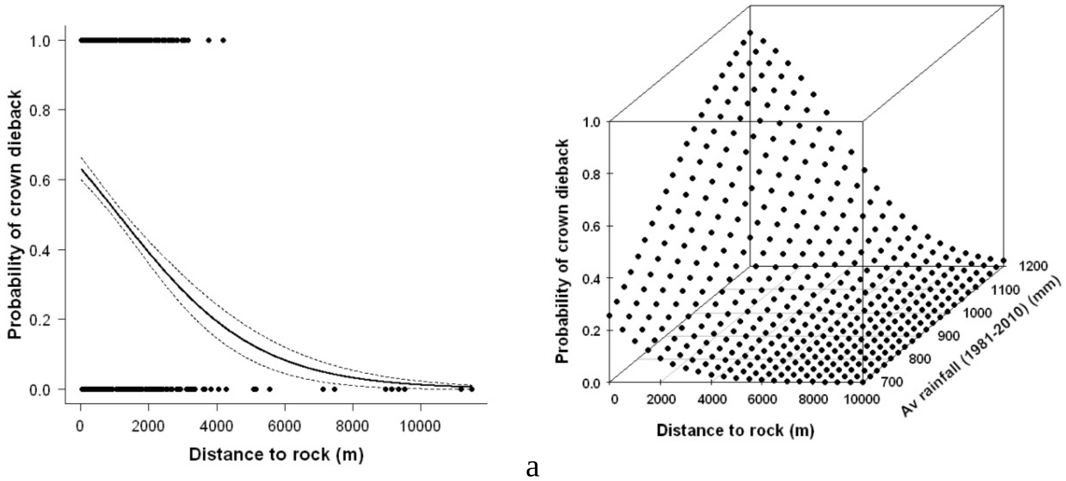


Fig. 2


Probability of crown dieback
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
Distance to rock (m)
Probability of crown dieback
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
Distance to rock (m)
700
800
900
1000
1100
1200
Av rainfall (1981-2010) (mm)

a b

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