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# Chronic historical drought legacy exacerbates tree mortality and crown dieback during acute heatwave-compounded drought

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## Environmental Research Letters



## LETTER

## Chronic historical drought legacy exacerbates tree mortality and crown dieback during acute heatwave-compounded drought

## OPEN ACCESS

## RECEIVED

29 June 2018

## REVISED

1 August 2018

## ACCEPTED FOR PUBLICATION

8 August 2018

## PUBLISHED

3 September 2018

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**Keywords:** global-change-type drought, compound events, heatwave, warming, die-off, Eucalyptus, Mediterranean

Supplementary material for this article is available [online](#)

### Abstract

Globally, combinations of drought and warming are driving widespread tree mortality and crown dieback. Yet thresholds triggering either tree mortality or crown dieback remain uncertain, particularly with respect to two issues: (i) the degree to which heat waves, as an *acute* stress, can trigger mortality, and (ii) the degree to which *chronic* historical drought can have legacy effects on these processes. Using forest study sites in southwestern Australia that experienced dieback associated with a short-term drought with a heatwave (heatwave-compounded drought) in 2011 and span a gradient in long-term precipitation (LTP) change, we examined the potential for chronic historical drought to amplify tree mortality or crown dieback during a heatwave-compounded drought event for the dominant overstory species *Eucalyptus marginata* and *Corymbia calophylla*. We show pronounced legacy effects associated with chronically reduced LTP (1951–1980 versus 1981–2010) at the tree level in both study species. When comparing areas experiencing 7.0% and 11.5% decline in LTP, the probability of tree mortality increased from low (<0.10) to high (>0.55) in both species, and probability of crown dieback increased from high (0.74) to nearly complete (0.96) in *E. marginata*. Results from beta regression analysis at the stand-level confirmed tree-level results, illustrating a significant inverse relationship between LTP reduction and either tree mortality ( $F = 10.39$ ,  $P = 0.0073$ ) or dieback ( $F = 54.72$ ,  $P < 0.0001$ ). Our findings quantify chronic climate legacy effects during a well-documented tree mortality and crown dieback event that is specifically associated with an heatwave-compounded drought. Our results highlight how insights into both acute heatwave-compounded drought effects and chronic drought legacies need to be integrated into assessments of how drought and warming together trigger broad-scale tree mortality and crown dieback events.

### Introduction

Compound climate events, including the combination of drought and atmospheric warming, are recognized as an important driver of widespread tree mortality events worldwide (Breshears *et al* 2013, Mitchell *et al* 2014, Allen *et al* 2015), and have implications for tree species distributions, forest composition, structure, and functioning (Mathys *et al* 2016). Severe droughts, with and without warming, have resulted in

several high-profile tree mortality events worldwide (Allen *et al* 2010), highlighting the need to understand the climate conditions and thresholds necessary to trigger such events.

Climatological drought and warming events are categorized in a variety of ways based on their duration, frequency, and intensity, and these have varying effects on trees and forests (McDowell *et al* 2008, Barbeta and Peñuelas 2016). Chronic water stress commonly increases background mortality rates in

tree populations (Pangle *et al* 2015, Berdanier and Clark 2016), and incites tree decline (Bigler *et al* 2006), especially when opportunistic pests and pathogens are present (Hart *et al* 2014). In contrast, short-term drying and heating events, such as acute drought and heat waves, cause severe acute water stress in trees, typified by rapid loss of stem conductivity and leaf turgor (Anderegg *et al* 2014, Bader *et al* 2014), leading to tree crown dieback, tree mortality, and widespread forest mortality in severe cases (Anderegg *et al* 2015). Of particular interest, however, are the interacting and compounded effects of *chronic* and *acute* drought and heat events on trees and forests, since both climatic averages and extreme events are predicted to change for many areas of the world over the coming decades (Collins *et al* 2013).

Under future climate scenarios, increasing average atmospheric temperatures (chronic warming) are expected to produce more intense, and more frequent acute heatwave events (Meehl and Tebaldi 2004), and are predicted to drive widespread tree mortality (McDowell *et al* 2015). To date, most research has focused on the effects of individual drought events on tree mortality. More recently, the important interaction between drought and heat has been identified as a driver of forest change (Adams *et al* 2009, Breshears *et al* 2013, Allen *et al* 2015). Efforts to distinguish between different types of warming, including chronic and acute warming, and their respective effects on trees and forests, are largely missing from the literature. A steady increase in anthropogenic warming (chronic warming) is now expected to amplify water stress, even in the absence of significant changes to precipitation, and lead to forest die-off (Williams *et al* 2012, McDowell *et al* 2015). Research investigating the effects of heat waves (i.e. acute warming) on trees is at its infancy. Heat waves have been shown to negatively affect the growth of trees (Pichler and Oberhuber 2007), and have sometimes occurred concurrently with observations tracking tree mortality (Matusick *et al* 2012, Bader *et al* 2014, Mitchell *et al* 2014). The resilience of trees to the primary and secondary effects of heat waves is not well understood, especially when combined with drought (Teskey *et al* 2015).

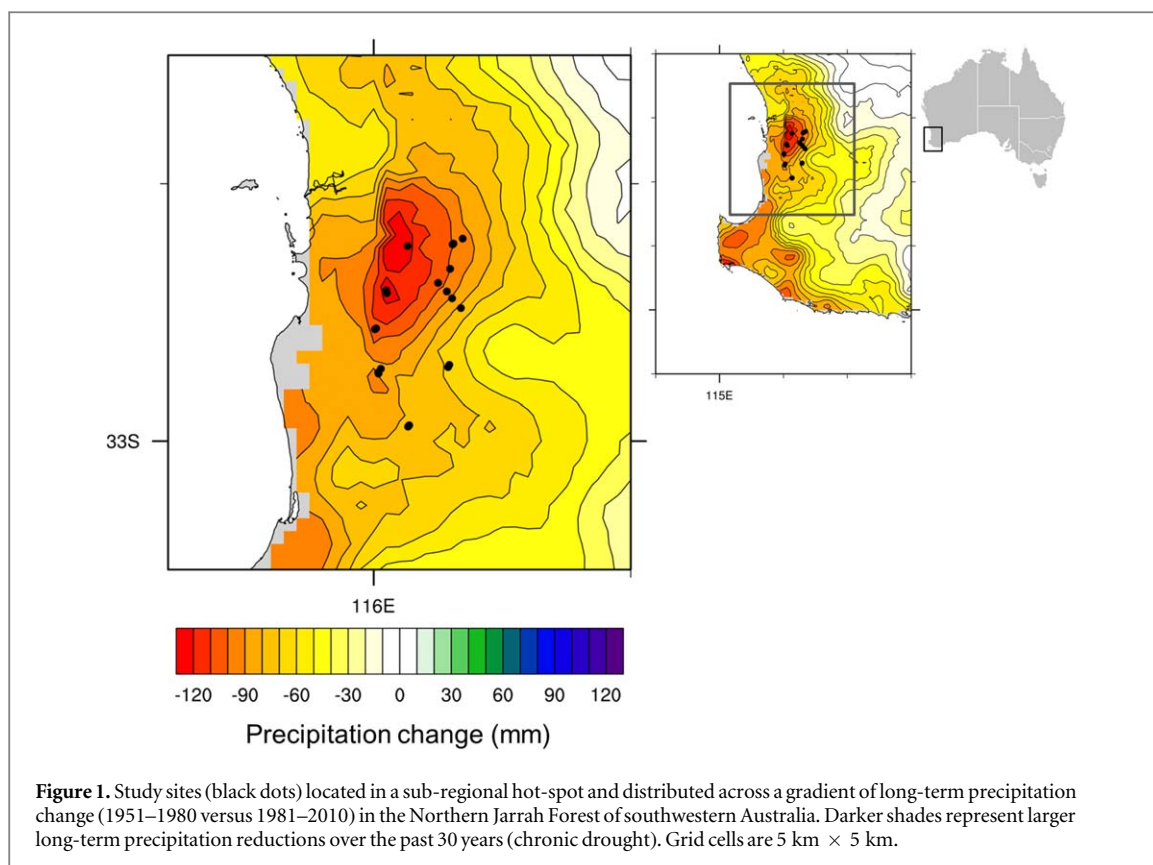
Several studies have shown the combined effects of chronic and acute drought conditions on trees, and that the response of trees to an acute drought, is partially determined by historical precipitation (Heres *et al* 2014, Macalady and Bugmann 2014, Barbeta *et al* 2015, Young *et al* 2017, Liu *et al* 2018). It remains unclear, however, whether the magnitude of chronic drought affects tree and forest responses to acute heatwave and drought events. Shifts in precipitation patterns with climate change are likely to be highly variable within a region, and therefore the magnitude of chronic drought experienced by trees is likely to vary. To examine the interactions between chronic drought and acute heatwave-compounded drought on

trees, we used a series of forest sites that experienced significant dieback triggered by a heatwave-compounded drought event and fall across a gradient of chronic drought in the Mediterranean-climate region of southwestern Australia. This region has experienced a significant reduction in precipitation in the past 40 years and experienced an acute heatwave-compounded drought event in 2011, making it an ideal location for examining the effects of compounded forest stress. A variety of previous studies in the region have examined sites affected and unaffected by drought in order to determine which factors predispose trees and forest patches to mortality and dieback (Matusick *et al* 2012, Brouwers *et al* 2013, Matusick *et al* 2013, and Challis *et al* 2016). Forest sites prone to dieback during drought included those that are water-shedding (Matusick *et al* 2012), at high landscape positions (Challis *et al* 2016), with shallow, rocky soils close to rock outcrops, on steep slopes (Brouwers *et al* 2013), and more densely stocked (Matusick *et al* 2013). In this work, we use only areas that experienced high mortality from drought to examine whether long-term drought and heat stress contributed to canopy loss during the 2011 heatwave-compounded drought event. Specifically, we sought to answer the following questions: (1) does chronic drought exacerbate tree mortality (i.e. death of aboveground structures) and crown dieback (i.e. partial death of tree crown) when triggered by an acute heatwave-compounded drought event, and (2) how does heatwave-triggered tree mortality and crown dieback vary along a gradient of chronic drought?

## Methods

The Mediterranean-type climate of southwestern Australia is characterized by long, dry summer periods followed by cool, wet winters, with nearly 80% of rainfall occurring from April to October (southern hemisphere autumn to spring) (Bates *et al* 2008). The region has experienced a significant shift in annual rainfall since the 1970s. The greatest precipitation reduction has occurred during the winter months, with winter declines ranging from 30% to 50% from 1969 to 2012 for most of the region (Indian Ocean Climate Initiative 2012). Regional climate projections for the southwest region show a continued, consistent reduction in winter rainfall and overall warming over the coming decades (Andrys *et al* 2017). In 2010, southwestern Australia experienced its driest winter in recorded history (42% below the long-term average, Cai *et al* 2011), which was followed by the hottest year on record in 2011, driven by a series of intense heat waves (Bureau of Meteorology 2012).

The study takes place on twenty study sites in the Northern Jarrah Forest, southwestern Australia, which were severely affected (>70% canopy dieback) by heatwave-compounded drought in 2011 and



randomly selected for field sampling (figure 1) from a population of sites identified during an aerial survey in May 2011 (~three months following the onset of damage) (see Matusick *et al* 2013 for methods pertaining to the aerial survey, site selection, and site delineation) (see supplemental material for detailed description of the disturbance event is available online at [stacks.iop.org/ERL/13/095002/mmedia](http://stacks.iop.org/ERL/13/095002/mmedia)). Within this severely affected forest, three points were randomly selected on a 20 m × 20 m grid using fGIS forestry cruise software (Wisconsin DNR-Division of Forestry), and were used as centers of 6 m fixed radius plots (0.011 ha). The network of study sites is considered a representative sample of drought-susceptible forest, and sites are generally located at similar elevations, landscape positions, and have similar edaphic properties (supplemental material, table S1).

During May/June 2011, each site and plot was visited and all trees greater than 1 cm diameter at breast height (DBH) were identified to species level, and measured for height and DBH using standard forestry methods. Each tree was also categorized by its crown condition into one of four classes, including healthy, dying, recently killed, and long dead (see Matusick *et al* 2013 for a more detailed description). Study sites were re-measured in April 2015 (49 months following the onset of damage) using identical methods to the first survey with the exception that only trees greater than 10 cm DBH in 2011 were re-identified, since many of the smaller diameter stems affected by the drought had fallen. Tree mortality was defined as those

trees considered dead (no living tissue above 1.3 m) in the second survey that were alive pre-drought. Crown dieback was defined as those trees showing crown effects in 2011 and having living foliage during the second survey.

Potential climate predictors of tree mortality and crown dieback were either extracted directly or derived from the Australian Water Availability Project (AWAP), 5 km × 5 km resolution gridded spatial dataset, which was developed by interpolating historical empirical data from climate stations throughout the Australian continent (Jones *et al* 2009, Raupach *et al* 2009). The AWAP dataset includes daily maximum and minimum temperature, daily precipitation available from the 1910s to present, and 0900 local standard time daily vapor pressure, available from the 1970s to present. It is one of the most widely used gridded observational climate products in Australia, and has been used for numerous studies concerning heat waves, drought (e.g. Gallant *et al* 2013, Lewis and Karoly 2013), and the evaluation of regional climate models (e.g. Andrys *et al* 2015, Kala *et al* 2015).

Potential climate predictors derived from the AWAP dataset examined in this study included precipitation, average annual temperature, average austral summer temperature (December–February), the 12 month Standardized Precipitation Index (SPI) (derived from daily precipitation), and the 12 month Standardized Precipitation Evapotranspiration Index (SPEI) (derived from daily precipitation and temperature) (see supplemental material for additional

**Table 1.** Independent variables considered in logistic regression models, including select summary statistics for 20 sites in the Northern Jarrah Forest of southwestern Australia experiencing tree mortality and crown dieback triggered by a heatwave-compounded drought.

Variable	Level	Range	Mean	Median
Pre-drought diameter (DBH) (cm)	Tree	10.0–105.1	22.0	17.0
Plot density (DEN) (trees ha <sup>-1</sup> )	Plot	91–1273	636	636
Plot basal area (BA) (m <sup>2</sup> ha <sup>-1</sup> )	Plot	6.0–154.6	37.2	31.6
LT <sup>a</sup> SPI <sup>b</sup> change (LTSPI) (%)	Site	–170.3 to –153.9	–162.7	–163.5
ST <sup>c</sup> SPI change (STSPI) (%)	Site	–2502.2 to –4973.3	–3217.2	–3119.0
LT SPEI <sup>d</sup> change (LTSPEI) (%)	Site	–160.9 to –148.4	–153.8	–153.3
ST SPEI change (STSPEI) (%)	Site	–2729.9 to –1778.1	–2068.5	–2049.4
LT precipitation change (LTP) (%)	Site	–10.9 to –7.2	–9.2	–9.7
ST precipitation change (STP) (%)	Site	–49.9 to –46.6	–48.5	–48.7
LT summer temperature change (LTST) (%)	Site	0.1–0.5	0.8	0.8
ST summer temperature change (STST) (%)	Site	5.3–5.7	5.6	5.5
LT annual temperature change (LTAT) (%)	Site	2.6–3.2	2.9	2.9
ST annual temperature change (STAT) (%)	Site	3.5–4.4	4.1	4.2

<sup>a</sup> Long-term change (1951–1980 versus 1981–2010).

<sup>b</sup> Standardized Precipitation Index.

<sup>c</sup> Short-term change (2010 versus 1951–2010).

<sup>d</sup> Standardized Precipitation Evapotranspiration Index.

details). The climate variables were selected to represent water supply (precipitation, SPI) and atmospheric water demand (temperature, SPEI); the two drivers of widespread tree mortality and crown dieback (Breshers *et al* 2013). For each potential predictor variable (e.g. precipitation, temperature, SPI, SPEI), long- and short-term changes were calculated. The long-term change for each predictor variable was defined as the difference in the 30 year mean prior to, and following 1980 (1951–1980 versus 1981–2010) and placed on a percent scale (see supplemental material for rationale). To represent the short-term climate conditions, the proportional change in 2010 versus the long-term average (1951–2010) was calculated for each predictor.

To assess which climate variables were suitable predictors of tree mortality and crown dieback, we performed analyses at both the tree- and stand (population)-levels. Since a previous tree-level analysis, 16 months following the event, showed the two dominant overstory species, *E. marginata* and *C. calophylla* responded differently shortly following the 2011 heatwave-compounded drought event (Ruthrof *et al* 2015), the species were analyzed separately for tree-level analysis here. However, the species were combined for stand-level analyses since (1) stand-level results reported after 49 months showed that species composition did not change (Matusick *et al* 2016), and (2) *C. calophylla* represented <20% of the overstory trees, and was found on only ~60% of the plots (Matusick *et al* 2013). At the tree-level, we assessed the ability for independent variables (table 1) to predict tree mortality and tree crown dieback using a multilevel, binary logistic regression modeling approach. Since the climate predictor variables included in the final logistic models were predominately restricted to long-term changes, the influence of short-term climate change variables (the effect of 2010) on tree mortality and dieback was examined separately using univariate binary

logistic models. At the stand-level, independent variables were assessed using beta regression analyses for proportional data (see supplementary material for additional statistical methods).

## Results

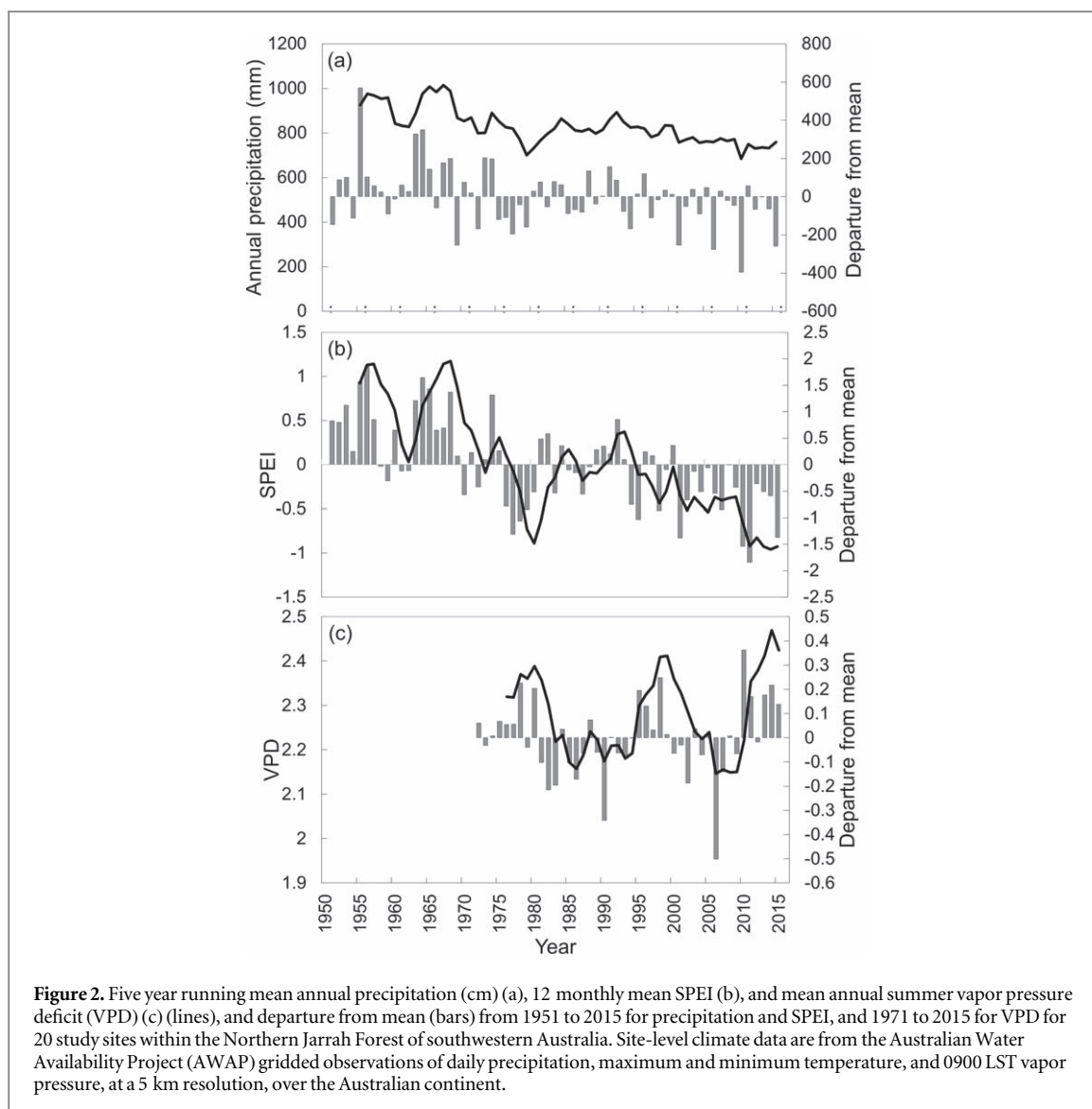
### Climate trends

A long-term reduction in precipitation since 1950 is evident across the study sites in the Northern Jarrah Forest, with the first, second, and third driest years on record occurring in 2010, 2006, and 2015, respectively (figure 2(a)). Corresponding with the drying trend, the Northern Jarrah Forest has experienced a steady decline in SPEI since 1950, including three of the four lowest values being observed since 2010 (figure 2(b)). In a shorter chronology (since 1972), the study sites have also experienced an increase in VPD since 2009, with the highest values occurring during the heat waves of 2011 (figure 2(c)).

### Tree-level

A total of 875 *E. marginata* and *C. calophylla* trees were tracked over the study. From the hierarchical cluster analysis, DBH (tree-level), DEN (plot-level), LTSPEI, STST, and LTP (site-level) had the highest correlations within and lowest correlations between clusters (table S2). Each of the selected site-level variables was independent from one another at  $P < 0.05$  from subsequent correlation analyses and therefore were eligible for inclusion in the logistic regression models (table S3). Additionally, results of correlation analysis of variables across measurement levels found each of the variables of interest are independent of one another (table S4).

Three hierarchical models (tree-level, tree-level + plot-level, tree-level + plot-level + stand-level) were

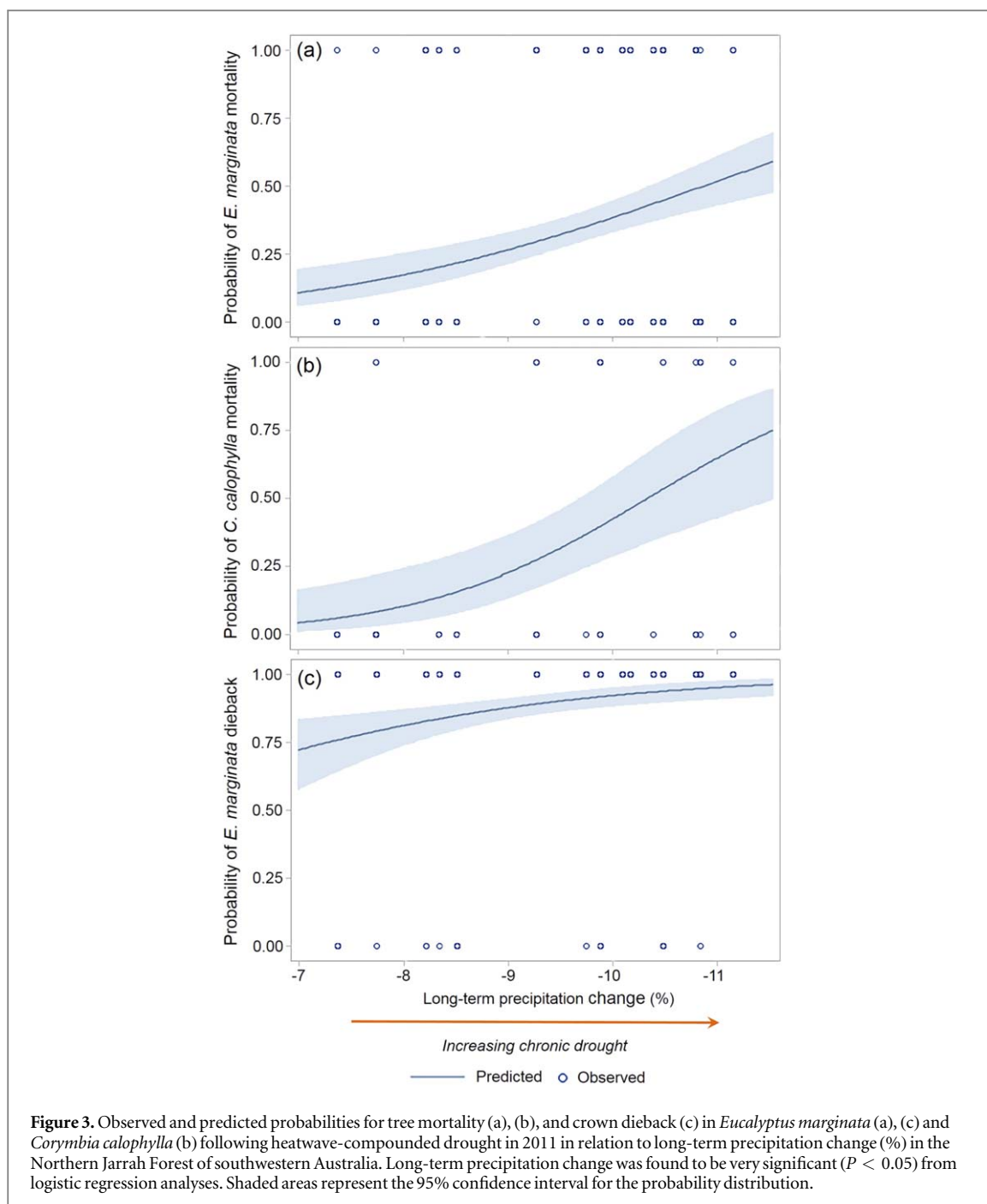


produced for each of the two dependent variables (tree mortality and crown dieback) and tree species. For species and dependent variables, the full model (tree-level + plot-level + stand-level) was selected, since each of the three nested models were significantly different from one another from Chi-square deviance tests ( $P < 0.05$ ).

Of the five predictor variables included in the logistic models, long-term precipitation change (LTP), representative of long-term drought and chronic water stress, was the only one found to be very significant at  $P < 0.05$  for *E. marginata* trees killed ( $T = -3.15$ ,  $P = 0.0018$ ) and those experiencing dieback ( $T = -2.04$ ,  $P = 0.0424$ ), and for *C. calophylla* trees killed ( $T = -2.45$ ,  $P = 0.0189$ ). However, this was not the case for *C. calophylla* experiencing dieback ( $T = -1.35$ ,  $P = 0.1857$ ). No other variables included in the models significantly explained trees killed or affected. Each of the final models has adequate discrimination based on the ROC area under the curve value (table S5). Additionally, each model passed the Standard Pearson

goodness-of-fit test, which is a conservative goodness-of-fit test (Kuss 2001). The probability of tree mortality increased with declining LTP (increasing chronic water stress) in both species, and crown dieback increased with declining LTP in *E. marginata* (figure 3). High variability was observed with respect to the mean proportion of *E. marginata* stems killed and affected by dieback, and *C. calophylla* stems experiencing dieback (figure 4). However, plot-level trends match findings from the probabilities calculated at the tree-level. Pre-drought tree density (DEN) was also moderately significant ( $P < 0.1$ ) for *C. calophylla* trees killed ( $T = 1.69$ ,  $P = 0.0981$ ), with a higher probability of mortality occurring on denser plots (figure 5).

Results from univariate binary logistic models suggests that the magnitude of the drought in 2010 (STP) had limited influence on the pattern of mortality and dieback observed 49 months post-drought in *E. marginata* and *C. calophylla* (table 2). The only short-term climate predictor that may have contributed to pattern explanation was the change in 2010 annual



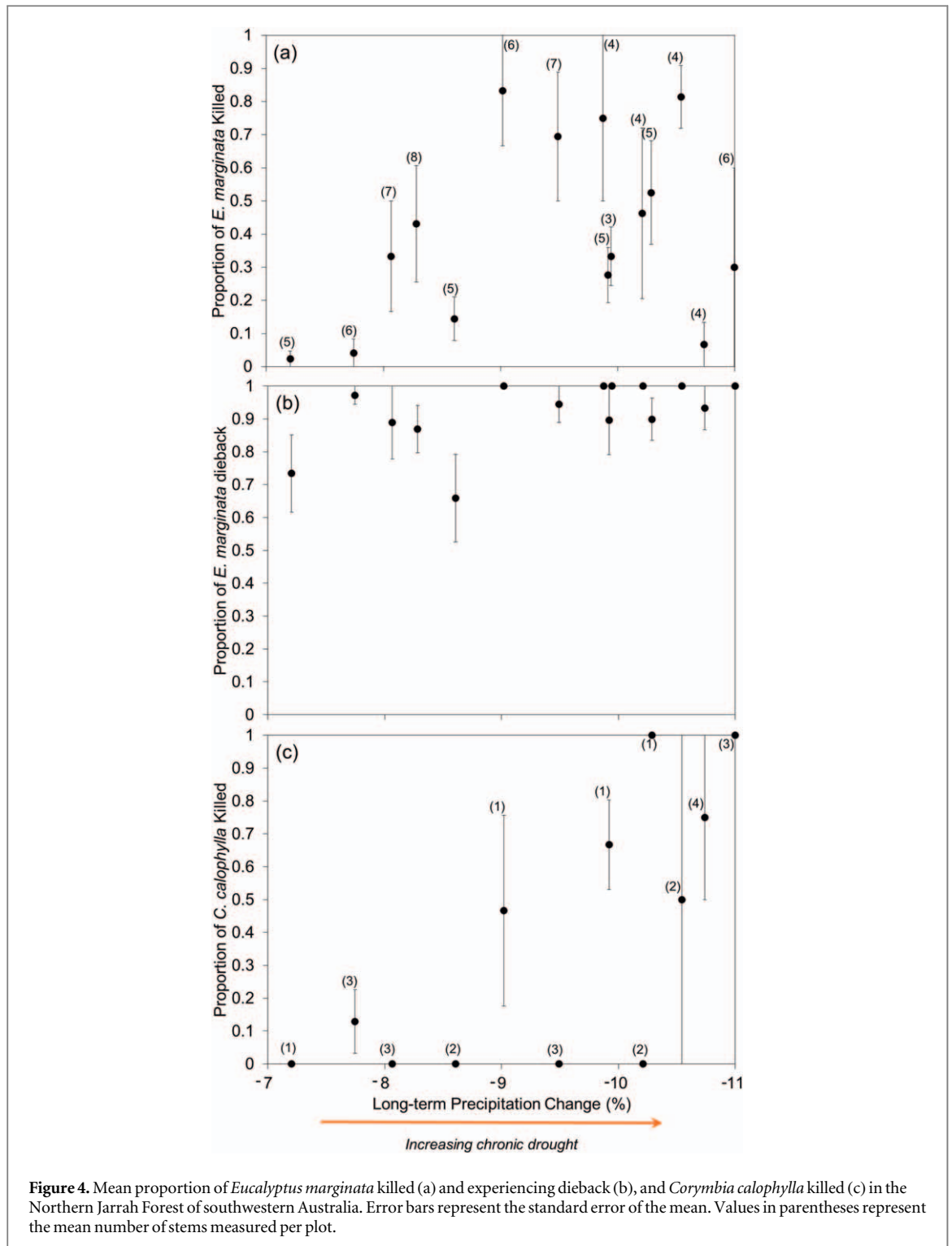
temperature compared to the long-term mean (STAT) for *C. calophylla* mortality and dieback, but not for *E. marginata*. In this case, *C. calophylla* tree mortality and dieback increased with the magnitude of 2010 annual temperature (figure 6).

#### Stand-level

From the beta regression, LTP was the only variable included in the model to contribute significantly to the pattern of stand mortality (table 3). Stand mortality increased with decreasing LTP (figure 7). Concerning stand dieback, STST, and LTP were found significant in the regression model (table 3). The proportion of canopy experiencing dieback was inversely related to LTP, and very weakly related to STST (figure 8).

#### Discussion

Our findings provide evidence that *chronic* drought conditions exacerbate tree mortality and crown dieback during an *acute* heatwave-compounded drought. A small but increasing list of studies are highlighting the important link between temperature (atmospheric moisture demand) and drought (water availability) on tree health, with most studies focusing on tree mortality occurring during drought with either no warming or an increasing temperature trend (table 4). However, climate change is also expected to cause more frequent and intense heat waves, which have largely not been considered in studies of tree mortality under drought. One explanation is that, aside from

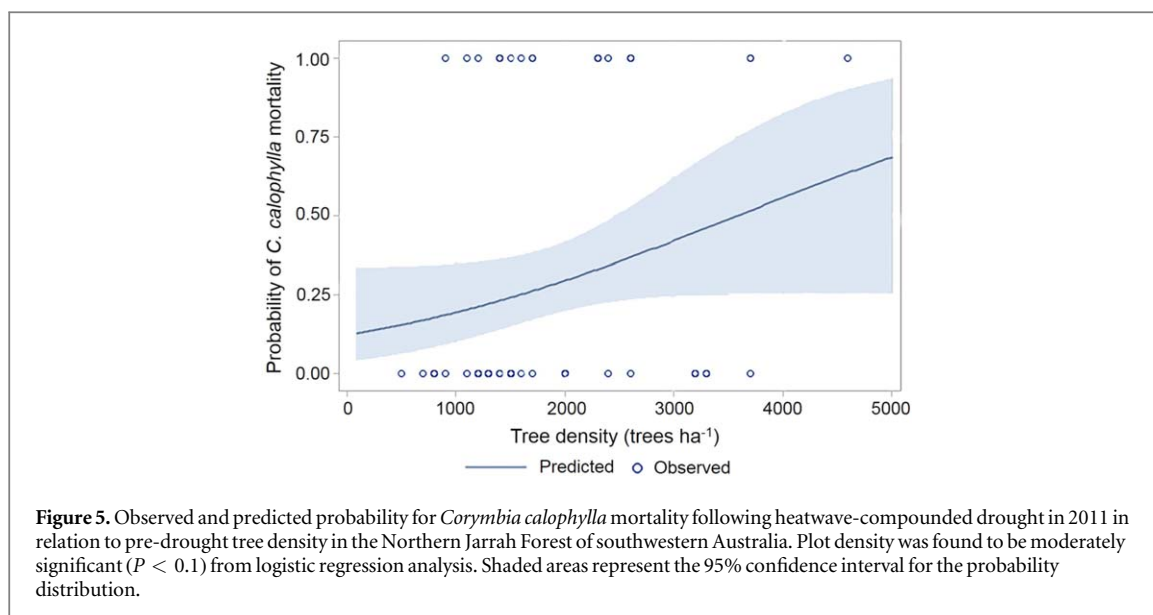


**Figure 4.** Mean proportion of *Eucalyptus marginata* killed (a) and experiencing dieback (b), and *Corymbia calophylla* killed (c) in the Northern Jarrah Forest of southwestern Australia. Error bars represent the standard error of the mean. Values in parentheses represent the mean number of stems measured per plot.

observations of rapid tree mortality associated with temperature spikes in Australia (Mitchell *et al* 2014), there has been limited evidence that heat waves have contributed to mortality events on a large-scale to date. In southwestern Australia, a heatwave-compounded drought triggered loss of stem conductivity and rapid tree mortality in multiple forest and woodland ecosystems (Matusick *et al* 2012, Matusick *et al* 2013, Bader *et al* 2015, Challis *et al* 2016). This current study uses observational data to document chronic legacy effects during one of the best-

documented tree mortality events that was triggered, in part, by a heatwave. Recently, Liu *et al* (2018) documented similar amplifying effects of chronic drought on tree mortality in a field experiment, where multiple heatwave-compounded droughts impacted their LTP exclusion experiment site. Collectively, these studies highlight the important interacting effects of chronic drought and acute heat events, both of which are expected to increase in Mediterranean and other climate regions in the coming decades (Andrjys *et al* 2017).





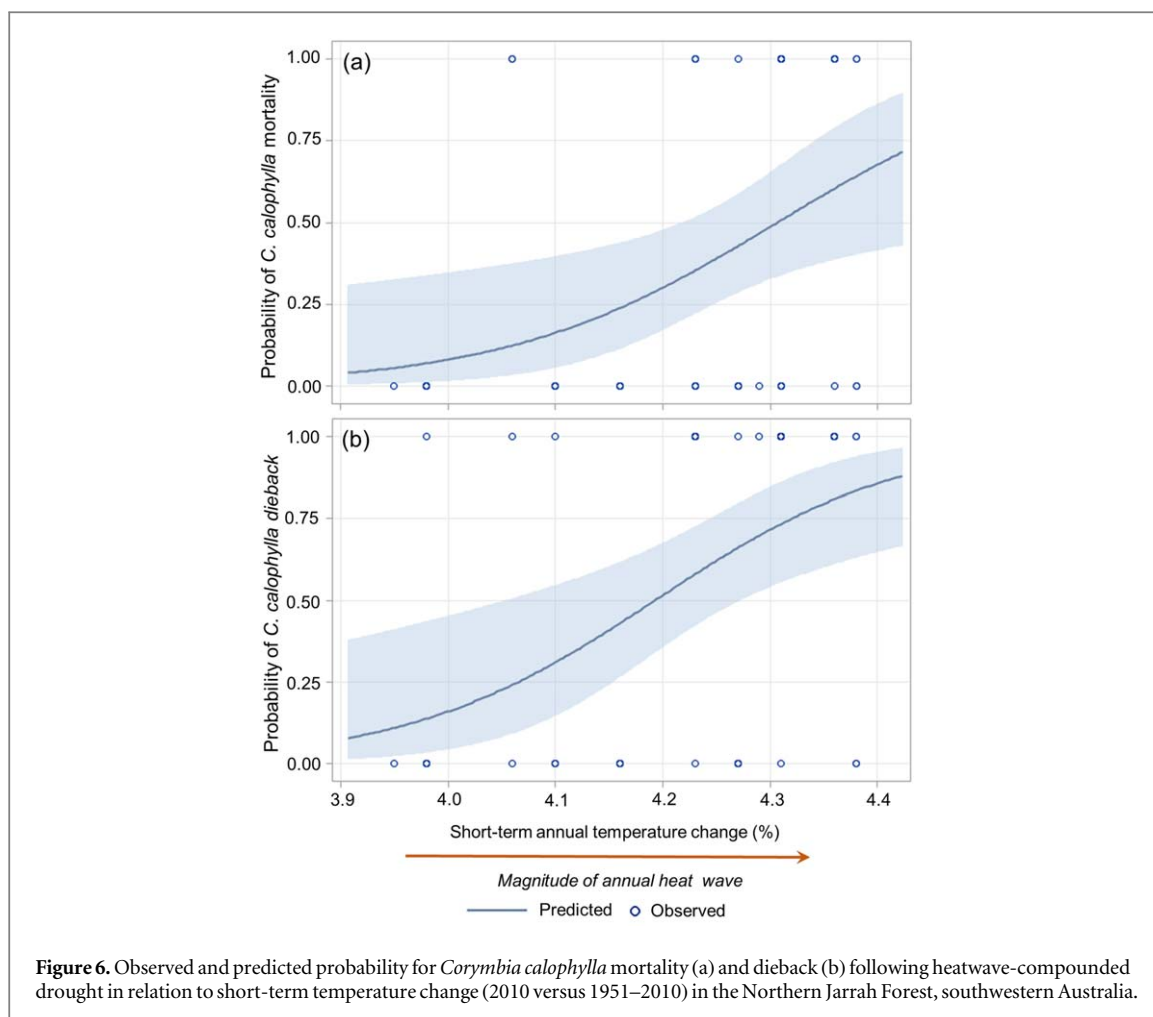
**Table 2.** Results from univariate binary logistic models examining the influence of short-term (2010 versus 1951–2010) climate change predictors on patterns of *E. marginata* and *C. calophylla* mortality and dieback in the Northern Jarrah Forest, southwestern Australia.

Dependent variable	Independent variable	Estimate	Standard error	df	T-value	P-value
<i>Eucalyptus marginata</i> mortality	STAT	177.03	184.46	237	0.96	0.3382
	STP	3.88	25.92	237	0.15	0.8810
	STSPI	-0.06	0.09	238	-0.67	0.5031
	STSPEI	-0.08	0.18	238	-0.46	0.6480
<i>E. marginata</i> dieback	STAT	366.52	230.26	237	1.59	0.1128
	STP	18.27	32.80	237	0.56	0.5779
	STSPI	0.10	0.11	238	0.85	0.3944
	STSPEI	0.22	0.22	238	0.97	0.3346
<i>Corymbia calophylla</i> mortality	STAT	839.76	390.31	24	2.15	0.0417
	STP	56.83	41.21	23	1.38	0.1812
	STSPI	0.18	0.14	23	1.33	0.1968
	STSPEI	0.32	0.30	24	1.06	0.2994
<i>C. calophylla</i> dieback	STAT	901.68	339.98	24	2.65	0.0140
	STP	4.13	37.85	23	0.11	0.9140
	STSPI	0.23	0.14	23	1.6	0.1239
	STSPEI	0.43	0.30	24	1.44	0.1637

A growing body of recent climatological studies examining compound climate events have shown that (1) extreme drought and heat events are correlated worldwide, and (2) their dependence gets stronger with increased atmospheric warming (Zscheischler and Seneviratne 2017), (3) the frequency of heatwave-compounded drought events are increasing (Mazdiyasi and AghaKouchak 2015), and (4) climate models predict heatwave-compounded drought events to become common by 2050 in certain regions (Sedlmeier *et al* 2018). Given these findings, even in the absence of change to precipitation patterns, atmospheric warming alone will drive more frequent and severe heatwave-compounded drought events, with significant impacts to trees ecosystems (Williams *et al* 2012). All characteristics of heat waves, including their magnitude, frequency, and duration are highly sensitive to global warming (Horton *et al* 2016). Therefore, it is very likely that forests will experience

additional future changes as concurrent heat waves and droughts drive interacting *acute* and *chronic* stress effects.

While studies highlighting the interacting effects of drought and heat waves on forests are more recent, the importance of climate legacy, including the pattern of past drought, has been recognized as an important factor regulating tree response to future drought (Anderegg *et al* 2013, Anderegg *et al* 2015, Peltier *et al* 2016). For example, experiments from a ground-water dependent Mediterranean-type forest have shown that isohydric species experience increased crown defoliation and synergistic mortality effects during acute drought if they have experienced chronic drought (Barbeta *et al* 2015, Liu *et al* 2018). Retrospective dendrochronological studies have consistently detected legacy impacts from drought on subsequent growth and mortality patterns (Heres *et al* 2014, Macalady and Bugmann 2014, Berdanier



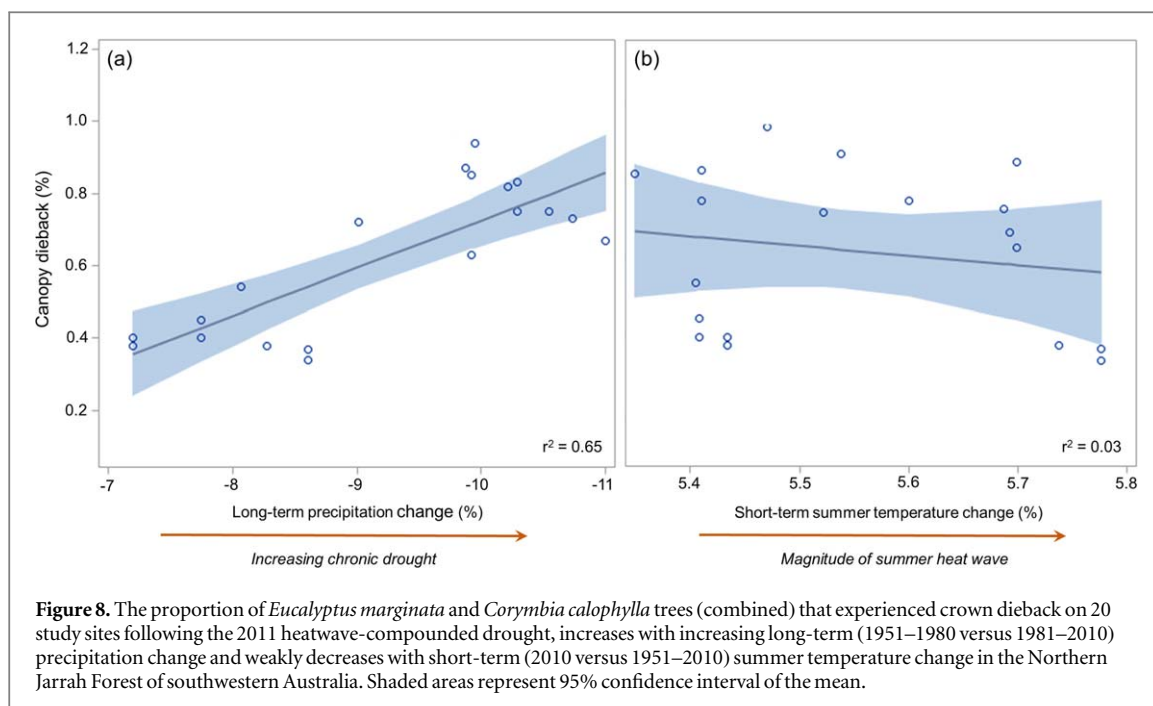
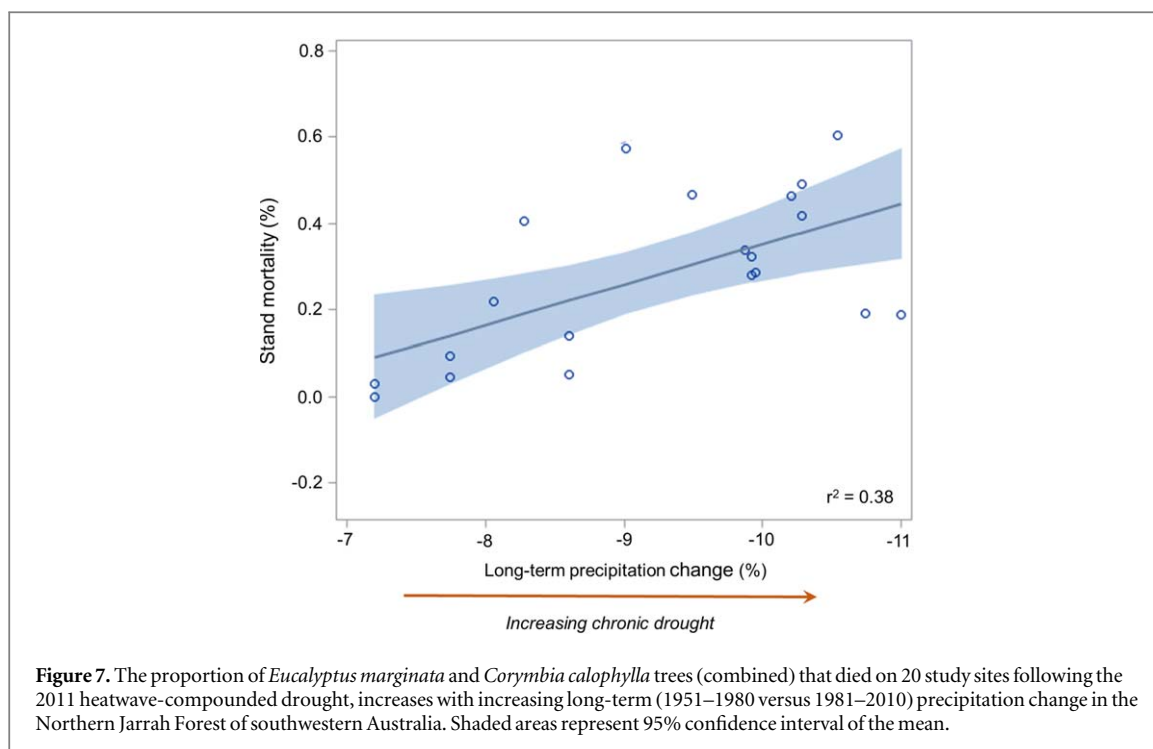
**Table 3.** Results of beta regression model examining the effects of independent variables on stand-level mortality and canopy dieback patterns 49 months following heatwave-compounded drought in the Northern Jarrah Forest, southwestern Australia.

Independent variable	Stand mortality		Canopy dieback	
	F-value	P-value	F-value	P-value
DBH	2.61	0.1322	1.42	0.2552
DEN	0.14	0.7157	0.14	0.7108
LTP	10.39	0.0073	54.72	<0.0001
LTSPEI	3.35	0.0921	1.67	0.2192
STST	1.71	0.2150	14.33	0.0023

and Clark 2016). Observational field studies are also showing that trees historically experiencing dryer conditions experience higher mortality rates during extreme drought (Anderegg *et al* 2013, Young *et al* 2017). This study adds to the growing body of literature on the topic by highlighting the *magnitude* of chronic drought as a significant factor at the landscape-scale. This factor may be particularly important in regions where strong climate change gradients are occurring, such as southwestern Australia, or regions where a single ecosystem or forest type occurs across a wide geographical area.

Although the climate legacy explanation is one that seems representative in light of our analysis, there are some possible alternative explanations for the patterns of tree mortality and crown dieback reported in this study. First, the response of highly resilient tree species to disturbance may also be dictated by the duration of stress events (van der Bolt *et al* 2018) and the post-disturbance climate, which may have varied across the sites. However, these climate factors were not considered here since the primary objective was to more broadly examine chronic and acute climate indicators. Second, land-use and land management history may influence tree mortality and crown dieback during heatwave-compounded drought. However, generally there is limited detailed information at the scale of our sites. In the absence of a comprehensive understanding of site history, the contribution of land-use and management history to forest effects from drought remains unclear. In order to explore these alternate explanations, and to make broader generalizations about drought legacies, a greater number of events and sites need to be examined.

Environmental stress periods leading to forest disturbance, acting singly, or in combination (e.g. Miao *et al* 2009), can reduce the resilience of ecosystems (Buma and Wessman 2011) and are expected to push ecosystems past critical tipping points in the future



(Laurance *et al* 2011, Reyer *et al* 2015). Ecosystems may change most rapidly and profoundly in regions experiencing compound events or multiple stress periods, occurring concurrently, or in quick succession (Allen *et al* 2015). In the Northern Jarrah Forest, and elsewhere, the combination of drought and warming has corresponded with beetle outbreaks (Seaton *et al* 2015), forest fires (Gouveia *et al* 2016), and associated widespread terrestrial carbon losses (Berner *et al* 2017). Not only do these processes have an impact on forest structure and functioning, but also the

potential to profoundly alter our future atmosphere and climate (Zemp *et al* 2017).

## Conclusions

This study highlights the important interacting effects of chronic historical drought legacies and acute heatwave-compounded drought on forest trees. Long-term precipitation change was the most significant climate predictor of tree mortality and crown dieback triggered by an acute heatwave-compounded drought

**Table 4.** Selection of example observational, experimental, and review studies that investigate the interacting effects of multiple types of warming as a catalyst for drought-induced tree mortality or dieback resulting shortly following drought (current) or from drought legacy.

Catalyst	Warming	Drought	
		Current	Legacy
None <sup>a</sup>	None <sup>a</sup>	<i>Observational:</i> Allen and Breshears (1998)	<i>Observational:</i> Anderegg <i>et al</i> (2013) Macalady and Bugmann (2014) Anderegg <i>et al</i> (2015) Berdanier and Clark (2016)
		<i>Experimental:</i> Plaut <i>et al</i> (2013) Pangle <i>et al</i> (2015)	<i>Experimental:</i> Anderegg <i>et al</i> (2013)
		Reviews: Allen <i>et al</i> (2010)	
Chronic <sup>b</sup>	Chronic <sup>b</sup>	<i>Observational:</i> Breshears <i>et al</i> (2005) Michaelian <i>et al</i> (2011) Herguido <i>et al</i> (2016)	<i>Observational:</i> Heres <i>et al</i> (2014) Peltier <i>et al</i> (2016)
		<i>Experimental:</i> Adams <i>et al</i> (2009) Duan <i>et al</i> (2014) Duan <i>et al</i> (2015)	
		Reviews: Allen <i>et al</i> (2010) Allen <i>et al</i> (2015)	
Acute Heatwave <sup>c</sup>	Acute Heatwave <sup>c</sup>	<i>Observational:</i> Matusick <i>et al</i> (2013) Bader <i>et al</i> (2014) Mitchell <i>et al</i> (2014)	<i>Observational:</i> This study
		<i>Experimental:</i> Zhao <i>et al</i> (2013) Liu <i>et al</i> (2018)	<i>Experimental:</i> Liu <i>et al</i> (2018)

<sup>a</sup> Minimal or no significant warming associated with drought.

<sup>b</sup> Long-term warming trends combined with drought.

<sup>c</sup> Short-term extreme heat event.

in the Northern Jarrah Forest. This study also illustrates a relationship between the *magnitude* of chronic drought and tree mortality and crown dieback. Forest experiencing a greater magnitude of chronic drought had lower resistance (crown dieback) and resilience (tree mortality) to the acute heatwave-compounded drought than forest experiencing less severe chronic drought. The relationships between interacting chronic and acute drought stress periods and their combined impacts on forests, such as those reported here, will, firstly, need to be integrated into assessments of how drought and warming together trigger broad-scale tree mortality and crown dieback events, and secondly, need to be incorporated into process-based and empirical models to improve predictions of how forest ecosystems will be altered with climate change into the future.

## Acknowledgments

This research was conducted as part of the Western Australian State Centre of Excellence for Climate

Change Woodland and Forest Health. D D Breshears was supported by a Sir Walter Murdoch Distinguished Collaborator award from Murdoch University, the US National Science Foundation (EF-1340649 and EF-1550756), the Consortium for Arizona-Mexico Arid Environments, and the Arizona Agriculture Experiment Station. We thank the Western Australia Department of Parks and Wildlife for providing permission to conduct the work, P Biggs (CSIRO) and M Raupach (CSIRO) for access to the Australian Water Availability Project (AWAP) datasets, and C Marbus, S Seaton, T Paap (Murdoch University), L Samuelson and J O'Donnell (Auburn University) for technical support, field assistance, and helpful comments on previous versions. The authors have no conflict of interest.

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