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LETTER

TERN, Australia’s land observatory: addressing the global challenge of forecasting ecosystem responses to climate variability and change

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Abstract

The global challenge of understanding and forecasting ecosystem responses to climate extremes and climate change is addressed in this review of research enabled through environmental research infrastructure (RI) provided by Australia’s Terrestrial Ecosystem Research Network (TERN). Two primary climatic drivers of ecosystem structure and function in Australia are fire and aridity, to which Australian flora and fauna have shown marked adaptability. Australian vegetation shows resilience to climate extremes of flooding rains, droughts and heatwaves such that variability in primary productivity of Australian vegetation has a tangible effect on the global carbon cycle. Nonetheless, Australian flora and ecosystems could be vulnerable to projected climate change (e.g. to increasing vapour pressure deficit). Refugia are also vulnerable to climate change, with conditions in these areas already near the tipping point for a change in community composition. Ensuring genetic diversity during directional change in climate (e.g. increasing aridity) requires proactive approaches to conservation and restoration projects. To address these challenges, TERN provides environmental RI at three scales of observation: (i) environmental monitoring using remote sensing techniques at a landscape and continental scale; (ii) a spatially extensive network of ecosystem monitoring plots; and (iii) intensely measured sites collecting detailed data on ecosystem processes. Through partnerships with international environmental RIs, TERN enables research that addresses global challenges, on the first steps toward the forecasting of ecosystem–climate interactions.

Introduction

As global climate change becomes more difficult to ignore, there is an urgent need to understand how terrestrial ecosystems can be expected to respond to the changes they experience. Ecosystem responses to climate change and extremes of variability include increasing drought-induced tree mortality and associated forest dieback (Allen et al 2010, Andercgg et al 2013, McDowell and Allen 2015), changing distributions of species and loss of habitat (McCallum et al 2014, Prober et al 2015), rising rates of soil heterotrophic respiration (Bond–Lamberty et al 2018), and reductions in primary productivity and soil organic
However, our understanding of ecosystem responses to climate change and variability has lagged far behind our ability to predict those responses using models. Environmental research infrastructure (RI) is required at national, regional, continental and global scales to address important environmental challenges such as the impacts of climate change, coral bleaching, biodiversity threats, geohazards and extreme events. Establishing a coherent RI across a diverse range of scientific disciplines and contributing networks is a vital challenge to solve, thus creating a goal for developing cooperation amongst environmental RI organisations, government and industry for the shared purpose of addressing global challenges.

The Terrestrial Ecosystem Research Network (TERN) is Australia’s terrestrial ecosystem observatory, providing environmental RI at three scales of observation (table 1 and figure 1): (i) ecosystem surveillance monitoring plots from which spatial

| Table 1. List of physical and data research infrastructure (RI) operated by TERN. |
|---------------------------------|----------------|---------------------------------|
| RI                              | Scale | References                        |
|---------------------------------|-------|-----------------------------------|
| Acoustic recorders              | P     | Karan et al (2016)                |
| Airborne and satellite remote sensing products | L   | Held et al (2015)                |
| Biomass¹                        | L, P  | Karan et al (2016)                |
| Data products and tools         | DS    | Beringer et al (2016)             |
| Flux towers                     | P     | Beringer et al (2016)             |
| Herbaria specimens              | S     | Tokmakoff et al (2016), Guerin et al (2017) |
| Leaf area index                 | S, P  | Macfarlane et al (2007a), Macfarlane et al (2007b) |
| Mangrove floristics             | L     | Macfarlane et al (2014)           |
| Meteorological and soil sensors | P     | Beringer et al (2016)             |
| Permanent plots                 | S     | Tokmakoff et al (2016), Guerin et al (2017) |
| Phenocams                       | L, P  | Karan et al (2016)                |
| Photopoints                     | S, P  | LeMetre et al (2017)              |
| Soil and landscape Grid of Australia | L   | Grundy et al (2015)              |
| Soil, vegetation and eDNA samples | S    | LeMetre et al (2017)              |
| Technical personnel to operate and maintain RI | All |                                    |

Note. P: Ecosystem processes; L: Landscapes; S: Ecosystem surveillance; DS: Data services and analytics.

¹ Allometric scaling from field collections of diameter at breast height, basal area, tree height, tree growth via dendrometric records.
changes in biodiversity are monitored continentally, and temporal changes over long timescales (5–10 years) (Tokmakoff et al 2016, Guerin et al 2017); (ii) ecosystem processes ‘SuperSites’ equipped with eddy covariance flux towers and from which temporal changes in ecosystem structure and function are monitored at a high level of detail in a spatially limited number of locations (Beringer et al 2016, Karan et al 2016, van Gorsel et al 2018); and (iii) landscapes, spatially distributed soil, environmental monitoring and remote sensing products at continental spatial scales (Grundy et al 2015, Mahoney et al 2016). TERN provides data infrastructure and analytic services to integrate across the three scales of observation, delivering open access to data publishing (Bissett et al 2016, Medeiros and Katz 2016, Lowe et al 2017), virtual computing facilities for data users (Guru et al 2016) and analysis-code commercialisation (Isaac et al 2017). Internationally, environmental RI observatories like TERN are joined together with international partners (e.g. the Strategic Collaboration Council, ILTER, OzFlux, NASA, FLUXNET, NEON, CERN, SAEON, ICOS) to enable research which addresses global challenges like that of ecosystem responses to climate change and variability.

In this letter, we review research across TERN’s scales of observation and through TERN’s international partners for addressing the global challenge of understanding and predicting terrestrial ecosystem responses to climate change and extreme variability. Characteristics of Australia’s sclerophyllous flora point to the ancient development of fire in shaping extensive open ecosystems (>80 Mya; Carpenter et al 2015). Development of fire has been associated with increasing aridity, for which the earliest evidence of arid-adapted vegetation appeared more than 30 Mya (Martin 2006). Ecosystem responses to fire and aridity will thus be reviewed first, followed by a review of ecosystem responses to Australia’s highly variable modern climate regime, which was more recently established (during the early Pleistocene, 2 Mya; Martin 2006). Ecosystem responses to climate extremes are further explored for each extreme, presented in sections focused upon (i) an extremely wet period which occurred since TERN’s establishment in 2009 and (ii) the dry extreme, which is associated with drought and heatwave. We will then finish with a section on ecosystem responses to climate change, the most recent of forces to affect ecosystems in Australia and globally. Examples from the literature were obtained upon review of the TERN publications catalogue (https://tern.org.au/Brochures-Publications-pg27411.html#Publications). Refer to the supplementary information, available online at stacks.iop.org/ERL/14/095004/mmedia for references from the TERN catalogue which were cited in this letter.

TERN and global cooperation

TERN was established in 2009 by the Australian government through the National Collaborative Research Infrastructure Strategy (NCRIS) to meet several objectives: to foster scientific interactions in the environmental sciences, to establish a national terrestrial site and observing network, to facilitate access to high-quality environmental data, and to provide a bridge between environmental science and policy (Thurgate et al 2017). TERN was originally developed as a network of networks, some of which were established wholly within TERN to fill gaps amongst existing networks (Thurgate et al 2017). This combined approach of joining pre-existing and new networks across the environmental space was particularly effective at avoiding duplication (Thurgate et al 2017) and thus reducing establishment costs. After expending the capital costs of establishing TERN’s continental RI, the first challenge involved reducing the scope of the RI to fit within the given operations budget whilst retaining a consistent, continental scope. Integration of TERN RI began by extensive consultation which resulted in the grouping of observational infrastructure by scale of measurement, ultimately leading to TERN’s current three scales of observation.

Integration across TERN’s three scales of observation began in the research community (Ma et al 2013, Barraza et al 2014, Bradford et al 2014, Joiner et al 2014, Mitchell et al 2014, Barraza et al 2015, Broich et al 2015). Examples of multiscale integration across TERN RI include: through remote-sensing calibration/validation activities (e.g. through NASA SMAP cal/val; Jones et al 2017), by informing model parameterisation (Haverd et al 2013) and for evaluating model predictability (Haughton et al 2018b). With endorsement from the TERN Advisory Board, TERN continues to foster increasingly close integration across three scales of measurement through regular executive group meetings which include programme leaders of RI at each scale of observation and members of TERN’s scientific advisory committee.

As the global research enterprise becomes increasingly interconnected, there is a growing need for internationalising national, regional and continental RI to serve a wider range of researchers as they join forces to tackle global challenges such as climate change, biodiversity loss, food security and infectious diseases. Growing internationalisation is facilitated by interactions with TERN’s international counterparts, which share common objectives, structure and functioning (e.g. NEON, CERN, TERENO, CZO USA). For example, TERN’s flux data are integrated into FLUXNET, a globally distributed environmental RI (Baldocchi et al 1996, Gu and Baldocchi 2002, Baldocchi 2008, Novick et al 2018) which is improving our understanding of ecosystem responses to fluctuations in environmental conditions (von Buttlar et al 2018). In addition, other
global initiatives and policy frameworks have emerged in recent years to provide global access to data products collected at local or regional scales (e.g. GEOSS, IPBES). In another example of growing internationalisation, the Global Environmental Research Infrastructure (GERI) was formed to foster cooperation amongst RIs by founding members TERN (Australia), SAEON (South Africa), CERN (China), NEON (USA) and eLTER (Europe). TERN is part of an international consortium of environmental RI organisations, with the goal of providing spatially comprehensive and integrated data streams which are model-ready and publicly available for global syntheses. See the supplemental information for further details on TERN’s international outreach activities and TERN’s twenty-year vision.

**Ecosystems and climate: fire and aridity**

An understanding of ecosystem—climate interactions is the foundation of forecasting ecosystem responses to climate change (figure 2; Beringer et al 2015), assuming that such predictability is accurate enough to be feasible (Haughton et al 2018a). Environmental RI in the form of ecological observatories provides a platform for improved understanding of how ecosystems respond to climate across a diversity of vegetation types. In Australia, 32 major vegetation types have been identified in a national vegetation information system (NVIS; https://environment.gov.au/land/native-vegetation/national-vegetation-information-system), although they can be simplified by combining similar types (e.g. arid and semi-arid *Acacia* forests, woodlands, shrublands and savannas are three major vegetation types which are all defined by a dominant canopy of Mulga *Acacia*). By example in a review of key findings from research using TERN RI at the Alice Mulga SuperSite of the Ti Tree basin, Eamus et al (2016) grouped NVIS vegetation types into forest, savanna, Mulga, shrubland, grassland and agriculture (figure 3). Across these landscapes, fire and aridity are key forces shaping ecological relationships with climate.

Bushfire is a primary attribute of the tropical wet-seasonal savannas and semi-arid grasslands of western and northern Australia, where annual fire frequencies are common across the northern tropical savanna (see figures 2 and 4). The concentration of TERN infrastructure in northern Australia at intermediate longitudes is organised around the North Australian Tropical Transect (NATT; figure 1) to support savanna research across a very large precipitation gradient (320 to >1200 mm annual precipitation; Hutley et al 2011, Cleverly et al 2013, Ma et al 2013). Heavy rainfall during the wet season at northernmost locations along the NATT is associated with a large accumulation of biomass (Hutley et al 2011), and this grassy biomass cures over the subsequent dry season that lacks rainfall, leading to the very high frequency of fire re-occurrence at the northern end of the NATT (ca. 1–2 years; figure 4). Fire is responsible for the majority of productivity losses in the northern savanna (63%), whereas large weather events such as cyclones contribute very little to the long-term net biome carbon budget (Hutley et al 2013). Burning is furthermore largely responsible for greenhouse gas emissions from savannas and consequential greenhouse gas forcing of climate (Bristow et al 2016), amongst a cascade of indirect feedbacks between climate and ecosystems which are mediated through local atmospheric dynamics (figure 2; Beringer et al 2015). The outcome of this work is that it has contributed to a better understanding of tropical savanna.
functioning globally, where similarities of savanna structure have been found to conceal large differences across continents amongst vegetation, climate and fire dynamics (Lehmann et al 2014). Without studies of savanna function such as these which were enabled by TERN RI (and similar RI on other continents), a large gap would exist in the understanding of the differences in savanna function globally.
Outside of the tropics, bushfire tends to follow two patterns. In drylands, fires occur as a result of fuel accumulation directly following the conclusion of very wet periods, whereas in sclerophyllous eucalypt forests, wildfires occur following drought, once fuel has cured sufficiently (Griffin et al. 1983, Bradstock 2010). At TERN’s Calperum Mallee SuperSite (FLUXNET code AU-Cpr) in a Mediterranean climate, bushfire can have little or no effect on soil respiration, but net ecosystem productivity (NEP) and thus gross primary production (GPP) can be reduced following fire (Sun et al. 2015, 2016, 2017b). Bushfire plays an important role in shaping Australian landscapes, but its observation by environmental RI is limited in time and space, and each event provides a few more hints toward a better understanding of ecosystem responses to fire.

Seventy per cent of Australia is arid or semi-arid (Eamus et al. 2006), where aridity is likely to dominate over warming and low levels of soil phosphorus in determining adaptation to future climate (Steane et al. 2017). For example, fauna such as ants, termites and lizards in the Australian tropical savanna are arid-adapted and are thus likely to be resistant to future increases in aridity (Andersen et al. 2015). By contrast, species in the arid-Mediterranean ectone are fully adapted to neither climate and are thus sensitive to variations in climate, both spatial and those projected for the future (Guerin et al. 2016). With aridity increasing globally, international integration of environmental RI organisations create further opportunities for discovering diversity responses to aridity.

Climate factors associated with aridity include temperature, vapour pressure deficit, solar radiation, precipitation and water availability. Aridity is moreover associated with patterns of water-use efficiency, light-use efficiency, species richness, productivity and adaptability of leaf traits to native growth conditions (Shi et al. 2014, Gibson et al. 2017, Rumman et al. 2018, Bloomfield et al. 2019). Grasslands are an important and widespread community across the drylands of Australia (figure 3), where climate dynamics are closely related to leaf tissue nutrients (Anderson et al. 2018). To meet the global challenge of understanding nutrient dynamics in grasslands, TERN is partnered with the Nutrient Network (NutNet) at the Great Western Woodlands SuperSite of southwestern Australia (FLUXNET code AU-GWW, NutNet site Mt. Caroline) (Seabloom et al. 2015, Firn et al. 2019). Established to test competing hypotheses for causal mechanisms of relationships between productivity and species richness, initial results from NutNet indicate that climate factors related to aridity such as temperature and the amount and timing of precipitation are positively related to both richness and productivity (Grace et al. 2016).

Ecosystems and climate: climate variability and extreme events

Australia’s climate is highly variable, with the cultural and economic significance of this highly variable climate illustrated in the well-known common parlance as ‘a land … of droughts and flooding rains’ (Dorothea Mackellar, https://dorotheamackellar.com.au/archive/mycountry.htm). A full range of vegetation and climate conditions are currently under-sampled by environmental RI globally (Jones et al. 2017), thus the high temperature anomalies experienced by Australian ecosystems provides the world with an important end-member for developing an understanding of ecosystem responses to climate extremes (e.g. heatwaves; De Kauwe et al. 2019).

Australia has recently experienced an increase in the frequency and severity of climate extremes (e.g. drought, flooding, heatwave; Cleverly et al. 2016a, Ellis and Albrecht 2017), and fire has mediated biodiversity responses to this rise in climate extremes in a biome-specific manner (Greenville et al. 2018). For example, many of the grasslands and savannas of Australia are pyrophytic or ‘fire promoting’, generating large conflagrations in response to a highly variable climate, either seasonally or episodically (Nicholas et al. 2011, Beringer et al. 2015, Wright 2018). By contrast, other vegetation associations like the Mulga (Acacia spp.) lands (shrublands, woodlands and savannas) which cover one-fifth of the Australian continent as shown in figure 3 (Bowman et al. 2008) are sensitive to fire, but they also act as a fire retardant (Murphy et al. 2010). Instead of burning, these ecosystems show adaptations to extreme climate fluctuations with large variations in water-use efficiency, allowing them to exert control on drainage and recharge which is unaffected by variability in hydroclimate (Chen et al. 2014, 2016). Across this myriad of different vegetation types and responses to extreme climate variability, adaptation to environmental variability in temperature and water availability in Australia is associated with gene regions (instead of complete genomes) (Christmas et al. 2016a) and has led to synchronisation of landscape productivity and greenness with hydroclimatic extremes (Cleverly et al. 2013, Ma et al. 2015, Rammig and Mahecha 2015).

Ultimately, climate and weather are influenced by ocean–atmosphere interactions within ocean-basin modes of variability. For example, El Niño–Southern Oscillation (ENSO) is driven by a seasonal gradient of sea-surface temperature along the equatorial Pacific Ocean (Trenberth 1997), and fluctuations between the warm phase (El Niño) and the cold phase (La Niña) generally bring contrasting conditions to Northern and Southern Hemispheres. El Niño is associated with maritime wet conditions to the Northern Hemisphere and dry conditions across the Southern Hemisphere, whereas La Niña is associated with reversed
impacts on precipitation and consequently ecosystems (Holmgren et al. 2001). Data from TERN RI have been used to demonstrate that Australia shows continental phenological responses to ENSO-driven climate variability (Broich et al. 2015) and that litterfall in the tropical rainforest of northeastern Australia is mainly driven by fluctuations in maximum temperature, which are related to ENSO (Edwards et al. 2018).

Although ENSO provides the dominant climate signal for global weather patterns, it is becoming apparent that ENSO alone cannot fully explain differences in regional climate variability. Strong coupling amongst the tropical Pacific, Atlantic and Indian Oceans can impact the state of the climate, although limitations still exist in our ability to project future climate without including these teleconnections in climate models (Cai et al. 2019). In Australia, extreme climate variability (floods, droughts, heatwaves) and resultant effects on water resources have been explained by interactions of the three nearest climate modes: ENSO, the Indian Ocean dipole (IOD) and the Southern annular mode (SAM) in the Southern Ocean (Ummenhofer et al. 2009, 2011, Perkins et al. 2015, Xie et al. 2016, Cleverly et al. 2016a, Rogers and Beringer 2017).

The relative strength of a particular climate mode depends upon a given continent’s location and the relative importance of direct (i.e. baroclinic) or indirect effects (i.e. Rossby-wave propagation) of the surrounding climate modes (Cai et al. 2011). For example in the northern savanna of Australia, TERN RI was used to show that interannual variability in productivity is associated with climate variability in SOI (Moore et al. 2018). In southern and central Australia, ENSO, IOD and SAM each contribute to variability in rainfall (He and Guan 2013, He et al. 2014, Cleverly et al. 2016a), and as a result of TERN RI, Australian ecosystems have been shown to be very resilient to these high levels of rainfall variability (Ma et al. 2016, Cleverly et al. 2016b, 2016c).

Wet extremes: flooding rain

The two wettest events on record in Australia occurred in 1973–1976 and 2010–2012, both bringing widespread flooding nationally (Meyer et al. 2013, Cleverly et al. 2016a, 2016b, Whelan and Frederiksen 2017). In this letter, we focus on the more recent event, which overlapped with the establishment of TERN. Augmentation of precipitation in the Southern Hemisphere during this very strong La Niña was so large that ocean levels reversed their long-term trend and dropped by 5 mm (Boening et al. 2012, Fasullo et al. 2013). As a result, much of Australia’s dryland flushed with greenness in satellite retrievals of both the normalised difference vegetation index and the enhanced vegetation index (Wardle et al. 2013, Cleverly et al. 2016a), leading to several ecological responses. Plagues of rats emerge during wet extremes which are absent during dry times (Greenville et al. 2013). Masting occurred in dryland plants, with reproductive structures increasing in mass 300%–7000% during 2010–2012 (Travers and Eldridge 2013). An ecosystem-wide compositional shift occurred in the Simpson Desert, with rooting patterns and soil texture explaining phenological timing and distribution of each plant form (annual grasses and forbs, perennial grasses, shrubs; Nano and Pavey 2013). Wet extremes have the potential to transform the ecology of vast portions of Australia.

Increased water availability resulted in an asymmetrically large increase in CO₂ uptake by semi-arid and temperate regions of Australia, Africa, South America and India (figure 5; Haverd et al. 2017), with
the majority of this global land C sink anomaly located in Australia (Poulter et al. 2014). Carbon fluxes and phenology measured by TERN’s RI in semi-arid and Mediterranean climates of Australia confirmed the continent’s role in the 2011 global land C sink anomaly (Cleverly et al., 2013, Eamus et al. 2013b, Ma et al. 2015, Sun et al. 2018). Photosynthesis and respiration are limited by water availability across much of Australia, with both responding positively to extreme precipitation (Cleverly et al. 2013, Haverd et al. 2016) and thus maintaining relatively small NEP and reduced carbon-use efficiency (i.e. NEP/GPP) during wet extremes. Low carbon-use efficiency during wet conditions and water limitations on soil respiration during subsequent dry periods contribute to minimisation of carbon emissions after the conclusion of the wet extreme, in the absence of abiotic decomposition (Cleverly et al. 2013, 2016c).

Multiple aspects of the climate contributed equally to increased CO₂ uptake in Australia (Trudinger et al. 2016), showing the 2011 global land C sink anomaly to be an integrated climatological, meteorological and ecosystem event (Cleverly et al. 2016a). However, there were two restrictions on Australia’s contribution to the land C sink anomaly. First, the asymmetric response of photosynthetic productivity to precipitation is dependent upon antecedent conditions, either amplifying or dampening their relationship (Sun et al. 2017a). The land C sink anomaly followed the driest and hottest year of the Millennium Drought, thus antecedent water resources were at a minimum (van Dijk et al. 2013). Second, energy-limited ecosystems did not show a similar asymmetric response to extrinsic forcing by precipitation and thus did not respond to climate forcing during the land C sink anomaly in the same way that semi-arid ecosystems did (figure 5, Haverd et al. 2017). Thus, the contribution of enhanced productivity in coastal, energy-limited ecosystems was expected to be small, whereas Australia’s vast drylands have a high capacity for enhanced productivity during wet extremes (figure 5). Even with these limitations, the land C sink provided an ecosystem service which might have helped to slow the rate of climate change (Keenan and Williams 2018).

An inevitable outcome of increased productivity is biomass accumulation, especially across grasslands globally, where biomass accumulation is related to climate variability (Morgan et al. 2016). Reduced diversity can result with the presence of a single species of invasive grass (e.g. buffel grass, Cenchrus ciliaris), which burns hotter and more completely than native grasses (Schlesinger et al. 2013). For hummock grasslands which cover one-quarter of the Australian land area (Bowman et al. 2008), the legacy of biomass accumulated during the 2011 land C sink anomaly persisted in the absence of burning for years as a strong carbon source due to photodegradation of the standing leaf litter (Cleverly et al. 2016c). C budgets like those of hummock grasslands are very difficult to predict using land surface models (Haughton et al. 2018a) due to a lack of theoretical foundation for the modelling of abiotic decomposition. This is thus an active area of research for which TERN’s environmental RI will play an important role in integrating measurements, monitoring, modelling and remote sensing of carbon and water balances (Eamus et al. 2016).

**Dry extremes: drought and heatwave**

Interannual variability in the global carbon cycle is strongly related to the large variability of the semi-arid land C sink (Ahlström et al. 2015). In a single example, the 2011 land C sink in Australia was immediately followed by the return of drought and associated heat, which shut down the Australian land C sink even whilst total water storage on the continent had persisted (figure 6; Fasullo et al. 2013, Ma et al. 2016). Thus, photosynthetic productivity of Australia is sensitive to meteorological drought (i.e. months to years of below-normal precipitation) and agricultural drought (i.e. yield reduction due to soil drying), but Australia’s hydroclimatic variability can moderate against a more severe hydrological drought (i.e. decline of water storage below the long-term mean; figure 6; Dai 2011). Even during long-term drought, moderately wetter-than-average years can have a strong positive effect on total water storage and productivity across Australia (figure 6). The Millennium Drought of 2001–2009 was the longest meteorological drought on record in Australia, but antecedent hydrological drought began in 1994 (van Dijk et al. 2013). During the Millennium Drought, a worldwide reduction in photosynthetic productivity was attributed to drying in the Southern Hemisphere (Zhao and Running 2010). Despite a widespread and severe reduction in CO₂ uptake during the Millennium Drought, Australian vegetation has shown resilience to a drought as extreme as even it was (figure 6; Campos et al. 2013, Ma et al. 2013, 2015).

Australia has experienced much dryer, longer droughts during previous glacial maxima (Martin 2006), and this long history of drought has conferred a level of adaptation in Australia’s vegetation. At the mesic end of the aridity gradient, the structure of tropical rainforest trees is adapted to the maximum historical water deficit (Pfeifer et al. 2018). In the more arid-adapted Mallee, a multi-stemmed eucalypt which is also fire adapted, survival of common dry periods is achieved by maintaining conservative (i.e. very small) rates of transpiration (Meyer et al. 2015). Two sequential years of much below-average precipitation in central Australia (mid-2011–2013) resulted in a shift from a strong carbon sink to a carbon source, whilst showing resilience during the subsequent return of average annual precipitation amounts (Cleverly et al. 2016b, 2016c). Australian ecosystems show a diversity of hydraulic traits, the presence of which confers...
resilience to water stress (Nolan et al 2017, Anderegg et al 2018).

Heatwaves have been increasing in frequency worldwide over the last 20–50 years, and they have been either combined with drought or have occurred under wet conditions, although heatwaves are more commonly associated with drought (Ding and Qian 2011, Bastos et al 2014, Teskey et al 2015, Kang and Eltahir 2018). Three characteristics of heatwaves, their frequency, intensity and duration, are projected to continue increasing through the end of the 21st century (Perkins–Kirkpatrick et al 2016). For example, the drought and heatwave which struck Europe in 2003 was so severe and so far outside of the historical record that the return interval estimates are in the range of thousands to millions of years (Schar et al 2004), but another similar heatwave is expected to occur within the next 30 years (Russo et al 2015). The combination of heatwave and drought, also known as global change-type drought, can have consequences on ecosystems as severe as tree mortality and forest dieback (Breshears et al 2009, Eamus et al 2013a), and the likelihood of mortality is expected to increase as the frequency, intensity and duration of heatwaves increases.

Soil–moisture–temperature and soil–moisture–precipitation feedbacks are important for development and maintenance of Australian heatwaves, albeit not as important as these mechanisms are for European heatwaves (Perkins et al 2015). Drier-than-average conditions in Australia’s interior push hot, dry winds into southern Australia from The North (Griebel et al 2016). One Australian example was the 2012/2013 ‘Angry Summer’ heatwave, which developed as drought across the interior of the continent, and an associated high-pressure ridge pushed high temperatures into forests and woodlands of southern Australia (van Gorsel et al 2016, Cleverly et al 2016c).

Ecosystem functional responses to both phases of the ‘Angry Summer’ heatwave (dry followed by wet) were evaluated using TERN’s flux tower infrastructure at seven TERN ecosystem processes sites across southern Australia (van Gorsel et al 2016). NEP and GPP declined sharply during the heatwave in Mediterranean woodlands and dry sclerophyll forests, although reductions were smaller during the wet phase than during the preceding dry phase (figure 7). By contrast, the wet sclerophyll forest at the Tumbarumba SuperSite maintained NEP and GPP at constant levels as before the heatwave, with evaporative cooling ameliorating the heatwave and weakening land–atmosphere feedbacks (figure 7; van Gorsel et al 2016). However, soil moisture reserves were nearly depleted in the wet sclerophyll forest during the relatively short ‘Angry Summer’ heatwave, showing afternoon reductions of NEP and GPP during the dry portion of the heatwave, which is consistent with a photosynthetic and stomatal down-regulation due to stress (see figure 7, Cowan and Farquhar 1977). Thus, this heatwave provided a second example of the associated effects of drought and heatwave on ecosystem productivity of Australian ecosystems (see figures 6 and 7) and further demonstrates that increases in the intensity, frequency or duration of heatwaves in future might have seriously detrimental consequences for even Australia’s wettest forests (van Gorsel et al 2016).
Ecosystems and climate: climate change

Ecosystems can be vulnerable to climate change due to restricted gene flow, habitat loss or restricted range (McCallum et al 2014). However, cool and mesic locations in the landscape can often provide refugia where higher resilience is encountered than would be otherwise predicted (Guerin et al 2013, Tapper et al 2014, Christmas et al 2017). Refugia on mountains and islands can buffer genetic diversity against a fluctuating climate (Christmas et al 2017), although climate change can remain a threat for isolated ecosystems such as for island cloud forests where decreasing precipitation and cloud cover have been observed (Auld and Leishman 2015). Furthermore, refugia can show a tipping point, described as a point in a spatial climate gradient at which ecosystem composition turns over rapidly (figure 8; Guerin et al 2013, Caddy-Retalic et al 2017). Tipping points occur at locations along an environmental climate gradient where the species composition of both generalists and specialists changes (figure 8). Such a transition zone would exist at the boundary of a climate refugium, where a turnover of multiple species occurs over a short distance (figure 8). The presence of a tipping point carries a further risk from climate change as the locations of tipping points contract toward the centre of a species’ range. Long-term ecological RI from various countries worldwide, including Australia, has been joined into the International Long Term Ecological Network (ILTER), which addresses the grand challenge of climate change and the resultant loss of biodiversity which is likely to occur (Mirtl et al 2018).

Thus far, we have discussed how adaptation, such as adaptation to aridity, can play an important role in protecting biodiversity from climate extremes, but considerations of adaptation and adaptability are also important for biodiversity conservation in a changing climate. Care must be taken, however, to avoid deprioritising refugia which are low in diversity and
thereby less adapted to areas outside of their refugium (Costion et al 2015). Otherwise, several conservation approaches are available for promoting diversity and adaptability to climate change, including climate-adjusted provenancing (figure 9), assisted migration, biodiversity corridors and ex situ strategies (Prober et al 2015, Christmas et al 2016b). In climate-adjusted provenancing, natural genetic variability is exploited to enhance climate resilience of restoration activities over time by predicting future changes in climate over incremental time steps (figure 9). This gradual approach over time allows for the detection of uncertainties (e.g. mismatch between predicted and actual climate change trajectories) before it is too late to correct for them (figure 9). TERN’s plot-based monitoring infrastructure, especially those arrayed in transects along climate gradients, provide a powerful tool for evaluating community responses to climate change and for promoting resilience in biodiversity (Caddy-Retalic et al 2017).

There are several aspects of projected climate change in relation to ecosystem carbon cycles, such as changes in precipitation, vapour pressure deficit, temperature and elevated $[CO_2]$. Changes in precipitation seasonality are projected to reduce carbon stocks in the northern Australian savannas and rainforests, even with little change to annual total precipitation (Cook et al 2015). Increasing vapour pressure deficit during one key season as a result of decreasing seasonal precipitation and increasing temperature is expected to carry detrimental effects upon the carbon cycle of Australian alpine grasslands and tropical rainforests worldwide (Fu et al 2018, Marchin et al 2018). Photosynthetic production in tropical rainforests is currently restricted by high vapour pressure deficit, and they are unlikely to tolerate a much drier atmosphere (Fu et al 2018). In alpine grasslands of Australia, a tipping point has been identified wherein vapour pressure deficits which exceed this threshold can prevent the typical recovery of vegetational greenness at the end of the growing season (Marchin et al 2018). Increasingly elevated vapour pressure deficit is a serious risk for tree mortality and ecosystem function worldwide (Allen et al 2010, Breshears et al 2013, Eamus et al 2013a).

Warming is predicted to have strongly negative effects on Australia’s temperate eucalypt forests, nearly 90% of which exist in temperature regimes above their thermal optimum for growth (11°C; Bowman et al 2014). In the absence of water or substrate limitations, respiration will increase along with rising temperatures, leading to global observations of increasing heterotrophic respiration and climate-driven loss of soil carbon (Bond-Lamberty et al 2018). Acting to counter the effects of increasing temperature, elevated $[CO_2]$ can contribute to maintenance of photosynthesis at reduced stomatal conductance, thereby improving water-use efficiency whilst reducing pressure on limited water resources. $CO_2$ fertilisation is projected to be the main driver of savanna responses to climate, leading to increased carbon sequestration in vegetation, although the magnitude

Figure 8. Conceptual diagram of a tipping point along a climate gradient. Tipping points occur where a clear transition occurs for both generalist and specialist species distributions. Panel (a) shows no tipping point and even transitions of community composition along the gradient. Natural ecosystems show a mix of generalists, specialists and intermediate species, with a tipping point (b) or with a tipping point and ecotonal transition zone. Reproduced from Caddy-Retalic et al (2017), CC BY 4.0.
of the fertilisation effect will depend strongly upon changes in fire return interval and seasonality (Scheiter et al 2015). Increasing aridity and elevated [CO$_2$] are likely to affect vegetation dynamics of tropical savannas, which will alter fire regimes and provide further carbon feedbacks to climate (figure 2; Beringer et al 2015).

**Final remarks**

There is an urgent need for environmental information from RI in remote Australian landscapes, which would provide important outcomes and impact related to environmental reporting and fostering research in the framework of global challenges.

*Figure 9. Diagram of provenancing strategies for revegetation in a changing climate. Reproduced from Prober et al (2015), CC BY 4.0.*
(van Dijk et al 2014). The risks of climate change as well as opportunities for conservation are emerging from this work, although there is still much to discover. Environmental RIs create the opportunity for identifying and evaluating the key drivers of ecosystem change by allowing researchers to observe state-changing events such as heatwaves, floods or droughts in locations which might be otherwise inaccessible. These are the first steps toward the development of an environmental forecasting system which can answer the global challenge of predicting ecosystem responses to climate change.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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References

Ahlström A et al 2015 The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink Science 348 895–9
Allen C D et al 2010 A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests Forest Ecol. Manage. 259 660–84
Anderegg W R L, Kane J M and Anderegg L D L 2013 Consequences of widespread tree mortality triggered by drought and temperature stress Nat. Clim. Change 3 50–6
Anderegg W R L et al 2018 Hydraulic diversity of forests regulates ecosystem resilience during drought Nature 561 338–41
Andersen A N, Toro I D and Parr C L 2015 Savanna ant species richness is maintained along a bioclimatic gradient of increasing latitude and decreasing rainfall in northern Australia J. Biogeogr. 42 2513–22
Anderson T M et al 2018 Herbivory and eutrophication mediate grassland plant nutrient responses across a global climatic gradient Ecology 99 822–31
Auld T D and Leishman M 2015 Ecosystem risk assessment for gnarled mossy cloud forest, Lord Howe Island, Australia Austral Ecol. 40 364–72
Baldocchi D 2008 Breathing of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems Aust. J. Bot. 56 1–26
Baldocchi D, Valentini R, Running S, Oechel W and Dahlman R 1996 Strategies for measuring and modelling carbon dioxide and water vapour fluxes over terrestrial ecosystems Glob. Change Biol. 2 159–68
Barranza V, Grings F, Ferrazzoli P, Huet e A, Restrepo-Coupe N, Beringer J, Van Gorsel E and Karsenbaum H 2014 Behavior of multitemporal and multisensor passive microwave indices in Southern Hemisphere ecosystems J. Geophys. Res.: Biogeosci. 119 2231–44
Barranza V, Restrepo-Coupe N, Huet e A, Grings F and Van Gorsel E 2015 Passive microwave and optical index approaches for estimating surface conductance and evapotranspiration in forest ecosystems Agric. For. Meteorol. 213 126–37
Bastos A, Gouveia C M, Trigo R M and Running S W 2014 Analysing the spatio-temporal impacts of the 2003 and 2010 extreme heatwaves on plant productivity in Europe Biogeosciences 11 3421–35
Beringer J et al 2015 Fire in Australian savannas: from leaf to landscape Glob. Change Biol. 21 62–81
Beringer J et al 2016 An introduction to the Australian and New Zealand flux tower network—OzFlux Biogeosciences 13 5895–916
Bissett A et al 2016 Introducing BASE: the Biomes of Australian Soil Environments soil microbial diversity database Gigascience 5 11
Bloomfield K J et al 2019 The validity of optimal leaf traits modelled on environmental conditions New Phytol. 221 1409–23
Boening C, Willis J K, Landerer F W, Nerem R S and Fasullo J 2012 The 2011 La Niña: so strong, the oceans fell Teleconnection pathways of ENSO and the IOD and the mechanisms for impacts on Australian rainfall J. Clim. 24 3910–23
Bowman D, Boggs G S and Prior L D 2008 Fire maintains an Acacia aneura shrubland—Triodia grassland mosaic in central Australia J. Arid. Environ. 72 34–47
Bowman D M J S, Williamson G J, Keenan R J and Prior L D 2014 A warmer world will reduce tree growth in evergreen broadleaf forests: evidence from Australian temperate and subtropical eucalypt forests Glob. Ecol. Biogeogr. 23 925–34
Bradford M G, Metcalfe D J, Ford A, Liddell M J and McKeown A 2014 Floristics, stand structure and aboveground biomass of a 25-ha rainforest plot in the wet tropics of Australia J. Tropical Forest Sci. 26 543–53
Braddock R A 2010 A biogeographic model of fire regimes in Australia: current and future implications Glob. Ecol. Biogeogr. 19 145–58
Breshears D D, Adams H D, Eamus D, McDowell N G, Law D J, Will R E, Williams A P and Zou C B 2013 The critical amplifying role of increasing atmospheric moisture demand on tree mortality and associated regional die-off Front. Plant Sci. 4 266
Breshears D D, Myers O B, Meyer C W, Barnes F J, Zou C B, Allen C D, McDowell N G and Pockman W T 2009 Tree death in response to global change-type drought: mortality insights from a decade of plant water potential measurements Front. Ecol. Environ. 7 185–9
Bristow M, Hutley L B, Beringer J, Livesley S J, Edwards A C and Arnold S K 2016 Quantifying the relative importance of greenhouse gas emissions from current and future savanna land use change across northern Australia Biogeosciences 13 6285–303
Broich M et al 2015 A spatially explicit land surface phenology data product for science, monitoring and natural resources management applications Environ. Modelling Softw. 64 191–204
Caddy-Retalic S et al 2017 Bioclimatic transect networks: powerful observatories of ecological change Ecol. Evol. 7 4607–19
Cai W et al 2019 Pantropical climate interactions Science 363 eaav4236
Cai W J, van Rensch P, Cowan T and Hendon H H 2011 Teleconnection pathways of ENSO and the IOD and the mechanisms for impacts on Australian rainfall J. Clim. 24 3910–23

13
Cleverly J, Boulain N, Villalobos-Vega R, Grant N, Faux R, Wood C, Christmas M J, Bif
Cleverly J, Eamus D, Luo Q, Restrepo Coupe N, Kljun N, Ma X, Eamus D, Boulain N, Cleverly J and Breshears D D 2013a Global
De Kauwe M G, Medlyn B E, Pitman A J, Drake J E, Ukkola A, Costion C M
Cowan I R and Farquhar G D 1977 Stomatal function in relation to
carbon and water
Eamus D, Hatton T, Cook P and Colvin C 2006 Ecophysiology: Vege
Environ. Res. Lett. 14 (2019) 095004
Campos G E P et al 2013 Ecosystem resilience despite large–scale
altered hydroclimate conditions Nature 494 349–52
Carpenter R J, MacK M K, Jordan G J and Hill R S 2015 Fossil
evidence for open, Proteaceae-dominated heathlands and fire in the Late Cretaceous of Australia Am. J. Bot. 102 2992–107
Chen C, Cleverly J, Zhang L, Yu Q and Eamus D 2016 Modelling
seasonal and inter-annual variations in carbon and water
fluxes in an arid-zone Acacia savanna woodland, 1981–2012 Ecosyste
Ewenz C, Li L, Yu Q and Huete A 2016a The importance of
carbon land sink anomaly
Environ. Res. Lett. 11 125011
Edwards W, Liddell M J, Frankis P, Nichols C and Laurance S G W
2018 Seasonal patterns in rainforest litterfall: detecting
endogenous and environmental influences from long-term sampling
Austral Ecol. 43 225–35
Ellis N R and Albrecht G A 2017 Climate change threats to family
farmers’ sense of place and mental wellbeing: a case study from the Western Australian Wheatbelt Soc. Sci. Med. 175
161–8
Fasullo J T, Boening C, Landerer F W and Nerem R S 2013
Australia’s unique influence on global sea level in 2010–2011
Geophys. Res. Lett. 40 4568–73
Finn J et al 2019 Leaf nutrients, not specific leaf area, are consistent
indicators of elevated nutrient inputs Nat. Ecol. Evol. 3 400
Fu Z et al 2018 The surface-atmosphere exchange of carbon dioxide
in tropical rainforests: sensitivity to environmental drivers and
flux measurement methodology Agric. For. Meteorol. 263
292–307
Gibson N, Prober S, Meissner R and van Leeuwen S 2017
Implications of high species turnover on the south-western Australian sandplains PLoS One 12 18
Grace J B et al 2016 Integrative modelling reveals mechanisms
linking productivity and plant species richness Nature 529
390–3
Greenville A C et al 2018 Biodiversity responses to increasing
climatic extremes in a biome-specific manner Sci. Total
Environ. 654 582–93
Greenville A C, Wardle D M and Dickman C R 2013 Extreme
rainfall events predict irruptions of rat plagues in central
Australian Austral Ecol. 38 754–64
Griepel A, Bennett L T, Metzen D, Cleverly J, Burba G and Arndt S K
2013 Stocks and dynamics of carbon in trees across a rainfall
gradient in a tropical savanna woodland, central Australia J. Geophys. Res.: Biogeosci. 118 1168–85
Griepel A, Eamus D, Luo Q, Restrepo Coupe N, Kljun N, Ma X, Ewenz C, Li L, Yu Q and Hucie A 2016a The importance of
interacting climate modes on Australia’s contribution to
global carbon cycle extremes Sci. Rep. 6 23113
Griepel A et al 2016b Soil moisture controls on phenology and
productivity in a semi-arid critical zone Sci. TotalEnviron.
568 1227–37
Griepel A et al 2016c Productivity and evapotranspiration of two
contrasting semi-arid ecosystems following the 2011 global
carbon land sink anomaly Agric. For. Meteorol. 220 151–9
Cook G D, Liedloff A C, Cuff N J, Brocklehurst P S and Williams R J
2015 Stocks and dynamics of carbon in trees across a rainfall
gradient in a tropical savanna Austral Ecol. 40 845–56
Costion C M et al 2015 Using phylogenetic diversity to identify
ancient rain forest refugia and diversification zones in a
biodiversity hotspot Diversity Distributions 21 279–89
Cowman I R and Farquhar G D 1977 Stomatal function in relation to
leaf metabolism and environment Integration of Activity in the
Higher Plant ed D H Jennings (Cambridge: Cambridge
University Press) pp 471–505
Crowther T W et al 2016 Quantifying global soil carbon losses in
response to warming Nature 540 104
Da I 2011 Drought under global warming: a review Clim. Change
24 45–65
De Kauwe M G, Medlyn B E, Pitman A J, Drake J E, Ukkola A,
Griebel A, Pendall E, Prober S and Roderick M 2019
Examining the evidence for decoupling between
photosynthesis and transpiration during heat extremes
Biogeosciences 16 903–16
Ding T and Qian W H 2011 Geographical patterns and temporal
variations of regional dry and wet heatwaves in china
during 1960–2008 Adv. Atmos. Sci. 28 322–37
Eamus D, Boulain N, Cleverly J and Breshears D D 2013a Global
type–drought–induced tree mortality: vapor pressure
deficit is more important than temperature per se in causing
decline in tree health Ecol. Evol. 3 2711–29
Eamus D, Cleverly J, Boulain N, Grant N, Faux R and
Villalobos–Vega R 2013b Carbon and water fluxes in an arid–zone Acacia savanna woodland: an analyses of seasonal
patterns and responses to rainfall events Agric. For. Meteorol.
182–183 225–38
Eamus D, Hatton T, Cook P and Colvin C 2006 Ecophysiology:
Vegetation Function, Water and Resource Management
(Collingwood, VIC: CSIRO Publishing) p 348
Eamus D, Hucie A, Cleverly J, Nolan R H, Ma X, Tarin T and
Santini N S 2016 Mulga, a major tropical dry open forest of
Australia: recent insights to carbon and water fluxes
Environ. Res. Lett. 11 125011
Eamus D, Boulain N, Grant N, Faux R and
Villalobos–Vega R 2016 Modelling seasonal and inter-annual variations in carbon and water
fluxes in an arid-zone Acacia savanna woodland, 1981–2012 Ecosyste
Rammig A and Mahecha M D 2015 Ecology: ecosystem responses to climate extremes Nature 527 315–6
Rogers C D W and Beringer J 2017 Describing rainfall in northern Australia using multiple climate indices Biogeosciences 14 597–615
Rumman R, Atkin O K, Bloomfield K J and Eamus D 2018 Variation in bulk-leaf 13C discrimination, leaf traits and water-use efficiency—trait relationships along a continental-scale climate gradient in Australia Glob. Change Biol. 24 1186–200
Russo S, Stillman J and Fischer E M 2015 Top ten European heatwaves since 1950 and their occurrence in the coming decades Environ. Res. Lett. 10 15
Schar C, Vidale P L, Luthi D, Frei C, Haberli C, Liniger M A and Appenzeller C 2004 The role of increasing temperature variability in European summer heatwaves Nature 427 332–6
Scheiter S, Higgins S J, Beringer J and Hutley L B 2015 Climate change and long-term fire management impacts on Australian savannas New Phytol. 205 1211–26
Schlesinger C, White S and Muldoon S 2013 Spatial pattern and severity of fire in areas with and without buffel grass (Cenchrus ciliaris) and effects on native vegetation in central Australian ecoregions: Environ. Res. Lett. 9 104002
Seabloom E W et al 2015 Plant species’ origin predicts dominance and response to nutrient enrichment and herbivores in global grasslands Nat. Commun. 6 7710
Shi H, Li L, Eamus D, Cleverly J, Huete A, Beringer J, Yu Q, van Gorsel E and Hutley L 2014 Intrinsic climate dependency of ecosystem light and water-use efficiencies across Australian biomes Environ. Res. Lett. 9 104002
Steane D A, McLean E H, Potts B M, Prober S M, Stock W D, Stylianou V M, Vaillancourt R E and Byrne M 2017 Evidence for adaptation and acclimation in a widespread eucalypt of semi-arid Australia Biol. J. Linn. Soc. 121 484–500
Sun Q, Meyer W S, Koerber G R and Marschner P 2015 Response of respiration and nutrient availability to drying and rewetting in soil from a semi-arid woodland depends on vegetation patch and a recent wildfire Biogeosciences 12 5093–101
Sun Q, Meyer W S, Koerber G R and Marschner P 2016 A wildfire event influences ecosystem carbon fluxes but not soil respiration in a semi-arid woodland Agric. For. Meteorol. 226–227 57–66
Sun Q, Meyer W S, Koerber G R and Marschner P 2017a Prior rainfall pattern determines response of net ecosystem carbon exchange to a large rainfall event in a semi-arid woodland Agric. Ecosyst. Environ. 247 112–9
Sun Q, Meyer W S and Marschner P 2018 Direct and carry-over effects of summer rainfall on ecosystem carbon uptake and water use efficiency in a semi-arid woodland Agric. For. Meteorol. 263 15–24
Sun Q Q, Meyer W S, Koerber G R and Marschner P 2017b Response of microbial activity to labile C addition in sandy soil from semi-arid woodland is influenced by vegetation patch and wildfire J. Soil Sci. Plant Nutrition 17 62–73
Tapper S L, Byrne M, Yates C J, Keppel G, Hopper S D, Niel K V, Schut A G T, Mucina L, Wardell-Johnson G W and Austin J 2014 Isolated with persistence or dynamically connected? Genetic patterns in a common granite outcrop endemic Diversity Distributions 20 987–1001
Teskey R, Wurtin T, Bauweraerts I, Ameye M, McGuire M A and Steppe K 2015 Responses of tree species to heat waves and extreme heat events Plant Cell Environ. 38 1699–712
Thurgate N, Lowe A J and Clancy T F 2017 Australia’s terrestrial ecosystem research network: a network of networks approach to building and maintaining continental ecosystem research infrastructure Terrestrial Ecosystem Research Infrastructures: Challenges and Opportunities ed A Chabbi and H W Loescher (Boca Raton FL, London: CRC Press, Taylor and Francis) pp 427–48
Tokmakoff A, Sparrow B, Turner D and Lowe A 2016 AusPlots Rangelands field data collection and publication: Infrastructure for ecological monitoring Future Gener. Comput. Syst. 56 537–49
Travers S K and Elford D J 2013 Increased rainfall frequency triggers an increase in litter fall rates of reproductive structures in an arid eucalypt woodland Austral. Ecol. 38 820–30
Trenberth K E 1997 The definition of El Niño Bull. Am. Meteorol. Soc. 78 2771–7
Trudinger C M, Haverd V, Briggs P R and Canadell J G 2016 Interannual variability in Australia’s terrestrial carbon cycle constrained by multiple observation types Biogeosciences 13 6363–83
Ummenhofer C C, England M H, McIntosh P C, Meyers G A, Pook M J, Risby J S, Gupta A S and Taschetto A S 2009 What causes southeast Australia’s worst droughts? Geophys. Res. Lett. 36 L04706
Ummenhofer C C, Sen Gupta A, Briggs P R, England M H, McIntosh P C, Meyers G A, Pook M J, Raupach M R and Risby J S 2011 Indian and Pacific Ocean influences on Southeast Australian drought and soil moisture J. Clim. 24 1313–36
van Dijk A, Beck H E, Crosbie R S, de Jeu R A M, Liu Y Y, Podger G M, Timbal B and Viney N R 2013 The Millennium Drought in southeast Australia (2001–2009): natural and human causes and implications for water resources, ecosystems, economy, and society Water Resour. Res. 49 1040–57
van Dijk A, Mount R, Gibbons P, Vardon M and Canadell P 2014 Environmental reporting and accounting in Australia: progress, prospects and research priorities Sci. Total Environ. 473 338–49
van Gorsel E, Cleverly J, Beringer J, Cleugh H, Eamus D, Hutley L B, Isaacs P and Prober S 2018 Preface: Ozflux: a network for the study of ecosystem carbon and water dynamics across Australia and New Zealand Biogeosciences 15 549–52
van Gorsel E et al 2016 Carbon uptake and water use in woodlands and forests in southern Australia during an extreme heat wave event in the ‘Angry Summer’ of 2012/2013 Biogeosciences 13 5947–64
von Buttler J et al 2018 Impacts of droughts and extreme-temperature events on gross primary production and ecosystem respiration: a systematic assessment across ecosystems and climate zones Biogeosciences 15 1293–318
Wardle G M, Pavey C R and Dickman C R 2013 Greening of arid Australia: new insights from extreme years Austral. Ecol. 38 731–40
Whelan J and Frederiksen J S 2017 Dynamics of the perfect storms: La Niña and Australia’s extreme rainfall and floods of 1974 and 2011 Clim. Dyn. 48 3935–48
Wright B R 2018 Evidence that shrublands and hummock grasslands are fire-meditated alternative stable states in the Australian Gibson Desert Desert Ecol. 188 525–35
Xie Z, Huete A, Ma X, Restrepo-Coupe N, Devadas R, Clarke K and Lewis M 2016 Landsat and GRACE observations of arid wetland dynamics in a dryland river system under multi-decadal hydroclimatic extremes J. Hydrol. 543 Part B 818–31
Zhao M S and Running S W 2010 Drought-induced reduction in global terrestrial net primary production from 2000 through 2009 Science 329 940–3