



An introduction to the Australian and New Zealand flux tower network – OzFlux*

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Abstract. OzFlux is the regional Australian and New Zealand flux tower network that aims to provide a continental-scale national research facility to monitor and assess trends, and improve predictions, of Australia's terrestrial biosphere and climate. This paper describes the evolution, design and current status of OzFlux as well as an overview of data processing. We analyse
50 measurements from the Australian portion of the OzFlux network and found that the response of Australian biomes to climate was largely consistent with global studies but that Australian systems had a lower ecosystem water-use efficiency. Australian semi-arid/arid ecosystems are important because of their huge extent (70%) and they have evolved with common moisture limitations. We also found that Australian ecosystems had similar radiation use efficiency per unit leaf area compared to
55 global values that indicates a convergence toward a similar biochemical efficiency. The paper discusses the utility of the flux data and the synergies between flux, remote sensing and modelling. Lastly, the paper looks ahead at the future direction of the network and concludes that there has been a substantial contribution by OzFlux and considerable opportunities remain to further advance our understanding of ecosystem response to disturbances including drought, fire, land use and land cover change, land management and climate change that are relevant both nationally and internationally. It is suggested that a synergistic approach is required to address all of the spatial, ecological, human and cultural challenges of managing the
60 delicately balanced ecosystems in Australia.

Keywords. Eddy covariance, flux tower networks, OzFlux, FLUXNET, remote sensing, modelling, climate drivers, water use efficiency, carbon cycle.



1 Introduction

65 *This paper is dedicated to the memory of our wonderful colleague and guiding light, Dr. Ray Leuning, who recently passed away.*

1.1 The role of flux research in Australia

Global environmental change is one of the greatest challenges facing the planet (Steffen et al., 2011). To mitigate or adapt to global environmental change we must provide a scientific basis, underpinned by observation that is then scaled using
70 models, for the development of national and global policies for improved land management (Vargas, 2002). Natural terrestrial ecosystems provide a range of services such as carbon sequestration and climate regulation, water balance, biodiversity, ecotourism, resources and food (Costanza et al., 1998; Eamus et al., 2005), yet they are at risk from climate change and variability, land use change and disturbance (Schroter et al., 2005). Natural ecosystems are also important sinks and sources of greenhouse gases that are sensitive to climate variability and can feed back to global climate change (Luo, 2007). Finally,
75 changes in physical land surface properties can occur through land use change, disturbance and biogeographical shifts in ecosystems (Burrows et al., 2014) that can, in turn, alter biophysical coupling and feedback to alter weather and climate patterns at multiple scales (Beringer et al., 2014; Bonan, 2008).

Future climate and land use change may push ecosystems towards tipping points (Laurance et al., 2011), with deleterious changes to vegetation structure, composition and function, thus compromising ecosystem health and viability
80 (Hughes, 2010). Of particular concern are potential increases in the effects of climate-induced physiological stress and interactions with other climate-mediated processes such as insect outbreaks and wildfire (Allen et al., 2010; Evans et al., 2013). This has important effects on carbon sequestration and greenhouse gases emissions because carbon stored in woody vegetation is vulnerable to increased fire risk through burning under climate change (Bowman et al., 2013). Death of vegetation from drought stress (Mitchell et al., 2014), extreme disturbance events, disease and pests could also result in
85 increased carbon release to the atmosphere and changes to CO₂ emissions from soils (Hutley and Beringer, 2011). It is imperative that we understand the value and dynamics of ecosystem structure and function to ensure that we can manage them successfully into the future under environmental change (fire, pests and invasive species, future land-use and climate change) (Beringer et al., 2014; Hutley and Beringer, 2011).



To address global concern over rising atmospheric CO₂ concentrations and global climate change, there has been a
90 growing need for studies of terrestrial ecosystems (Peters and Loescher, 2014). Studies using the eddy covariance technique
from micrometeorological flux towers (Baldocchi, 2003) can contribute significantly to our understanding of ecological,
biogeochemical, and hydrological processes by, amongst others:

- 1) providing accurate, continuous half-hourly to annual estimates of sinks and sources of greenhouse gases and water
from ecosystems for carbon accounting and water management (Eugster and Merbold, 2015; Hutley et al., 2005);
- 95 2) evaluating the effects of disturbance, topography, biodiversity, stand age, land use, insect/pathogen infestation and
extreme weather on carbon and water fluxes (Baldocchi, 2008);
- 3) examining the effects of land management practices, such as harvest, fertilisation, irrigation, tillage, thinning,
cultivation and clearing (Bristow et al., 2016; Prescher et al., 2010; Vote et al., 2016); and
- 4) producing important ground-truth data for parameterising, validating, and improving satellite remote sensing and
100 global inversion products (Running et al., 1999).

Direct measurements from diverse biomes are essential for developing bio-geochemical and ecological models that
diagnose and forecast the state of the land's carbon and water budgets (Baldocchi, 2014b; Haverd et al., 2013a), which
ultimately allow us to better respond and adapt to environmental change (Steffen et al., 2011). Given the utility of eddy
covariance studies and the demand for these types of data, global and regional networks have come together to maximise their
105 scientific value. The international network FLUXNET is a "network of regional networks" that coordinates regional and global
analysis of observations from micrometeorological flux tower sites (Baldocchi et al., 2001), where at present over 650 sites
are operated on a long-term and continuous basis. Biomes in FLUXNET include temperate conifer and broadleaved (deciduous
and evergreen) forests, tropical and boreal woodlands and forests, crops, grasslands, chaparral, arid woodlands and scrublands,
wetlands and tundra. Within FLUXNET are a number of regional networks such as AmeriFlux (USA), AsiaFlux (Asia),
110 ChinaFlux, Fluxnet Canada and OzFlux (Australia and New Zealand). The aim of this paper is to describe the evolution,
design and current status of the Australian network of eddy covariance flux towers (OzFlux). Although New Zealand flux sites
have been an integral part of OzFlux from the outset and have made many important contributions (Hunt et al., 2002; Rutledge
et al., 2010, 2015; Thompson et al., 1999), these sites have had a different history and data availability, thus this paper will



focus on Australian sites. An overview of data processing will be given first, followed by a summary and analysis of
115 measurements from the entire Australian OzFlux network. This is followed by an examination of synergies between flux
measurements, remote sensing and modelling. Australia is a vast continent and up-scaling using validated terrestrial biosphere
modelling and remote sensing products is essential for complementing limited ground based biophysical observations. We will
conclude by looking ahead at the future direction of the network.

120 1.2 Evolution of OzFlux in Australia

Australia has a long and rich history of significant contributions to the field of micrometeorology, including the
development of theory around turbulence in and above plant canopies (Deacon, 1959; Priestley, 1967; Raupach and Thom,
1981; Webb et al., 1980) and instrumentation (Deacon and Samuel, 1957; Raupach, 1978; Taylor and Dyer, 1958) along with
some of the first field measurements (Denmead and McIlroy, 1970; Hicks and Martin, 1972). Initial micrometeorological field
125 measurements were designed to validate the methodology and were often conducted in short campaigns over agricultural
landscapes (Leuning et al., 2004). Micrometeorological measurements for research purposes accelerated in the 1990s with
studies such as the Maritime Continent Thunderstorm Experiment (MCTEX) (Beringer and Tapper, 2002) and OASIS (Isaac
et al., 2004). Long-term flux measurements using the eddy covariance technique began in Australia in 2000 with the
establishment of the wet temperate eucalypt forest site at Tumbarumba (Leuning et al., 2005), closely followed by the tropical
130 savanna site at Howard Springs (Hutley et al., 2000) and the tropical rainforest site at Cape Tribulation in 2001 (Liddell et al.,
2016) (Fig. 1). Almost all of the sites in the OzFlux network have been initially established under short term research grants
for specific purposes. However, due to the vision of the investigators who recognised the importance of long-term
measurements, these sites were kept operational on minimal budgets, which has provided a legacy of important flux and
ancillary data. At about this time the ‘OzFlux’ network was founded by Ray Leuning and colleagues at an inaugural meeting
135 at Monash University in 2001 (Leuning et al., 2001). Leuning was the pioneer and leader of the network for many years and
a mentor of many Australian and internationally based micrometeorologists and ecophysiologicalists (Cleugh, 2013). We dedicate
this paper to him.



After the establishment of OzFlux, the community lobbied the Federal Government to allocate financial resources for an ecological observational network. Over the next decade, the national collaborative research infrastructure strategy (NCRIS) established the terrestrial ecosystem research network (TERN, 2016) as a crucial platform to integrate datasets collected by different state agencies, CSIRO (Commonwealth Scientific and Industrial Research Organisation) and Universities for supporting decision-making to overcome Australia's developing environmental problems (State of the Environment 2011 Committee, 2011). In 2009 initial funding was provided to TERN, which provided nominal support for many OzFlux sites along with other capabilities such as intensive ecosystem monitoring (SuperSites), remote sensing (AusCover), modelling (eMAST), TERN synthesis (ACEAS), coastal, soils and plot based networks (AusPlots), long term ecological research network facilities (LTERN) and transects (Australian Transect Network). OzFlux has had a central network capacity and from the outset this has been hosted by the CSIRO with data services provided at present through the NCI (Australia's National Computational Infrastructure). Despite the critical information provided by TERN and OzFlux Networks, recent funding and programmatic cuts may compromise sustained environmental research in Australia.

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2 OzFlux network architecture

2.1 Network overview

OzFlux aims to provide a national research facility for monitoring and assessing trends, and to improve predictions of Australia's terrestrial biosphere and climate. It underpins the data collection and process understanding needed to: 1) support sound management of natural resources including water, carbon and nutrient resources for environmental and production benefits; 2) monitor, assess, predict and respond to climate change and variability; 3) improve weather and environmental information and prediction; 4) support disaster management and early warning systems needed to meet Australia's priorities in national security; and 5) ensure that Earth system models used to underpin Australia's policies and commitments to international treaties adequately represent Australian terrestrial ecosystem processes.

The key ecosystem science questions are focused on improved understanding of the responses of carbon and water cycles of Australian ecosystems to current climate and future changes in precipitation, temperature and CO₂ levels, as follows; 1)



what are the key drivers of ecosystem productivity (carbon sinks) and greenhouse gas emissions; 2) how resilient is ecosystem productivity to a variable and changing climate and 3) what is the current water budget of the dominant Australian ecosystems and how will it change in the future?

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2.2 Network design

OzFlux established an agreed set of core measurements and common protocols for measurements of carbon, water and energy fluxes across the national network to provide consistent observations to serve the land surface and ecosystem modelling communities. In addition to long-term fluxes of carbon, water and energy, ecosystem structural and functional properties are being measured, along with biodiversity and soil characteristics in collaboration with the TERN SuperSite Network (Australian SuperSite Network, 2015). The OzFlux network design is based on a hub and spoke model, wherein a critical element is the central node that coordinates the network, proposes protocols for measurements, has oversight of data processing and quality control, maintains a database to archive data from each site, data licencing and access via an online portal and provides scientific and technical training to flux station operators (Isaac et al., 2016). The central node implements a centralised database and provides feedback on live data feeds (equipment failure) and measurement quality to site operators. Site operators have responsibility for operation, data processing, data quality control, gap filling and delivery of data streams to the central database. Through annual meetings, training workshops and technical support, OzFlux also provides a critical capacity-building opportunity to further build Australian expertise, infrastructure, and data processing across the broader Australian research community in ecosystem and climate sciences.

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2.3 Network climate and biome space

The modified Köppen climate classification of Stern and Dahni (2013) shows that the greater part of the Australian continent is either desert climate (i.e. arid) (38% of land) or grassland climate (i.e. semi-arid) (36% of land). Only the south-east and south-west corners have a temperate climate (10%) and moderately fertile soil (McKenzie et al., 2004). The northern



185 third of the continent is dominated by sub-tropical (7%), tropical (9%) and grassland (36%) climates, with tropical rainforests, tropical savanna, grasslands and deserts the dominant ecosystems. Mean annual precipitation (MAP) across the continent varies from 134 to 2804 mm, and mean annual temperature (MAT) varies from 3.8 to 29.0 °C (from 1961-1990 MAP and MAT gridded data at 0.1 degree resolution (Bureau-of-Meteorology, 2013)). Many individual stations exceed the spatially gridded data due to topographical/spatial issues such as Mount Bellenden Ker that has the highest mean annual rainfall of any
190 Bureau of Meteorology station at 8173 mm (station ID 031141 for period 1973 to 2015). The OzFlux sites are relatively uniformly distributed over this climate space (Fig. 2).

Using the modified Köppen scheme, Stern and Dahni (2013) showed that the major Australian climate zones were (from largest to smallest by area) desert, grassland, temperate, tropical, sub-tropical, equatorial and polar. Stern and Dahni (2013) also reported changes in the distribution of Australian climate zones due to climate change during the past century, the
195 most notable one being the contraction of the area covered by 'desert' climates (from 51.1% to 37.9%) and the corresponding increase in the area covered by 'grassland' (from 26.3% to 36.1%) and 'tropical' (from 5.5% to 9.0%) climates. Therefore, a large portion of the continent is arid or semi-arid (74%) and ecosystems in the semi-arid climate zone have been recognized recently as of critical important in driving inter-annual variability in the global CO₂ growth rate cycle (Bastos et al., 2013; Poulter et al., 2014). Poulter et al. (2014), Haverd et al. (2015) and Cleverly et al. (2016a) found that a large sink anomaly in
200 2011 was mainly attributed to increases in net primary productivity (NPP) across the semi-arid regions of the southern hemisphere (30-60% from Australian semi-arid ecosystems), during a large La Niña event where Australian MAP exceeded the long-term by 55% (Boening et al., 2012). As a consequence the water-limited ecosystems responded by rapid growth and productivity. Ahlström et al. (2015) subsequently demonstrated that both the inter-annual variability and trend of the global sink were dominated by semi-arid ecosystems whose carbon balance is strongly associated with circulation-driven variations
205 in both precipitation and temperature. This and similar dynamics have been captured at the semi-arid sites in OzFlux as discussed in Eamus and Cleverly (2015) and Cleverly et al. (2016a).

In terms of vegetation classification, we have used the Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (Environment, 2012) throughout (Table 1, Fig. 1) to describe the Australian vegetation types (bioregions) and ecoregions (global classification). Flux sites located in natural vegetation (n=27) (Table 1) cover a wide geographical and



210 biome space, although each ecoregion is not equally represented (Table 2, Fig. 1). Despite the dominance of deserts and xeric shrublands (49%) and the areal importance of arid/semi-arid climate (74%), only a small fraction of the OzFlux sites (two towers, 8% of the network) are located in this region. There is a strong representation of flux towers in the tropical and sub-tropical moist broadleaf forests. In addition, of the 32 flux tower sites in Table 1, only five (16%) are located in predominantly agricultural/managed/modified landscapes. Vote et al. (2016) give a comparative analysis of flux observations in Australian
215 managed landscapes of varying vegetation structure, composition and management intensities in different bioclimatic regions and Bristow et al. (2016) provide a specific case study of land use transitions in tropical savannas.

Of the 11 currently TERN funded OzFlux sites 10 are also TERN SuperSites that carry out a standard set of measurements using agreed protocols that provide a considerable set of ancillary measurements available at each OzFlux site (<http://www.supersites.net.au>). Included in this suite of data are soil characterisation, plant biodiversity, leaf area index (LAI),
220 vegetation structure, groundwater data, stream chemistry and faunal biodiversity (Karan et al., 2016). In addition, each SuperSite has been supported by the TERN Auscover remote sensing facility with ground based (terrestrial laser scanner) and air-borne (lidar, hyperspectral) remote sensing data collected in a 5 km x 5 km pixel centered at each tower. Like all TERN data these data sets are publically available from the TERN data portals with metadata made available across the portals at TERN (<http://portal.tern.org.au>).

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3 Eddy covariance data

3.1 Instrumentation and data collection

In 2016 the OzFlux network comprised 23 active flux towers across Australia (Fig. 2, Table 1). There is a high degree of consistency in instrumentation across the OzFlux network. The general tower configuration consists of a CSAT3 sonic
230 anemometer (Campbell Scientific, Logan, Utah, USA) and a Li-7500[A] (LI-COR, Lincoln, Nebraska, USA) or EC-150/155 (Campbell Scientific, Logan, Utah, USA) infra-red gas analyser mounted at the top of the tower. All sites record three components of the wind field, air temperature and the H₂O and CO₂ concentrations at 10 or 20 Hz. Complementary measurements of slow response wind speed (Gill Instruments Ltd, Lymington, Hampshire, UK; R.M. Young, Traverse City,



Michigan, USA), air temperature and humidity (various, Vaisala, Helsinki, Finland) are also made at least one height. Soil
235 water content (various, Campbell Scientific, Logan, Utah, USA), soil temperature (TCAV, Campbell Scientific, Logan, Utah,
USA) and ground heat flux (CN3, Middleton, Newtown, VIC, Australia; HFT3, Campbell Scientific, Logan, Utah, USA;
HFP01, Hukseflux, Delft, The Netherlands) are measured in soil pits adjacent to the towers and often replicated in space and
depth. Radiation (4-component) is measured at the tower top (CNR1, CNR4 Kipp & Zonen; NR01 Hukseflux; Delft,
Netherlands). Precipitation (CS702, Campbell Scientific, Logan Utah, USA; CS7000, Hydrological Services, Warwick Farm,
240 NSW, Australia) is measured at ground level at most sites. Systems measuring the profiles of H₂O and CO₂ concentration in
the canopy are installed at Tumarumba, Wombat Forest, Cumberland Plains, Whroo and Robson Creek. Details of the
instrumentation at each site are available from the OzFlux web site (<http://www.ozflux.org.au/monitoringsites/index.html>).

Data are recorded at most sites by Campbell data loggers (various, Campbell Scientific, Logan, Utah, USA).
Tumarumba, Otway and Virginia Park use purpose-built micro-computers. At all sites using Campbell data loggers, the
245 averaged and high frequency data are retrieved via modem or recorded on compact flash (CF) cards, which are retrieved
periodically, read and archived at the site PI's institute.

3.2 Data quality control and post-processing

Most sites with Campbell data loggers begin with the average (over 30 minutes) covariances recorded by the logger
250 and processed through six levels using the OzFluxQC standard software processing scripts. For details see Isaac et al. (2016)
but in brief, levels 1, 2 and 3 represent the raw data as received from the flux tower (L1), quality-controlled data (L2) and post-
processed, corrected but not gap-filled data (L3). OzFlux sites submit their data to FLUXNET at L3. Levels 4, 5 and 6
represent data with gap-filled meteorology (L4), gap-filled fluxes (L5) and partitioned into gross primary production (GPP)
and ecosystem respiration (ER) (L6). The L1 to L3 data used in this paper have been produced using OzFluxQC (Isaac et al.,
255 2016) and Level 3 are then gap filled and partitioned using the Dynamic INtegrated Gap filling and partitioning for Ozflux
(DINGO) system developed by Beringer as described in Donohue et al. (2014).

OzFluxQC quality control measures are applied at L2 and include checks for plausible value ranges, spike detection
and removal, manual exclusion of date and time ranges and diagnostic checks for all quantities involved in the calculations to



correct the fluxes. The quality checks make use of the diagnostic information provided by the sonic anemometer and the infra-
260 red gas analyser. For sites calculating fluxes from the averaged covariances, post-processing includes 2-dimensional
coordinate rotation, low- and high-pass frequency correction, conversion of virtual heat flux to sensible heat flux and
application of the WPL correction to the latent heat and CO₂ fluxes (see Burba (2013) for general description of the data
processing pathways). Steps performed at L3 include the correction of the ground heat flux for storage in the layer above the
heat flux plates (Mayocchi and Bristow, 1995) and correction of the CO₂ flux data for storage in the canopy (where available).
265 OzFlux data are available at <http://data.ozflux.org.au/>.

4 Biotic and abiotic controls on land-surface exchanges

We used the conceptual framework for carbon balance terms following Chapin et al. (2006), including their sign
convention where net and gross carbon uptake (net ecosystem production (NEP) and gross primary production (GPP)) are
270 positive directed toward the surface and ecosystem respiration (ER) is positive directed away from the surface. For ease, the
following analysis has been aggregated by ecoregion (Table 2) from the individual site data that are detailed in Table 3. Note
that the number of years representing each site is different. Net ecosystem production (NEP) across the ecoregions varied with
forests generally the strongest sink (followed by grasslands, savannas and shrublands). The Mediterranean ecosystems were
close to carbon neutral and deserts and xeric shrublands were a carbon source overall (Table 3). This can be compared to
275 AsiaFlux, where NEP varied across the network between -2 and 8 tC ha⁻¹ yr⁻¹ with the differences due mainly to tree species
and mean annual temperature (MAT) (Yamamoto et al., 2005). Across all of the OzFlux sites the average NEP was 1.8 tC ha⁻¹
yr⁻¹ which is comparable to the global average of 1.6 tC ha⁻¹ yr⁻¹ (Baldocchi, 2008).

There was also a large variation in the seasonality of carbon fluxes (Fig. 3) between the ecoregions, which followed
patterns in temperature and/or rainfall and moisture availability across the continent. Tropical moist broadleaf forests had the
280 smallest seasonality followed by savannas, which are seasonally water limited with seasonal variation driven by large dry
season decline in fluxes from the C₄ grass-dominated (Whitley et al., 2011). Tropical grasslands showed the largest seasonality
and notably had the largest peak NEP of 4.5 gC m⁻² d⁻¹ which occurs after re-sprouting and green-up during rapid growth



when soil respiration remains low (Fig. 3a). Only later during the season, when the grasses senesce is carbon returned to the atmosphere via fire and respiration and to the soil through litter and root carbon. Across the ecoregions, GPP generally scaled
285 with leaf area index (LAI) and water availability (precipitation) (Fig. 5), with desert shrublands having the lowest GPP and tropical moist broadleaf forests having the highest (Table 2) (Fig. 3b). Tropical grassland GPP was similar to that of forests during the monsoonal summer wet season; however, GPP in the grassland collapsed to near zero during the dry season (Fig. 3b). In general, the magnitude of ecosystem respiration (ER) was near a constant fraction of GPP across the annual cycle for each ecoregion (Fig. 3c and Fig. 4).

290 Following on from the average fluxes (discussed above), there are periods when substantial inter-annual variability is superimposed on Australia's mean climate (Cleverly et al., 2016b) and this variability has been captured by bush poet Dorothea Mackellar as the land of "droughts and flooding rains" (Mackellar, 2011). Australia's weather is primarily driven by three climate modes: El Niño-Southern Oscillation (ENSO), the Indian Ocean dipole (IOD) and the southern annular mode (SAM) and when these climate modes synchronise, fluctuations between drought and extreme precipitation can be extreme
295 and rapid (Cleverly et al., 2016b). Extreme weather across Australia during the 21st century has been the result of synchronisation amongst these climate modes, such that wet conditions created by one climate mode were reinforced by similarly wet conditions in the other modes (Cleverly et al., 2016b). The El Niño phase brings warmer and drier than average conditions, whilst cooler and wetter conditions are characteristic of La Niña phase (Nicholls et al., 1991; Power et al., 1999) and together all three modes of variability influence patterns of vegetation fluxes (Cleverly et al., 2016b). In general, rainfall
300 is limiting to productivity across much of Australia whereas temperature is not. Raupach et al. (2013), through a modelling study, showed that evapotranspiration (ET) from Australian ecosystems is expected to increase with increasing precipitation and temperature, but decrease with rising CO₂ through increased plant water-use-efficiency. They also showed that NEP is expected to increase with rising CO₂ concentration but this may be offset by reduced NEP in response to warming. Much of the network is, either directly or indirectly, contributing critical data to refine our understanding of the drivers of NEP and the
305 role of precipitation events on carbon and water cycles (Chen et al., 2014; Eamus et al., 2013a; Kanniah et al., 2011; Ma et al., 2013a).



Climate variability and land management also drives recurrent fire on the Australian landscape, with Australia being one of the most fire-prone continents on earth (Bradstock et al., 2012). Using AVHRR satellite data from 1997-2005, Russell-Smith et al. (2007) showed that the distribution of large fires varied with biophysical variables, and continental fire patterns varied substantially with rainfall seasonality. Their results highlight the importance of anthropogenic ignition sources, especially in the northern wet-dry tropics and demi-arid/arid Australia. These recent patterns differ greatly from assumed fire regimes under Indigenous occupancy, and the differences in fire regime can cause significant effects on biodiversity that are likely to increase in the future (Russell-Smith et al., 2007). Interestingly, a number of Australian flux sites have been influenced by wildfire including: 1) a catastrophic, stand replacing wildfire in the old growth Mountain ash forests (*Eucalyptus regnans*, Au-Wac) during February 2009; 2) a fire at Calperum (Au-Cpr) in January 2014 that burned spinifex (*Triodia* sp) ground cover and leaves and branches of eucalypt species; 3) frequent and relatively low intensity fires across all the savanna sites (Au-How, Au-Ade, Au-DaS, Au-Dry) and at a tropical grassland (Au-Stp). Many of the research questions, particularly in savannas, are focused on the influence of burning at scales from leaf to landscape (Beringer et al., 2003, 2007, 2014).

Annual NEP as measured by flux towers is the difference between GPP and ER (Chapin et al., 2006). On a site-by-site basis across the network, ER and GPP are strongly correlated ($r^2=0.93$) (Fig. 4) (Reichstein et al., 2005). The slope of the line is 0.76, which compares well with an international synthesis that found a slope of 0.77 (Baldocchi, 2008). The results from the international study are shown in the background of Fig. 4, where disturbed sites fall along a secondary line (carbon source). Interestingly, few Australian sites are close to this disturbed level, except for Au-RDF, which had undergone a transition from savanna to pasture, and Au-Wrr, which is a tall forest with potential advection issues such that the ratio of GPP to ER might be unreliable. Despite this, there are many flux towers in the network that have captured varying levels of disturbance including fire, insect attack (van Gorsel et al., 2013), logging, grazing, termite herbivory (Jamali et al., 2011) and tropical cyclones (Hutley et al., 2013). Curiously, as pointed out by Baldocchi (2008), Australian systems that are burnt frequently (i.e. savannas) do not fall in line with other types of disturbance (Fig. 4) because these low intensity fires form a type of rapid respiration that does not significantly alter carbon pools on annual timescales, either for vegetation (Beringer et al., 2003, 2007) or as soil carbon (Allen et al. 2014).



We used a simple heat map to identify correlations between fluxes, driving variables and functional attributes of Australian ecosystems (Fig. 5). We used the following ecosystem indices: radiation use efficiency (RUE) following Garbulsy et al. (2010); ecosystem water-use-efficiency (WUE* calculated as the ratio of GPP to AET, where * indicates ecosystem scale) and inherent ecosystem WUE* (IWUE* calculated as the ratio of GPP to AET x VPD) following Beer et al. (2009);
335 Bowen ratio (BR) is defined as the ratio between sensible and latent heat fluxes (Bowen, 1926); leaf area index (LAI) obtained from the average of the MODIS MOD15 product for the site years available and has been de-spiked using the procedure described in Kanniah et al. (2009a); and rainfall use efficiency (Rain Use Eff) following Huxman et al. (2004) and defined as the ratio of GPP to precipitation. Note that the magnitude of LAI from the MODIS LAI product utilised in this paper varies from site based estimates but has been used for consistency.

340 In general, the major controls on site-averaged GPP and NEP were precipitation, vapour pressure deficit (VPD) and LAI (Fig. 5) as expected (Yi et al., 2010). Counterintuitively, incoming solar radiation (F_{sd}) was negatively correlated with GPP, suggesting that F_{sd} is not limiting; we speculate that the negative correlation is explained by an association between regions of high sunlight (F_{sd}) in arid-semi/arid climates that have vegetation that tends to have lower GPP due to water limitations. Given LAI is such an important driver (and LAI is strongly correlated with precipitation), we normalised the
345 fluxes and indices by dividing them by LAI. Subsequently, these normalised ratios showed that after accounting for LAI, GPP was only weakly positively correlated ($r < 0.3$) with temperature (T_a) and negatively correlated with precipitation (Fig. 5). We hypothesise that the negative correlation of GPP/LAI with rainfall is due to the lower radiation due to cloud associated with high rainfall.

We further explored the relationships of GPP *versus* mean annual temperature (MAT) and mean annual precipitation
350 (MAP). We followed Garbulsy et al. (2010) to allow for a direct comparison with that global study where they used 35 eddy covariance (EC) flux sites (none from Australia) spanning between 100 and 2200 mm MAP and between -13 and 26°C MAT. The global relationships are shown in the background to aid comparison (Fig. 6). The range of GPP across the Australian sites was 32 to 2370 $\text{gC m}^{-2} \text{yr}^{-1}$ which is consistent with the range of global values (50 to 3250 $\text{gC m}^{-2} \text{yr}^{-1}$) (Fig. 6). The relationship between GPP and MAP follows the global function (Fig. 6a) although the range of MAP across the Australian sites is larger
355 than is observed from the global flux network due to the high MAP of the sites in the tropical rainforest region. In contrast to



the global study, MAT had no significant relationship with GPP (Fig. 6b) in Australia. This is partly because there are no sites in Australia with MAT below zero and MAT is generally not limiting to GPP, however, high temperature can limit NEP in the desert ecoregion (Cleverly et al., 2013, 2016a). The most highly productive sites were obviously not moisture limited, including cool temperate forests (MAT < ~12°C) and hot wet tropical forests (MAT > ~25 °C, MAP > 2000 mm) (Fig. 6a, b). The peak in GPP seen at MAT ~12 °C is consistent with an analysis of plot data from Australian temperate forests by Bowman et al. (2014) who noted maximum growth occurring at a mean annual temperature of 11 °C and maximum temperature of the warmest month of 25–27 °C. They found that lower temperatures directly constrained growth whilst high temperatures primarily reduced growth by reducing water availability.

Radiation-use-efficiency (RUE) across Australian ecoregions was tightly coupled with GPP and was similar (but perhaps higher) than the international relationship (Fig. 6d). There is a similarly large range in RUE across Australian ecoregions, from pasture (0.65 gC MJ PAR⁻¹), temperate and Mediterranean woodland (0.75 gC MJ PAR⁻¹), tropical savanna (1.0 gC MJ PAR⁻¹) and temperate and tropical forest (1.5 gC MJ PAR⁻¹). Global values across FluxNet showed RUE to be approximately 0.2 gC MJ PAR⁻¹ and 0.35 gC MJ PAR⁻¹ for grassland and savanna respectively (Reichstein et al., 2014). The correlation between RUE and GPP decreased when GPP was expressed per unit LAI (i.e. GPP / LAI – see Fig. 5) suggesting that all Australian ecosystems have similar efficiency per unit leaf and converge toward a similar biochemical efficiency.

The ecosystem water-use-efficiency (WUE*) of Australian systems was systematically lower than the global relationship (Fig. 6c) suggesting that these ecosystems have a low C gain per unit water loss. This surprising result is likely to reflect high soil evaporation ratios from open canopied woodlands and shrublands of the arid/semi-arid regions that dominate Australia. Haverd et al. (2013a) showed in BIOS2 modelling that over half (64%) of Australian ET is attributable to soil evaporation, which is much higher than the global fraction of 27%, that results in higher water loss per unit of C gained at the ecosystem scale. There are other important factors that could explain the smaller ecosystem WUE* of the non-arid Australian systems including: 1) it may reflect reduced leaf-scale instantaneous transpiration efficiency (ITE=A/E) (Barton et al., 2012); 2) the high degree of sclerophylly of Australian vegetation whereby C assimilation rates per unit leaf area will be low (compared to the USA or European flora) because of the large investment in thick cell walls and defensive compounds characteristic of long-lived sclerophyllous leaves (Eamus and Prichard, 1998); 3) leaf-level ITE of deciduous species is



generally larger than that of evergreen species (Eamus and Prichard, 1998; Medina and Francisco, 1994) and the flora of US and European broadleaf forests are almost exclusively deciduous; 4) optimality theory of stomatal behaviour predicts that ITE is inversely proportional to VPD (Medlyn et al., 2011) and since mean VPD is generally larger in Australia than the US and Europe, a smaller ITE is expected for Australian sites compared to global analyses that omit Australian sites and 5) low soil
385 nutrient availability of Australian soils (McKenzie et al., 2004) that limits photosynthetic capacity, reducing ITE (Schutz et al., 2009).

The WUE* and IWUE* of Australian sites ranged from 0.5 to 3.5 gC kgH₂O⁻¹ and 5.6 to 29.8 gC hPa kgH₂O⁻¹, respectively (Table 3), which is lower than global estimates (Beer et al. (2009)). A direct comparison with global results is difficult due to the dissimilar ecosystem types; however, Beer et al. (2009) obtained values of 3.1 gC kgH₂O⁻¹ and 30.3 gC
390 hPa kgH₂O⁻¹ for WUE* and IWUE*, respectively, in the evergreen broadleaf biome type. Across similar C3 broadleaf systems in Australia, both WUE* and IWUE* were lower at 2.2 gC kgH₂O⁻¹ and 16.7 gC hPa kgH₂O⁻¹. Previous research using Australian data have shown WUE* to be largest in evergreen broadleaf forest (EBF) sites (~3.0 gC kgH₂O⁻¹), followed by savanna sites (1.5 gC kgH₂O⁻¹) and grassland (~0.9 gC kgH₂O⁻¹) (Shi et al., 2014). They demonstrated the climate dependency of WUE* on VPD and soil water content, hence the preferred use of IWUE* here. Eamus et al. (2013b) examined WUE* and
395 IWUE* for a tropical Mulga woodland and observed: 1) that daily WUE* declined with increasing soil moisture content in both wet and dry seasons and declined with increasing VPD only in the dry season, a result attributed to an interaction of soil moisture content with VPD in the wet; 2) IWUE* declined with increasing soil moisture content and increased with increasing VPD in both seasons.

400 5 Synergies with modelling and remote sensing

5.1 Synergies between remote sensing and the OzFlux network

Satellite derived meteorology and optical spectral vegetation indices (VIs) have been used extensively to scale flux tower datasets in space and time (Chen et al., 2007; Huete et al., 2008; Muraoka and Koizumi, 2008; Verma et al., 2014). Satellite-derived land cover data provide information on spatial variations in vegetation type and structure, which is then used



405 to interpolate between flux tower sites. Moreover, intra-annual and long term remote sensing products can elucidate the timing of plant growth / seasonality (Ma et al., 2013b) and extent of prior climate, fire, land use, and disturbances, thus helping better understand observed fluxes (Asner, 2013; Baumann et al., 2014; Wulder and Franklin, 2006). In some instances, satellite data have been used to gap fill meteorological data when required for the generation of model drivers and annual budgets (de Goncalves et al., 2009; Reichle et al., 2011; Restrepo-Coupe et al., 2013). Vegetation indices and other biophysical products
410 (e.g. MODIS LAI and fPAR) constitute measures of ecosystem structure (e.g. quantity of leaves, (Sea et al., 2011) and function (e.g. quality of leaves) and represent the phenological drivers of productivity, transpiration and other key ecosystem fluxes (Restrepo-Coupe et al., 2015; Zhang et al., 2010). Therefore, quantification of surface characteristics via satellite products improves flux studies and provides a more robust analysis of carbon, energy and water cycles. The integration of eddy covariance and remote sensing datasets has driven recent efforts to measure optical properties at flux sites, closing the gap
415 between sampling of temporal and spatial scales (Gamon et al., 2006, 2010).

Conversely, flux data and ancillary *in situ* measurements associated with eddy covariance systems have been extensively used for the validation of different satellite products (e.g. MODIS GPP and ET (Kanniah et al., 2009b; Restrepo-Coupe et al., 2015)) and to assist in the parameterisation of models that rely on remotely sensed data (e.g. GPP, ET, canopy conductance, and light use efficiency (LUE)) (Barraza et al., 2014, 2015; Glenn et al., 2011; Goerner et al., 2011). Given the
420 challenge of managing water in the dry Australian continent, remote sensing of actual ET is a crucial task and Glenn et al. (2011) provide an overview of the Australian experience in this task. Similarly, *in situ* fluxes can provide the basic information required for the interpretation of satellite derived measures of greenness (Huete et al., 2006, 2008; Restrepo-Coupe et al., 2015). Recently, comparisons between flux data and satellite products have been proposed as a tool to evaluate sensor continuity, e.g. transition from MODIS derived VIs to the Visible - Infrared Imaging Radiometer Suite (VIIRS) instrument
425 (Obata et al., 2013). Ground-based flux tower measures, however, offer much more than validation of remote sensing products and models. An understanding of why satellite – flux tower relationships hold or don't hold can greatly advance and contribute to our understanding of mechanisms underpinning carbon and water cycles and scaling factors.



5.2 Synergies between terrestrial biosphere modelling and the OzFlux network

430 Development and validation of terrestrial biosphere models are reliant on observational data. Here we refer to examples of the utility of OzFlux data for advancing these models. OzFlux data were instrumental in constraining a continent-wide assessment of terrestrial carbon and water cycles (Haverd et al., 2013a). That paper explored the utility of multiple observation types (streamflow, measurements of evapotranspiration (ET) and net ecosystem production (NEP) from 12 eddy-flux sites, litterfall data and data on carbon pools) to constrain a terrestrial biosphere land surface model of Australian terrestrial
435 carbon and water fluxes. They conclude that eddy flux measurements provide a significantly tighter constraint on continental net primary production (NPP) than all the other data types. Nonetheless, simultaneous constraint by multiple data types is important for mitigating bias from any single type. Four significant results emerged from the multiply constrained model of the 1990–2011 period: 1) on the Australian continent, a predominantly semi-arid region, over half the water loss through ET (0.64 ± 0.05) occurred through soil evaporation and bypassed plants entirely; 2) mean Australian NPP was quantified at 2.2 ± 0.4
440 PgC yr^{-1} , with a significant reduction in uncertainty compared with previous estimates; 3) annually cyclic (“grassy”) vegetation and persistent (“woody”) vegetation accounted for 0.67 ± 0.14 and $0.33 \pm 0.14 \text{ PgC yr}^{-1}$, respectively, of NPP across Australia; 4) the average inter-annual variability of Australia’s NEP ($\pm 0.18 \text{ PgC yr}^{-1}$) was larger than Australia’s total anthropogenic greenhouse gas emissions in 2011 ($0.149 \text{ PgC equivalent yr}^{-1}$) and was dominated by variability in semi-arid regions. Results from the above model-data synthesis were used to produce major flux components of the first ever full terrestrial carbon budget
445 of Australia (Haverd et al., 2013b) as part of a larger international effort to reconcile bottom-up and top-down estimates of the global carbon budget. Further applications include an assessment of the climate sensitivity of Australian carbon and water cycles (Raupach et al., 2013) and an assessment of the magnitude of the Australian contribution to the record global sink anomaly of 2011, with counter-evidence to the assertion by Poulter et al. (2014) that Australian semi-arid ecosystems have entered a regime of increased sensitivity of NEP to precipitation (Haverd et al., 2015).

450 OzFlux data have also featured in the development of new models. For example, they have been used as constraints and validation for reductionist approaches to modelling evapotranspiration and canopy conductance at continental Australian (Guerschman et al., 2009) and global scales (Yebra et al., 2012). They have also been critical to the development of novel model parameterisations for heat storage in vegetation (Haverd et al., 2007), in-canopy turbulence (Haverd et al., 2009), stable-



isotope transport in soil and vegetation (Haverd and Cuntz, 2010) and canopy radiative transfer (Haverd et al., 2012). More
455 recently they have been employed as constraints in the development of a novel approach to modelling coupled carbon
allocation and phenology in savanna ecosystems, leading to emergent predictions about the controls of tree cover in Australian
savannas (Haverd et al., 2016). Alternate modelling strategies such as use of stomatal optimality theory has been developed
and tested in Australian savannas using OzFlux data (Schymanski et al., 2008a, 2008b).

460 **6 Future outlook**

The OzFlux network has been highly successful in generating standardised measurements and protocols, as well as for
providing advanced QA/QC data compatible with international databases (FLUXNET) (Papale et al., 2006) under an open
access data policy. OzFlux has contributed to the FLUXNET community efforts to improve data processing algorithms to
minimise potential errors associated with night-time bias, gap filling and lack of energy balance closure (Baldocchi, 2003; van
465 Gorsel et al., 2009). This has enabled a significant uptake of the eddy covariance data for application to a range of research
questions as exemplified above. OzFlux is also aligned with the long-term plan for Australian ecosystem science (Andersen
et al., 2014).

Dynamic global models are based on the notion that the same environmental controls will produce the same vegetation
structure irrespective of environmental and evolutionary history (Lehmann et al., 2014). The unique evolutionary history of
470 the Australian continent, climate and vegetation underpins the importance of the OzFlux network as it provides Australian
derived data for key ecosystem metrics such as NEP, GPP, RUE and IWUE* for use in continental and global vegetation
models. Despite the dominance of the semi-arid/arid climate and the importance of semi-arid ecosystems in Australia and
globally, there still remains a gap in our knowledge about the effect of soil water deficits, soil evaporation, extreme
temperatures and vapour pressure deficits (Eamus et al., 2013b) both as ecosystem drivers and as extreme events that
475 accompany drought. Currently, ecosystem response to drought is not well understood, particularly because low precipitation
events themselves are unpredictable in timing, duration and severity. It is expected that the frequency and severity of drought
will increase with climate change; therefore, our current understanding of responses to rainfall scarcity will aid in our
understanding of ecological responses to future climate and the potential consequences and adaptation that may be required.



480 A number of drought related questions can be addressed by OzFlux including: 1) how do droughts affect physiological processes such as photosynthesis at leaf to landscape scales; 2) what is the effect of seasonal droughts *versus* multi-year droughts; 3) are there critical thresholds or compensatory reductions in productivity due to drought; and 4) are there multi-year drought legacy or feedback effects?

We have demonstrated that OzFlux has already contributed to other areas of importance such as ecosystem responses to fire, pest outbreaks, cyclones, and the impact of land use and land cover change (including urban flux systems (Coutts et al., 2007, 2010)) (Baldocchi, 2014a). Future climate is likely to be more variable and extreme and the network is well placed to capture and understand these events (Frank et al., 2015).

490 While there is no significant influence of temperature on NEP or GPP across Australian biomes the strong dependence of these variables on MAP indicates that even in currently well-watered areas the combined effect of increased temperature and VPD, similar or reduced water availability will potentially place these systems under stress. OzFlux then is well positioned to provide continuous assessment of the long-term condition of these ecosystems and provide early warning across multiple ecosystems of changes in plant performance as the planet moves into the more forceful climate of the Anthropocene.

There are also opportunities for OzFlux to play a core role in investigating processes within the ‘Critical Zone’, defined as the Earth’s outer layer from vegetation canopy and through the soil and groundwater that sustains human life (Lin, 2010). Critical zone science extends us from the thin surface layer to the larger critical zone domain that allows a comparison of the environmental effects across gradients of climate (Cernusak et al., 2011), time, lithology, human disturbance, biological activity and topography (Lin, 2010). This should also involve a focus on greenhouse gas exchanges (not just CO₂ but also N₂O and CH₄) from the soil and understanding the linkages with microbial and rhizosphere processes (Hinsinger et al., 2009; Livesley et al., 2011). Some of OzFlux contribution here can be to utilise overstorey and understorey flux measurements to understand the role of distinct understorey vegetation such as the grasses versus trees in savannas (Moore et al., 2015)

500 Baldocchi (2014b) reminds us that additional ecological and physiological measurements (function, structure, pools and turnover) add significant value to our flux data and are required for modelling carbon pools. OzFlux works closely with the SuperSite Facility (Karan et al., 2016) in TERN as each SuperSite is required to co-host an OzFlux tower. Over the last 4 years ecophysiological data have been collected across 7 sites and along with prior data from a number of OzFlux sites this



has allowed an early assessment of plant performance to be made across many of the OzFlux sites. The SuperSites facility
505 complements the OzFlux measurements by measuring the biotic community and biophysical environment. Co-location of
activities for both facilities has been important as this has enabled both networks to share resources and survive through tough
financial times. Like any long-term network in Australia this ability to survive is a hall-mark of success (Lindenmayer et al.,
2012). Hence, it is imperative that going forward OzFlux enhances and utilises the synergies and research collaborations
between OzFlux and other TERN platforms such as remote sensing (AusCover), modelling (eMAST) and plot networks such
510 as transects, AusPlots and the long term ecological research network (LTERN). No single capability is able to address all of
the spatial, ecological, human and cultural challenges required. Instead a synergistic approach (Peters and Loescher, 2014) that
is policy relevant (with political commitment) is required to monitor and manage our planet.

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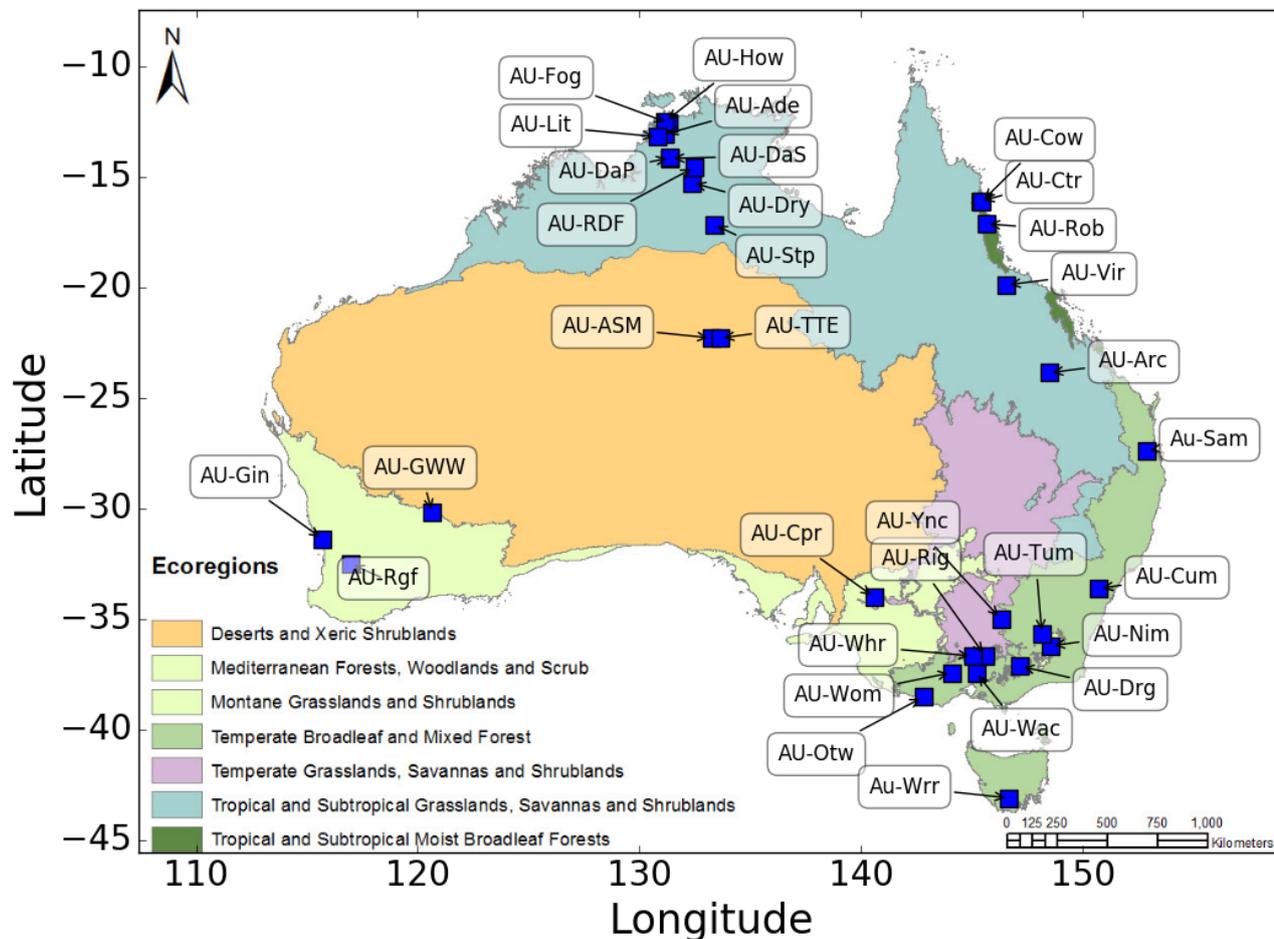


Figure 1: Major Australian biomes defined using the Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (Environment, 2012). Flux sites from Table 1 are shown illustrating the wide geographical and biome space but each biome is not equally represented. Only a small fraction of the OzFlux sites (8%) are located in the arid/semi-arid biomes that comprises 74% of the landscape.

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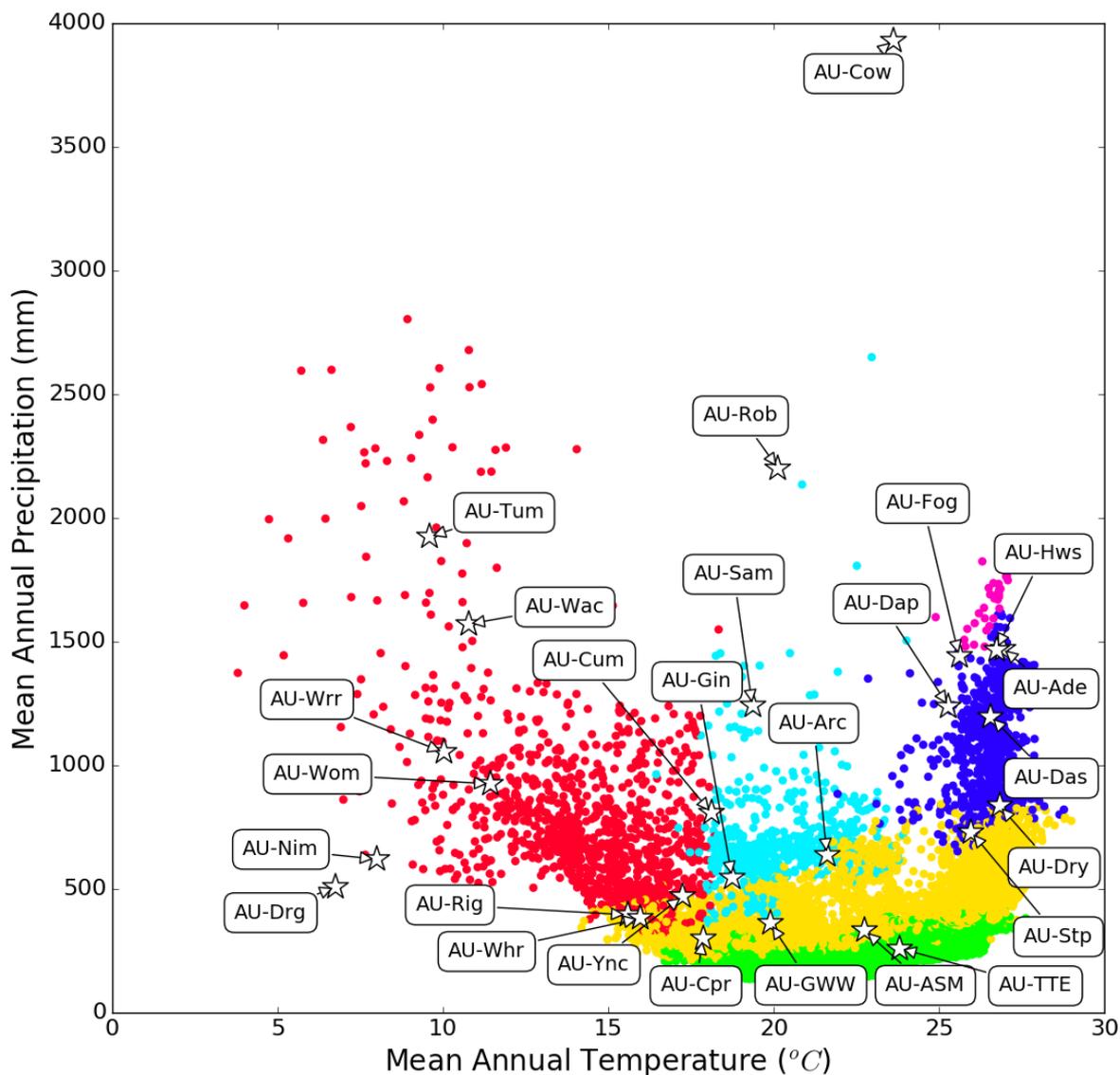
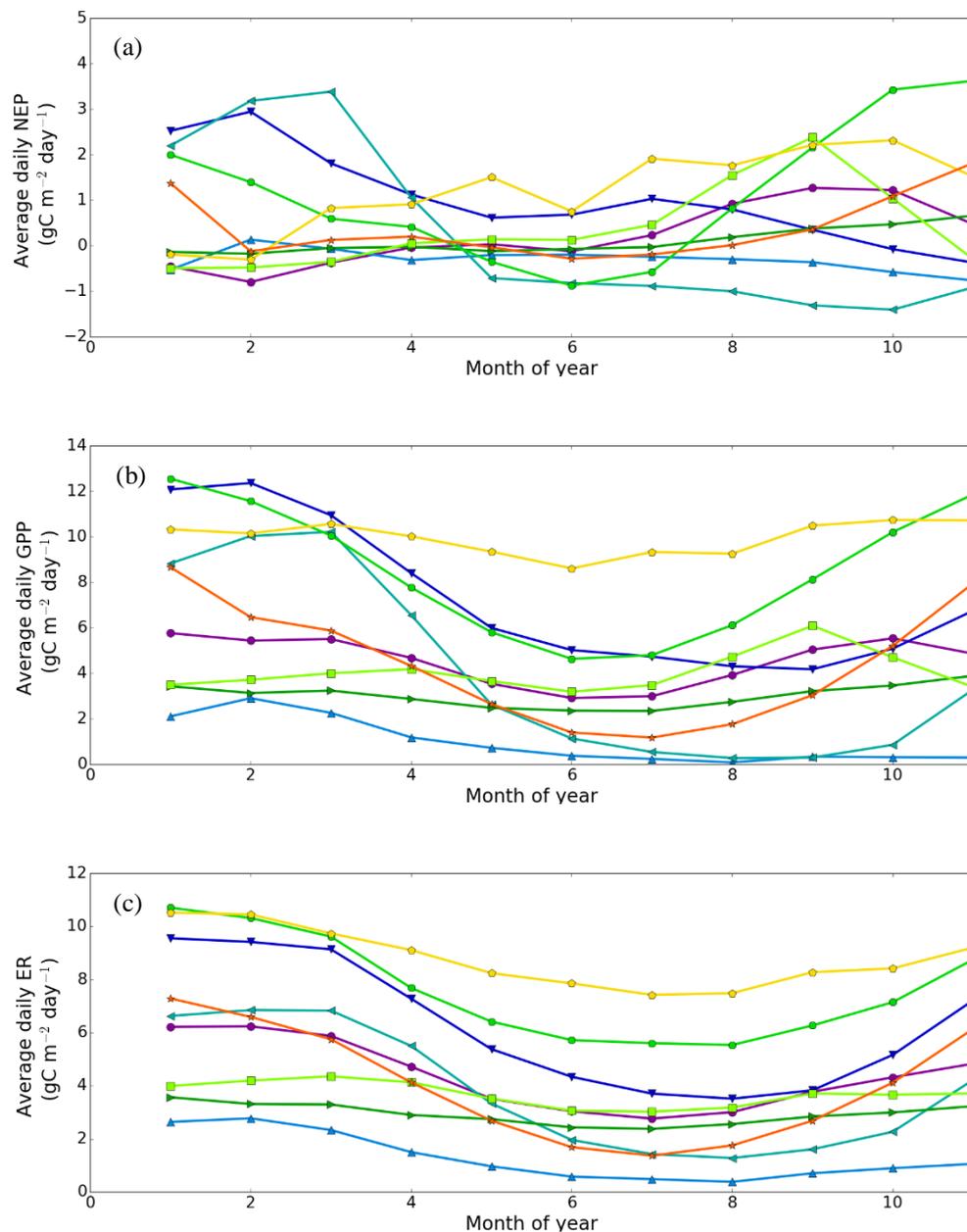


Figure 2: OzFlux sites (white stars) across bioclimatic space with Fluxnet codes (Table 1). Mean annual temperature and mean annual precipitation are shown as the climate space using mean annual (1961-1990) gridded data (0.1 degree resolution) (Bureau-of-Meteorology, 2013). The colours represent the major modified Köppen climate classes (Stern and Dahni, 2013) as follows: 1) Equatorial (Pink), Tropical (Dark Blue), Sub-tropical (Light Blue), Desert (Green), Grassland (Yellow) and Temperate (Red).

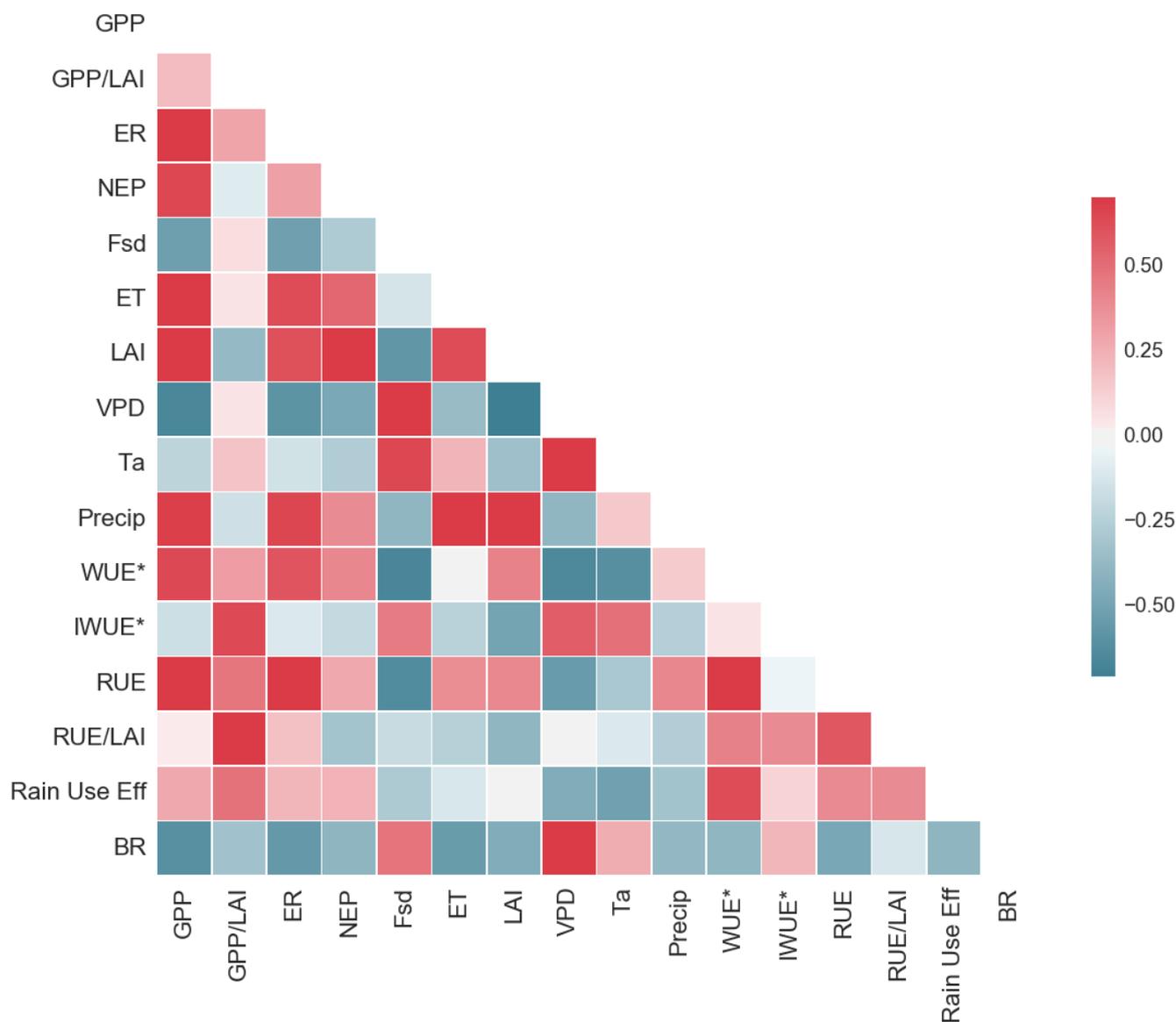
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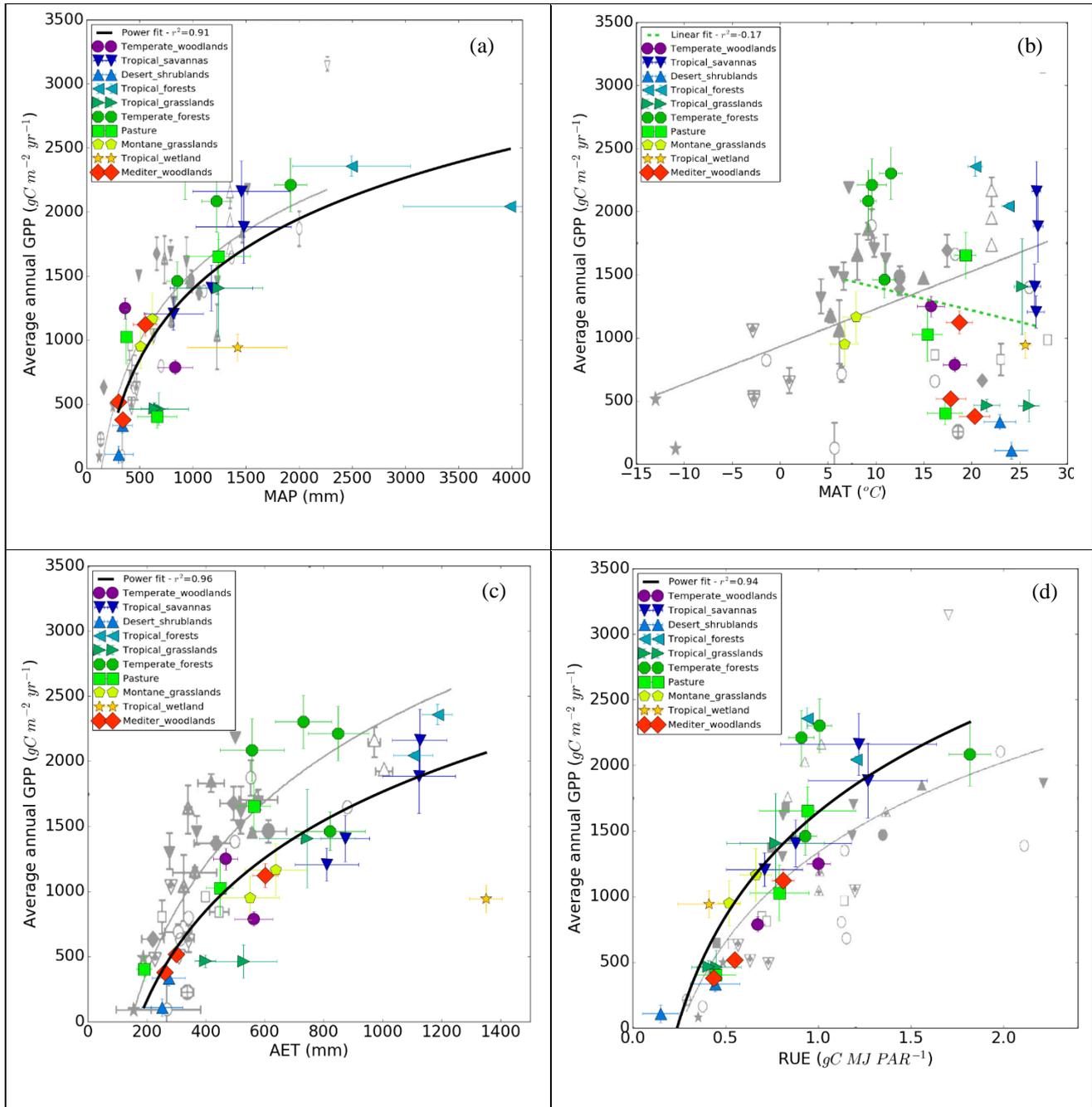
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Figure 3: Weekly ensemble of the measured Net Ecosystem Productivity (NEP) (a) and component Gross Primary Production (GPP) (b) and Ecosystem Respiration (ER) (b) for all OzFlux tower sites in each biome as follows temperate woodlands, tropical savannas, desert shrublands, tropical grasslands, mediterranean woodlands, temperate broadleaf forests, pasture, tropical moist broadleaf forests and montane grasslands. The sites used in each biome are shown in Table 1. GPP generally scales with Leaf Area Index (LAI) and water availability. Most of the variability follows the respective rainfall patterns associated with the tropical, mediterranean, and temperate climates.

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990 **Figure 5:** Simple heat map of annual average OzFlux tower measurements to identify the correlations between fluxes, driving
 variables and ecosystem indices using all available site years of data. Fluxes are gross primary productivity (GPP), ecosystem
 respiration (ER), net ecosystem production (NEP), evapotranspiration (ET). Drivers are leaf area index (LAI), precipitation
 (Precip), air temperature (T_a), incoming solar radiation (F_{sd}) and vapor pressure deficit (VPD). We used the following ecosystem
 indices: radiation use efficiency (RUE) following Garbulsky et al. (2010); ecosystem water-use-efficiency (WUE*) and inherent
 ecosystem WUE* (IWUE*) following Beer et al. (2009); Bowen ratio (BR) is defined as the ratio between sensible and latent heat
 995 fluxes (Bowen, 1926); Leaf area index (LAI) was obtained from the average of the MODIS MOD15 product for the site years
 available that has been de-spiked using the procedure described in Kanniah et al. (2009a); and rainfall use efficiency (Rain Use Eff)
 was defined following Huxman et al. (2004) as the ratio of GPP to precipitation. GPP and RUE are also normalized by LAI by
 dividing them by LAI to produce series such as GPP/LAI. Colour scale indicates the strength of Pearson correlation co-efficient (r).



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Figure 6: The relationships of OzFlux tower data by ecoregion type (Table 1) between gross primary production (GPP) and the major climate drivers (a) mean annual precipitation (MAP) and (b) mean annual temperature (MAT). Also shown is the relationship between GPP and (c) actual evapotranspiration (AET) and (d) radiation use efficiency (RUE). The global relationships in Garbulsky et al. (2010) are shown in the background to aid comparison. Simple curve fits are shown to aid visualization.



Table 1: A summary of the OzFlux tower sites along with the available data range and site history. The associated IBRA vegetation class is given (IBRA) along with the broader world ecoregion classification, both from the Interim Biogeographic Regionalisation for Australia v. 7 (IBRA) (Environment, 2012).

Site name	FLUXNET ID	Date range	Latitude S	Longitude E	Elevation (m)	IBRA	World ecoregion	Site history
Adelaide River	AU-Ade	2007-2009	-13.08	131.12	100	PCK	Tropical savannas	Woodland savanna on shallow loamy sand (hydrosol) with low level grazing pressure, fire frequency 1 in 3 years.
Alice Springs	AU-ASM	2010-present	-22.28	133.25	606	BRT	Deserts and Xeric Shrublands	Pine Hill cattle station. Cattle grazing in low numbers has continued for decades.
Arcturus	AU-Arc	2011-2013	-23.86	148.47	178	BBN	Tropical grassland	Pasture (to W) Lightly forested tussock grasslands: Crop (to E): 2011-June 2012: Barren land due to flooding, followed by remediation work, June 2012-November 2012: Chickpeas, November 2012-June 2013: Fallow, June 2013-November 2013: Wheat, November 2013-January 2014: Fallow



Calperum	AU-Cpr	2010- present	-34.00	140.59	53	MDD	Mediterranean woodlands	Multi-stemmed, 3-5m high eucalypt trees centred 2-4m apart with limited mid-story species, extensive perennial spinifex and occasional annual grasses. Regrowth of trees after fire ~ 35years ago with sheep grazing ceased in 1994. Site burned by wildfire in January 2014 and regrowth now occurring.
Cape Tribulation	AU-Ctr	2001- present	-16.10	145.45	66	WET	Tropical and Sub-tropical moist broadleaf	Selective logging finished. World Heritage, National Park fetch region.
Cow Bay	AU-Cow	2009- present	-16.24	145.43	86	WET	Tropical and Sub-tropical moist broadleaf forests	Selective logging finished. World Heritage, National Park fetch region.
Cumberland Plains	AU-Cum	2012- present	-33.62	150.72	54	SYB	Temperate woodlands	Not been managed but is a remnant woodland at the urban-wildland interface.



Daly River Pasture	AU-DaP	2007-2013	-14.13	131.39	67	DAB	Tropical pasture	Tropical improved pasture (C ₄ grass and legume mixture), cleared 1982, low grazing pressure (~1 head ha ⁻¹), fire 1 in 5 years.
Daly River Savanna	AU-DaS	2007-present	-14.16	131.39	53	DAB	Tropical savannas	Woodland savanna on deep sandy loam soils (kandosol), native pasture grazing, very low grazing pressure (~0.1 head ha ⁻¹), fire 1 in 5 years.
Dargo	AU-Drg	2007-present	-37.13	147.17	1648	AUA	Montane grasslands	Low density historical and current grazing during the warmer months .
Dry River	AU-Dry	2008-present	-15.26	132.37	180	STU	Tropical savannas	Woodland savanna on sandy loam soils, native pasture grazing, low grazing pressure (~0.5 head ha ⁻¹), fire 1 in 8 years.
Fogg Dam	AU-Fog	2006-2008	-12.55	131.31	4	DAC	Tropical wetland	Seasonally inundated wetland, conservation reserve, heavy clay soils (vertisol).



Gingin	AU-Gin	2011- present	-31.38	115.71	53	SWA	Mediterranean woodlands	The only current active (and accidental) management is fire, with the Dept of Parks and Wildlife conducting controlled fuel reduction burns approximately every 20 years. The area immediately to the north was burned in a wildfire in 2006, and to the south has not been burned for at least 30 years.
Great Western Woodland	AU-GWW	2013- present	-30.19	120.65	486	COO	Mediterranean woodlands	Managed as conservation reserve since 2007; sheep and cattle grazing from 1906 to 2007 led to some soil surface degradation.
Howard Springs	AU-How	2001- present	-12.49	131.15	41	DAC	Tropical savannas	Open-forest savanna on sandy loam soils, peri-urban water catchment reserve, previously grazed (1960s), fire frequency 1 in 2 years .



Litchfield	AU-Lit	2015- present	-13.18	130.79		DAC	Tropical savannas	Open-forest savanna on sandy loam soils, national park, fire frequency 1 in 2 years.
Nimmo	AU-Nim	2007- present	-36.22	148.55	1337	AUA	Montane grasslands	Low density historical and current grazing during the warmer months.
Otway	AU-Otw		-38.53	142.81		SCP	Pasture	
Red Dirt Melon Farm	AU-RDF	2011- 2013	-14.56	132.48	171	DAB	Tropical savannas	Woodland savanna on sandy loam soils, cleared and converted to cropland in 2012, fire frequency (in uncleared state) 1 in 12 years.
Ridgefield	AU-Rgf	2015- present	-32.51	116.97		AVW	Pasture	
Riggs Creek	AU-Rig	2010- present	-36.65	145.58	162	RIV	Pasture	Ongoing cattle and sheep grazing.
Robson Creek	AU-Rob	2013- present	-17.12	145.63	710	WET	Tropical and Sub-tropical moist broadleaf forests	Selective logging finished 1969. World Heritage, National Park fetch region. Traditional use of the forest by Tablelands Yidinji had finished by the 1960s.



Samford	AU-Sam	2010- present	-27.39	152.88	87	SEQ	Pasture	Native woodland clearly over 100 years ago, grazed tropical native and improved grasses supporting subsistence livestock production until 2009. Simulated grazing from 2009.
Sturt Plains	AU-Stp	2008- present	-17.15	133.35	225	MGD	Tropical grasslands	Mitchel grassland plain on cracking clay soils (vertosol), very low grazing pressure (<0.1 head ha ⁻¹), fire 1 in 16 years.
Ti Tree East	AU-TTE	2012- present	-22.29	133.64	553	BRT	Deserts and Xeric Shrublands	Pine Hill cattle station. Cattle grazing ceased between 2009 – 2013 but was re-introduced in in July 2014 and stocked continuously in low-to-moderate densities (~3000 head of cattle on ca. 700 km ²).
Tumbarumba	AU-Tum	2001- present	-35.66	148.15	1249	NSS	Temperate Broadleaf and mixed Forest	2003 insect attack, 2004 selective logging in footprint.
Virginia Park	AU-Vir		-19.88	146.55		EIU	Savanna	



Wallaby Creek	AU-Wac	2005- 2013	-37.43	145.19	738	SHE	Temperate Broadleaf and mixed Forest	Old growth forest burned by stand replacing fire in Feb 2009 and now regrowing forest.
Warra	AU-Wrr	2013- present	-43.10	146.65	121	TSR	Temperate Broadleaf and mixed Forest	Natural forest that has originated from natural disturbance by period wildfire (most recent wildfire was in 1898).
Whroo	AU-Whr	2011- present	-36.67	145.03	143	VIM	Temperate woodlands	Clearing in the broader area during the 19th century to supply timber for gold mining. It is also thought that there was selective logging in the area during much of the 20th century. Some of this is most likely relatively recent, with numerous tree stumps present at the site.
Wombat	AU-Wom	2010- present	-37.42	144.09	715	VIM	Temperate broadleaf forest	Site is a ~ 25 years old secondary regrowth forest with a tree height of 21–25 m. Forest



Yanco	AU-Ync	2012- present	-34.99	146.29	128	RIV	Temperate Grasslands	management includes rotational prescribed burns of understorey vegetation and shelter wood harvesting. Ongoing cattle and sheep grazing.
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Table 2: Summary of the representation of OzFlux tower sites within each ecoregion compared with the total percentage of the continent comprising this ecoregion (Environment, 2012). The mean carbon fluxes are given for each ecoregion type.

Ecoregion	Percentage of the continent comprising this ecoregion (%)	Percentage of flux towers in that ecoregion (%)	GPP (tC ha ⁻¹ yr ⁻¹)	NEP (tC ha ⁻¹ yr ⁻¹)	ER (tC ha ⁻¹ yr ⁻¹)
Tropical and subtropical moist broadleaf forests	<1	12	22.1	2.8	19.3
Temperate broadleaf and mixed forest	7	16	21.5	3.9	17.6
Tropical and subtropical grasslands, savannas and shrublands	30	28	14.1	1.7	12.4
Temperate grasslands, savannas and shrublands	3	16	14.5	3.4	11.1
Montane grasslands and shrublands	<1	8	10.6	1.2	9.4
Mediterranean forests, woodlands and scrub	11	12	6.7	0.2	6.5
Deserts and xeric shrublands	49	8	1.8	-1.1	2.8



Table 3: Site averaged data for each OzFlux tower for available data periods (Table 1) showing mean and standard deviation of the daily fluxes. Fluxes are gross primary productivity (GPP), ecosystem respiration (ER), net ecosystem production (NEP), evapotranspiration (ET). Drivers are leaf area index (LAI), precipitation (Precip), air temperature (Ta), incoming solar radiation (Fsd) and vapour pressure deficit (VPD). We used the following ecosystem indices: radiation use efficiency (RUE) following Garbulska et al. (2010); ecosystem^(*) water-use-efficiency (WUE*) and inherent ecosystem WUE* (IWUE*) following Beer et al. (2009); Bowen ratio (BR) is defined as the ratio between sensible and latent heat fluxes (Bowen, 1926); Leaf area index (LAI) was obtained from the average of the MODIS MOD15 product for the site years available that has been despiked using the procedure described in Kanniah et al. (2009a); and rainfall use efficiency (Rain Use Eff) was defined following Huxman et al. (2004) as the ratio of GPP to precipitation. Some quantities are also normalized by LAI by dividing them by dividing by LAI to produce series such as GPP/LAI.

Site	Data years inclusive	GPP	GPP/LAI	ER	NEP	Fsd	Fn	LAI	VPD	Ta	Ah	Precip	WUE*	IWUE*	IWUE*_LAI	RUE	Rain	BR	ET
		tC ha ⁻¹ yr ⁻¹	tC ha ⁻¹ yr ⁻¹ m ² m ⁻²	tC ha ⁻¹ yr ⁻¹	tC ha ⁻¹ yr ⁻¹	MJ m ⁻² d ⁻¹	MJ m ⁻² d ⁻¹	m ² m ⁻²	kPa	°C	g m ⁻³	mm yr ⁻¹	gC kgH ₂ O	gC kgH ₂ O hPa	gC kgH ₂ O m ² m ⁻² hPa	gC MJ PAR ⁻¹	tC ha ⁻¹ yr ⁻¹ mm ⁻¹		mm yr ⁻¹
Adelaide River	2007-2009	18.8 ± 10.5	15.9 ± 5.2	15.3 ± 7.0	3.5 ± 5.0	20.5 ± 2.3	12.2 ± 2.5	1.1 ± 0.4	1.4 ± 0.5	26.9 ± 1.7	16.2 ± 4.7	1472.7 ± 1612.3	1.6 ± 0.4	21.1 ± 8.2	21.8 ± 12.9	1.2	12.8	0.7 ± 0.6	1120.8 ± 457.4
Alice Springs	2010-2014	3.2 ± 3.5	8.6 ± 5.9	3.5 ± 3.1	-0.3 ± 1.3	22.6 ± 3.7	11.2 ± 3.0	0.3 ± 0.1	2.1 ± 0.8	22.8 ± 5.7	6.9 ± 2.8	331.3 ± 451.3	1.9 ± 1.7	29.8 ± 18.9	108.8 ± 89.3	0.4	9.6	15.1 ± 21.4	263.9 ± 272.5
Arcturus	2011-2013	4.7 ± 3.1	6.6 ± 3.7	5.1 ± 1.3	-0.4 ± 2.7	19.6 ± 4.2	10.5 ± 3.2	0.7 ± 0.3	1.3 ± 0.5	21.6 ± 4.7	10.7 ± 2.8	638.8 ± 575.2	1.2 ± 0.6	13.8 ± 6.9	20.2 ± 8.3	0.4	7.3	2.1 ± 1.4	398.9 ± 165.7
Calperum	2010-2014	5.2 ± 2.3	10.5 ± 3.1	4.6 ± 1.5	0.6 ± 1.5	18.4 ± 6.9	8.7 ± 4.6	0.5 ± 0.1	1.3 ± 0.7	17.9 ± 5.3	7.5 ± 1.3	300.6 ± 312.8	1.7 ± 0.7	20.7 ± 10.9	44.2 ± 21.6	0.6	17.1	2.9 ± 2.0	300.4 ± 139.9
Cow Bay	2009-2014	20.5 ± 1.4	4.6 ± 1.1	18.1 ± 2.0	2.4 ± 2.3	12.1 ± 2.9	7.3 ± 2.2	4.7 ± 0.9	0.6 ± 0.1	23.6 ± 2.2	17.4 ± 2.5	3930.0 ± 4631.5	1.9 ± 0.4	11.0 ± 4.5	2.4 ± 1.1	1.3	5.2	0.1 ± 0.2	1087.1 ± 251.7
Cumberland	2013-2014	9.1 ± 3.1	7.4 ± 2.1	9.8 ± 3.5	-0.7 ± 3.0	12.6 ± 8.8	7.2 ± 5.3	1.3 ± 0.2	0.8 ± 0.3	18.1 ± 4.1	10.6 ± 2.8	806.3 ± 787.3	1.5 ± 0.7	11.7 ± 3.9	9.0 ± 3.5	0.4	9.7	0.7 ± 0.7	550.1 ± 273.1
Daly River Pasture	2007-2013	14.0 ± 13.5	6.9 ± 5.5	12.9 ± 8.1	1.1 ± 6.3	21.3 ± 2.1	10.9 ± 1.8	1.5 ± 0.8	1.4 ± 0.5	25.3 ± 2.9	14.6 ± 4.6	1237.8 ± 1701.0	1.5 ± 0.7	18.0 ± 6.6	13.7 ± 8.3	0.6	11.3	3.4 ± 4.0	740.7 ± 580.3
Daly River Uncleared	2007-2014	14.3 ± 6.7	11.6 ± 2.9	13.9 ± 5.7	0.5 ± 2.7	20.8 ± 2.3	11.8 ± 2.7	1.2 ± 0.3	1.6 ± 0.5	26.6 ± 2.5	14.5 ± 4.4	1197.5 ± 1550.0	1.6 ± 0.3	24.5 ± 8.4	22.2 ± 10.4	0.9	12	0.9 ± 0.5	869.6 ± 297.9



Dargo	2007-2014	9.5 ± 5.8	4.3 ± 1.5	7.8 ± 4.1	1.8 ± 2.0	16.6 ± 6.6	7.6 ± 5.5	2.1 ± 0.9	0.3 ± 0.2	6.8 ± 5.0	5.7 ± 1.3	509.2 ± 420.3	1.6 ± 0.4	5.6 ± 3.5	2.6 ± 1.1	0.5	18.7	0.3 ± 0.6	551.4 ± 331.8
		4.9		± 3.7	2.4	± 2.3	± 2.5	0.2	0.6	± 3.4	± 4.6	1093.2	0.4	13.2					1.1
Dry River	2008-2014	12.3 ± 4.9	10.3 ± 2.6	-11.4 ± 3.7	0.9 ± 2.4	22.0 ± 2.3	11.8 ± 2.5	1.2 ± 0.2	1.8 ± 0.6	26.8 ± 3.4	13.7 ± 4.6	836.4 ± 1093.2	1.6 ± 0.4	28.3 ± 13.2	26.7 ± 16.1	0.7	14.7	1.2 ± 1.1	805.4 ± 361.5
Fogg Dam	2006-2008	9.5 ± 3.8	4.2 ± 1.3	6.3 ± 0.8	3.2 ± 3.4	21.3 ± 2.4	13.4 ± 1.8	2.2 ± 0.3	1.0 ± 0.3	25.6 ± 2.4	17.1 ± 3.8	1440.2 ± 1650.0	0.7 ± 0.2	6.5 ± 1.2	3.0 ± 0.7	0.4	6.6	0.3 ± 0.3	1355.3 ± 260.6
Gingin	2011-2014	11.2 ± 3.2	12.8 ± 2.3	10.9 ± 1.5	0.3 ± 2.2	19.8 ± 7.0	11.0 ± 4.9	0.9 ± 0.2	1.0 ± 0.6	18.7 ± 4.9	10.2 ± 1.4	546.7 ± 479.5	1.9 ± 0.5	20.5 ± 14.5	22.0 ± 13.4	0.9	20.5	1.5 ± 1.3	601.1 ± 184.8
Great Western Woodland	2013-2014	3.9 ± 0.8	10.2 ± 1.7	4.1 ± 1.5	-0.2 ± 1.1	20.0 ± 6.3	11.4 ± 5.0	0.4 ± 0.1	1.5 ± 0.7	19.9 ± 5.2	7.8 ± 1.5	361.1 ± 430.1	1.6 ± 0.4	21.6 ± 9.1	55.7 ± 19.5	0.5	10.7	3.0 ± 1.3	261.7 ± 105.9
Howard Springs	2001-2014	20.5 ± 7.3	13.3 ± 2.7	16.3 ± 5.2	4.2 ± 3.3	20.2 ± 2.2	13.2 ± 2.4	1.5 ± 0.4	1.2 ± 0.4	26.7 ± 1.8	16.9 ± 3.8	1468.6 ± 1890.1	1.7 ± 0.3	21.3 ± 5.9	15.7 ± 8.0	1.1	14	0.6 ± 0.5	1135.1 ± 350.2
Nimmo	2007-2014	11.7 ± 7.3	6.6 ± 2.4	11.0 ± 5.9	0.7 ± 2.7	17.2 ± 6.9	9.0 ± 5.3	1.6 ± 0.5	0.4 ± 0.2	8.0 ± 4.9	6.1 ± 1.4	620.5 ± 443.2	1.8 ± 0.5	6.8 ± 3.9	3.9 ± 1.5	0.6	18.8	0.4 ± 0.3	637.0 ± 366.5
Riggs Creek	2010-2014	10.5 ± 8.0	8.1 ± 4.3	9.2 ± 3.0	1.3 ± 5.6	17.5 ± 7.5	8.2 ± 4.4	1.3 ± 0.9	0.9 ± 0.6	15.6 ± 5.4	8.1 ± 1.3	395.8 ± 397.6	2.2 ± 1.5	12.5 ± 9.8	17.5 ± 35.1	0.7	26.6	1.3 ± 1.7	462.7 ± 228.9
Robson Creek	2013-2015	23.7 ± 3.2	5.8 ± 1.3	20.6 ± 3.8	3.2 ± 2.3	18.2 ± 4.8	12.7 ± 3.3	4.3 ± 1.1	0.4 ± 0.1	20.1 ± 2.8	14.7 ± 2.4	2199.4 ± 2420.8	2.0 ± 0.4	8.7 ± 4.1	2.0 ± 0.7	1	10.8	0.4 ± 0.3	1185.8 ± 223.6
Samford	2010-2014	16.6 ± 7.2	9.3 ± 3.3	14.3 ± 5.1	2.2 ± 3.3	17.0 ± 4.2	9.9 ± 3.3	1.7 ± 0.3	0.9 ± 0.3	19.4 ± 3.9	11.3 ± 4.0	1240.6 ± 1430.2	2.8 ± 0.5	24.1 ± 10.0	14.3 ± 6.9	0.9	13.3	0.9 ± 0.5	564.2 ± 215.7
Sturt Plains	2008-2014	4.8 ± 5.0	7.5 ± 7.4	4.6 ± 2.5	0.2 ± 2.9	22.7 ± 2.4	9.9 ± 2.4	0.5 ± 0.2	2.0 ± 0.7	26.0 ± 3.9	11.1 ± 4.6	730.5 ± 1172.5	0.8 ± 0.5	13.1 ± 7.5	26.5 ± 15.9	0.4	6.5	3.8 ± 4.4	549.6 ± 427.4
Ti Tree East	2012-2014	0.4 ± 2.7	0.4 ± 5.9	2.2 ± 2.2	-1.8 ± 1.2	22.5 ± 3.9	9.6 ± 2.7	0.3 ± 0.1	2.4 ± 0.9	23.8 ± 6.0	6.1 ± 2.5	259.9 ± 468.2	0.5 ± 0.3	11.7 ± 8.1	30.3 ± 10.6	0	1.4	19.2 ± 23.0	214.0 ± 275.4
Tumbarumba	2001-2014	22.1 ± 7.7	5.3 ± 1.7	17.0 ± 6.5	5.1 ± 3.7	16.6 ± 7.0	8.7 ± 5.3	4.1 ± 0.6	0.5 ± 0.3	9.6 ± 5.3	6.4 ± 1.4	1924.2 ± 1400.4	2.6 ± 0.5	11.7 ± 7.6	2.8 ± 1.7	1	11.5	0.6 ± 0.3	850.7 ± 361.7



Wallaby Creek	2005-2013	19.8 ± 5.4	5.2 ± 1.2	10.4 ± 5.9	9.3 ± 6.7	12.1 ± 5.3	7.5 ± 5.3	3.9 ± 0.8	0.4 ± 0.3	10.8 ± 4.0	7.2 ± 1.3	1571.2 ± 1098.1	2.4 ± 0.9	9.9 ± 5.9	2.5 ± 1.4	1.3	12.6	0.3 ± 0.4	911.3 ± 472.2
		8.8		± 2.5	6.8	± 6.1	12.2	0.7	0.2	± 2.7	0.6	459.8	0.7	4.9					0.6
Warra	2013-2014	22.1 ± 8.8	13.8 ± 2.0	23.8 ± 2.5	-1.7 ± 6.8	10.4 ± 6.1	2.5 ± 12.2	1.6 ± 0.7	0.4 ± 0.2	10.0 ± 2.7	7.1 ± 0.6	1053.0 ± 459.8	3.5 ± 0.7	11.9 ± 4.9	7.4 ± 1.3	2.8	21	-0.1 ± 0.6	643.2 ± 325.5
Whroo	2011-2014	13.0 ± 3.0	14.1 ± 2.8	10.0 ± 2.0	3.0 ± 2.2	17.7 ± 7.9	9.7 ± 5.8	0.9 ± 0.1	0.9 ± 0.5	16.0 ± 4.9	8.1 ± 1.2	381.3 ± 329.5	2.6 ± 0.5	23.2 ± 14.6	25.0 ± 15.2	1.1	34.2	1.4 ± 0.9	494.9 ± 157.7
Wombat	2010-2014	22.5 ± 7.3	5.5 ± 1.4	13.5 ± 4.6	9.1 ± 3.9	15.4 ± 7.3	10.4 ± 5.8	4.1 ± 0.7	0.4 ± 0.3	11.4 ± 4.1	8.0 ± 1.3	924.9 ± 567.4	3.2 ± 0.6	12.1 ± 8.5	3.0 ± 2.2	1.1	24.3	0.3 ± 0.5	724.2 ± 331.9
Yanco_JAXA	2012-2014	4.8 ± 3.6	8.0 ± 4.0	4.7 ± 1.7	0.1 ± 2.2	19.0 ± 7.7	9.5 ± 4.8	0.5 ± 0.3	1.3 ± 0.8	17.3 ± 6.2	7.1 ± 1.0	472.1 ± 374.6	1.9 ± 1.2	16.2 ± 9.1	37.9 ± 37.2	0.5	10.1	4.0 ± 4.5	266.5 ± 135.3