



Productivity and evapotranspiration of two contrasting semiarid ecosystems following the 2011 global carbon land sink anomaly



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ABSTRACT

Global carbon balances are increasingly affected by large fluctuations in productivity occurring throughout semiarid regions. Recent analyses found a large C uptake anomaly in 2011 in arid and semiarid regions of the southern hemisphere. Consequently, we compared C and water fluxes of two distinct woody ecosystems (a Mulga (*Acacia*) woodland and a *Corymbia* savanna) between August 2012 and August 2014 in semiarid central Australia, demonstrating that the 2011 anomaly was short-lived in both ecosystems. The Mulga woodland was approximately C neutral but with periods of significant uptake within both years. The extreme drought tolerance of *Acacia* is presumed to have contributed to this. By contrast, the *Corymbia* savanna was a very large net C source (130 and 200 g C m⁻² yr⁻¹ in average and below average rainfall years, respectively), which is likely to have been a consequence of the degradation of standing, senescent biomass that was a legacy of high productivity during the 2011 anomaly. The magnitude and temporal patterns in ecosystem water-use efficiencies (WUE), derived from eddy covariance data, differed across the two sites, which may reflect differences in the relative contributions of respiration to net C fluxes across the two ecosystems. In contrast, differences in leaf-scale measures of WUE, derived from ¹³C stable isotope analyses, were apparent at small spatial scales and may reflect the different rooting strategies of *Corymbia* and *Acacia* trees within the *Corymbia* savanna. Restrictions on root growth and infiltration by a siliceous hardpan located below *Acacia*, whether in the Mulga woodland or in small Mulga patches of the *Corymbia* savanna, impedes drainage of water to depth, thereby producing a reservoir for soil moisture storage under *Acacia* while acting as a barrier to access of groundwater by *Corymbia* trees in Mulga patches, but not in the open *Corymbia* savanna.

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1. Introduction

Inter-annual variability in atmospheric concentrations of CO₂ is large (Le Quéré et al., 2014), and much of this variability is driven by fluctuations in the source/sink strength of terrestrial ecosystems (Cox et al., 2013). During the latter half of the twentieth century, global net primary productivity (NPP) may have increased

(Nemani et al., 2003), resulting in a potential increase in uptake of 0.05 Pg C per year (Ballantyne et al., 2012). Then, global NPP was reduced by 0.55 Pg C during the period 2000–2009, a result ascribed to large-scale drought in the southern hemisphere (Zhao and Running, 2010). Thereafter, Le Quéré et al. (2014) identified the 2011 land sink anomaly, which was a year of exceptional productivity, and Poulter et al. (2014) confirmed this anomaly by using a combination of modelling and remote sensing approaches. This land sink anomaly was driven by growth in semiarid vegetation of the southern hemisphere, with almost 60% occurring in Australia (Poulter et al., 2014). Importantly, Fasullo et al. (2013) showed that Australia, unlike continental South and North America, maintained a positive water mass anomaly (i.e., the extra water received in 2011 remained detectable throughout 2012),

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suggesting that increased C uptake may have persisted beyond 2011 in arid Australia. Carry-over of water from one hydrologic year to the next has been shown to have strong positive effects on productivity in many arid ecosystems (Flanagan and Adkinson, 2011). We have previously shown, using field observations of landscape fluxes of CO₂, that one of the dominant ecosystems of semiarid central Australia was indeed a large sink for C over almost all of the 12 months between October 2010 and October 2011 (Cleverly et al., 2013a; Eamus et al., 2013). Large fluctuations in productivity, evapotranspiration (ET) and ecosystem water-use efficiency (eWUE) across these semiarid regions reflect the very high ecosystem resilience of vegetation (Ponce Campos et al., 2013), which can have large effects on global C relations and consequently drive events such as the land sink anomaly of 2011.

Globally, dryland regions (arid, semiarid, and subhumid) cover 41% of the land area (Reynolds et al., 2007). Within these regions, arid and semiarid environments are characterised by chronic water shortages. Thus, productivity and ET are closely dependent upon the timing, frequency and amount of precipitation (Huxman et al., 2004), through which plant water availability is mediated by local hydrology (Breshears et al., 2009; Loik et al., 2004; Reynolds et al., 2004).

The semiarid regions of Australia cover 70% of the continent (Eamus et al., 2006; Warner, 2004) and are dominated by three major biomes along a woodland-savanna-grassland continuum: (1) Mulga woodlands (*Acacia* spp.), which cover approximately 20–25% of the continental land area (Bowman et al., 2008), and (2) *Corymbia* savanna over a hummock grass (*Triodia* spp.) understory that grades into (3) treeless hummock grasslands. Hummock grasslands and savannas occupy another 20–25% of the Australian land surface (Bowman et al., 2008). The co-occurrence of two widely distributed and highly distinctive vegetation types (i.e., Mulga and hummock) within a single climate zone in central Australia (O'Grady et al., 2009) provides an opportunity to compare and contrast their behaviour and to establish their respective contributions to regional C, water and energy budgets.

Mulga trees range in height (2–10 m) and ground cover (10–70%) (Nix and Austin, 1973), and they are preferentially located where storage of soil moisture occurs near the surface in sand dunes, clay-rich soil or over the siliceous hardpans that are common across semiarid Australia (Bowman et al., 2007; Ludwig et al., 2005; Maslin and Reid, 2012; Nano and Clarke, 2010; Nix and Austin, 1973; Thiry et al., 2006; Tongway and Ludwig, 1990). In contrast, tree density (stems per hectare) and cover in *Corymbia* savannas are very low, and tree height ranges from 5 to 15 m. *Corymbia opaca* is deep-rooted (8–20 m), and tends to be groundwater dependent in semiarid areas (Cook and O'Grady, 2006; O'Grady et al., 2006a,b). The understory in the *Corymbia* savanna is characterised by a continuous cover of perennial hummock grasses (*Triodia* spp.), which are widespread throughout Australia and cover an additional 20–25% of the continental land area (Bowman et al., 2008; Nano and Clarke, 2010; Reid et al., 2008).

Water-use-efficiency (WUE) has traditionally been measured at leaf-scales (as the ratio of net assimilation to transpiration), but eddy covariance measurements also allow determination of ecosystem-scale WUE as the ratio of net ecosystem productivity (NEP) to ET (eWUE; Eamus et al., 2013). Given the very large difference in LAI of the C₄ grass understory between Mulga and *Corymbia* savannas, we hypothesised that ecosystem-scale WUE of the two biomes would differ. Furthermore, given the large differences in phyllode structure of the C₃ trees, comparisons of leaf-scale measures of WUE across two co-occurring species within a single biome (i) provide information about C and water economies and (ii) contribute to our understanding of hydraulic niche separation of co-occurring species (Peñuelas et al., 2011) that cannot be addressed through eWUE.

The aim of this study was to investigate fluctuations in the fluxes of C and water from iconic Australian semiarid vegetation in response to reductions in precipitation subsequent to the 2011 land sink anomaly. In this manuscript we compare and contrast the behaviour of two disparate arid-zone tropical ecosystems (Mulga woodland and *Corymbia* savanna) in central Australia to address four over-arching questions: (a) did the 2011 anomaly persist into 2012/2013/2014 in either biome; (b) do these two contrasting ecosystems respond similarly to almost identical weather patterns; (c) how do ecosystem water-use efficiencies compare across ecosystems; and (d) at small spatial scales within the *Corymbia* savanna, how do leaf-scale water-use efficiencies across the two tree species (*Acacia* and *Corymbia*) differ?

2. Materials and methods

2.1. Site descriptions

This study was located on Pine Hill cattle station in the Ti Tree catchment of central Australia and was co-located with several previous hydrological, ecological and ecophysiological studies (Calf et al., 1991; Cleverly et al., 2013a; Eamus et al., 2013; Harrington et al., 2002; Ma et al., 2013; O'Grady et al., 2009; Scanlon et al., 2006). The Ti Tree catchment is an enclosed basin that covers 5500 km² and contains two main ecosystems: Mulga woodlands and *Corymbia* savanna (Harrington et al., 2002). Measurements were collected from two locations: one in the Mulga woodland and one in the *Corymbia* savanna. An eddy covariance tower was located in each ecosystem, separated by 40 km at the same latitude ([22.3° S 133.25° E] and [22.3° S 133.65° E]).

A full description of the soil, floristics, leaf area index (LAI), energy balance and C relations of the Mulga woodland can be found in Cleverly et al. (2013a) and Eamus et al. (2013). Briefly, the Mulga woodland is characterised by a discontinuous canopy of short (3–7 m), evergreen *Acacia* trees (*Acacia aptaneura* and *Acacia aneura*) with an understory of shrubs, herbs and grasses (C₃ and C₄) that are conditionally active depending upon moisture availability and season (Cleverly et al., 2013a). The cover of *Acacia* is 74.5% of the land area in the Mulga woodland; *C. opaca* is essentially absent from the Mulga woodland (one tree within the EC footprint, cf. Section 2.2). The basal area of *Acacia* within the woodland is 8 m² ha⁻¹ (Eamus et al., 2013).

The second eddy covariance site contains two species of trees: widely spaced and tall *C. opaca* trees above a matrix of hummock grass (*Spinifex*, *Triodia schinzii*) and small patches of Mulga (*Acacia sericophylla*, *Acacia melleodora* and *A. aptaneura*) that contain an understory of herbs and tussock grasses (*Aristida* spp., *Eremophila latrobei* subsp. *glabra*, *Eragrostis eriopoda* subsp. *red earth*, *Paraneurachne muelleri* and *Psydrax latifolia*). Although the distribution of *T. schinzii* does not substantially overlap with Mulga, *C. opaca* trees were present in both habitats. Representing only 0.4% cover (basal area of 0.21 m² ha⁻¹), *C. opaca* are found predominantly in the open savanna, although they are found occasionally in the isolated small Mulga patch close to the EC tower within the *Corymbia* savanna. Soil texture is sandier in the *Corymbia* savanna (loamy sand) than in the Mulga woodland (sandy loam). Soil organic matter is less than 1% at both sites. In the *Corymbia* savanna, the energy balance ratio $(H + LE)/(R_n - G)$ was 0.97 ± 0.005 (January 2013–July 2014), wherein H is sensible heat flux, LE is latent heat flux, R_n is net radiation and G is ground heat flux. Over the same period in the Mulga woodland, the energy balance ratio was 0.89 ± 0.005 . The Bowen ratio (H/LE) was large at both sites: 37.5 (range 0.78–408) in the Mulga woodland and 37.9 (0.23–511) in the *Corymbia* savanna.

Long-term annual average precipitation (1987–2014) at the nearest meteorological station (Territory Grape Farm, 18 km due

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