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Can we predict groundwater discharge from terrestrial ecosystems using eco-hydrological principals?

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Abstract

There is increasing recognition of the role that groundwater plays in the maintenance of ecosystem structure and function. As a result, water resources planners need to develop an understanding of the water requirements for these ecosystems. However, their capacity to do this is constrained by a lack of empirical information on groundwater discharge from terrestrial systems. In this study we reviewed estimates of groundwater discharge from around Australia focussing particularly on terrestrial groundwater discharge. The review examined detailed water balance studies where discharge has been identified as a component of evapotranspiration and we have explored this data set for empirical relationships that could be used to aid in predicting groundwater discharge in data poor areas. In general, terrestrial groundwater systems discharging groundwater lie above the theoretical water limit line as defined by the Budyko framework. However, when climate wetness was recalculated to include groundwater discharge there was remarkable convergence of these sites along the water limit line. Similarly, the leaf area index of ecosystems with access to groundwater had higher LAI than those without access to groundwater, for a given climatic regime. However, when discharge was included in the calculation of climate wetness index there was again strong convergence between the two systems, providing support for ecological optimality frameworks that maximize LAI under given water availability regimes. The simplicity and utility of these simple ecohydrological insights potentially provide a valuable tool for predicting groundwater discharge from terrestrial ecosystems.

1 Introduction

Applying the definition proposed by Budyko (1974), the Australian landscape is predominantly water-limited, as evaporation exceeds rainfall across most of the continent (Donohue et al., 2009). As a result, there has been considerable focus on understanding the water balance in Australian landscapes, driven by a motivation to ensure that this valuable and limiting resource is used sustainably and that sufficient water resources are allocated for the maintenance and protection of key environmental assets and services. In recent years there has been increasing recognition of the role that groundwater plays in the maintenance of ecosystem structure and function (Eamus and Froend, 2006). Groundwater dependence has been demonstrated in a range of terrestrial ecosystems around Australia including woodlands in Mediterranean environments (Groom, 2000), riparian ecosystems (Thorburn et al., 1993; Lamontagne et al., 2005), temperate plantations (Benyon et al., 2006), tropical and arid woodlands and tropical forests (Drake and Franks, 2003; O'Grady et al., 2006, 2009). Recognition of the importance of this water resource to ecosystem functioning imposes an imperative on water resources managers to account for these environmental water requirements within their water allocation plans. However, the capacity to do so is significantly constrained by a lack of detailed information on extent of groundwater dependence.

There is a close coupling between ecosystem productivity and water balance (Specht and Morgan, 1981; Specht, 1983; Eamus, 2003; Liu, 2009). In a review of this topic, Eamus (2003) demonstrated that above ground biomass and the productivity of fine tissues (roots and leaves) increased asymptotically with rainfall and that the net annual increment (a common measure of forest productivity) in *Eucalyptus globulus* (Labill.) plantations increased as an asymptotic function of rainfall and potential evapotranspiration. Specht (1972), Specht and Morgan (1981) and Specht (1983) demonstrated that foliage cover in the overstorey of perennial plant communities was linearly related to the water balance of these communities via its relationship with k in the relationship:

$$E_a/E_0 = k(P + S_{ext}),$$

Where E_a is actual evapotranspiration and E_0 is potential evapotranspiration, k is a parameter related to the complexity of the vegetation structure and physiology and S_{ext} is the maximum extractable water in the soil profile (Specht, 1972). The relationship is conceptually similar to the water balance framework of Budyko (1974). Although not explicitly linking productivity with water balance, Budyko's analysis partitions rainfall into evapotranspiration and runoff through linking the E_a/E_0 with climate. Recently, Donohue et al. (2007) argued that explicit consideration of vegetation dynamics within the Budyko framework could potentially increase the utility of this framework for addressing land management and water resources planning issues.

While Specht's (1972) foliage projective cover provides an index of plant productivity, it is the leaf area index (LAI) of a community, defined as the projected leaf area (m^2) per unit ground area (m^2) that is the main determinant of light interception and hence the productivity and water use of ecosystems (Landsberg and Waring, 1997; Donohue et al., 2007; White et al., 2010). Variation in LAI in response to water availability has been demonstrated in a number of environments and at a range of spatial and temporal scales (Grier and Running, 1977; Battaglia et al., 1998; Carter and White, 2009; White et al., 2010). However, incorporation of these observations into a sound predictive ecohydrological framework remains problematic.

The theory of ecological optimality (Eagleson, 1978, 1982) states that in water-limited environments, ecosystems evolve in a manner such that over short time scales (i.e. one to a few generations), canopy density (analogous to LAI), will equilibrate with the climate and soil to the value at which equilibrium soil moisture will be maximised. At longer time scales (i.e. over many generations), species will be selected whose potential transpiration efficiency results in the maximum equilibrium soil moisture and over evolutionary time scales, vegetation will alter soil physical properties towards equilibrium values which maximises canopy density (Eagleson, 1982; Eagleson and Tellers, 1982; Hatton et al., 1997). The framework thus predicts close coupling between canopy structure and water availability. Kerkhoff et al. (2004) criticised the ecological optimality theory, in particular the assumption that soil water availability would be maximised. Despite this, it has been argued that ecological optimality provides a potentially useful underpinning framework for the emerging field of ecohydrology (Hatton et al., 1997). In support of ecological optimality, Ellis and Hatton (2008) demonstrated that across southern Australia, there was a strong linear relationship between LAI and rainfall. Correlations between LAI and a range of climate indices have been previously demonstrated for other ecosystems (Grier and Running, 1977; Nemani and Running, 1989;

Baldocchi and Meyers, 1998). Furthermore, Macfarlane et al. (2010) recently demonstrated that understorey LAI increased rapidly in response to thinning of the overstorey canopy, so that community LAI was maintained at a level consistent with the predictions from ecohydrological optimality.

In these previous studies it has been implicit that rainfall is the major source of water for evapotranspiration. However, access to groundwater potentially provides additional water for terrestrial ecosystems. In this paper we have examined the relationships between LAI, climate and the water balance of ecosystems dependent on groundwater. Specifically we ask the question; can ecohydrological principals be used to estimate groundwater discharge in groundwater dependent ecosystems? In particular, we hypothesised that the LAI of terrestrial ecosystems with access to groundwater would be higher than that of terrestrial ecosystems without access to groundwater for any given climatic regime and that the increase in LAI would be proportional to the volume of water accessed from groundwater. In addition to this, we expected that ET from these communities would be higher, but this increase would still be broadly consistent with existing theoretical frameworks such as the Budyko framework that describes the relationship of ET with potential evaporation as a function of incoming energy and water availability. To explore these hypotheses we analysed published water balance studies that have identified groundwater discharge through the ecosystem and examined relationships between the volume of groundwater discharged and the existing ecological and climatic regimes.

2 Methods

We analysed existing Australian water balance studies that identified groundwater discharge as a component of evapotranspiration. The water balance of a site can be described as:

$$Q_{\mathrm{wt}} = P - (I + E + T) - \Delta S_{\mathrm{w}} \tag{1}$$

Where Q_{wt} = net water balance (drainage +ve, discharge −ve), P = rainfall, I = rainfall interception losses (i.e. direct evaporation from the canopy and stem, usually estimated as the difference between rainfall and throughfall), E = evaporative losses from the soil surface (usually measured with mini lysimeters), T = transpiration (measured directly e.g. using sapflow techniques) and ΔS_w is the change in the volumetric soil water content between two time periods (Benyon et al., 2006). All the studies included in this review were plot scale water balance studies, conducted for a period of at least 12 months, where evapotranspiration was calculated as the sum of E, T and I. We have restricted our analysis to studies where LAI was also reported.

Ellis and Hatton (2008) reviewed relationships between LAI and climatic variables including rainfall and evaporation for southern Australia. In this paper, we extend their analysis and include more recent measurements of LAI, therefore characterising this relationship over a broader range of climatic conditions. Leaf area index of the various communities was estimated using a range of techniques including visual estimation, light interception techniques such as canopy photography or the LAI 2000 plant canopy analyser (Licor Lincoln, USA) or via allometric equations between leaf area and plant size (generally stem diameter) developed during destructive harvesting.

To assess the effect of groundwater access on the relationship between climate and LAI, we compared the slope and intercept of the linear relationships between Climate Wetness Index (CWI, the ratio of annual rainfall to evaporation) and LAI, observed by Ellis and Hatton (2008) to; (i) quantify the relationship between CWI and LAI for the water balance studies that identified groundwater discharge reviewed here, and (ii) to examine the relationship between LAI and a modified CWI that accounts for additional water available from groundwater:

$$\mathrm{CWI_g} = \frac{(P+g)}{E_0} \tag{2}$$

Where $\mathrm{CWI_g}$ = is the dimensionless climate wetness index that includes the groundwater component, P = total precipitation (mm), g = groundwater discharge (mm) and E_0 = potential evaporation (mm).

In evaluation of Budyko's framework, long-term steady state evapotranspiration from a catchment can be described by the relationship between two climatic variables, precipitation (P) and the evaporative demand (E_0):

$$\frac{E}{E_0} = 1 + \frac{P}{E_0} - \left[1 + \left(\frac{P}{E_0}\right)^w\right]^{1/w} \tag{3}$$

Where w is a parameter that describes the shape of the function between E_a/E_0 and CWI and is related to catchment properties (Zhang et al., 2004). Ecosystems discharging groundwater have access to water other than rainfall, thus in order to compare the groundwater discharge sites to the Zhang et al. (2004) formulation of ET (Eq. 3) we have included groundwater discharge and recalculated ET such that:

$$\frac{E}{E_0} = 1 + \frac{P_{+\mathrm{gw}}}{E_0} - \left[1 + \left(\frac{P_{+\mathrm{gw}}}{E_0}\right)^w\right]^{1/w} \tag{4}$$

Where $P_{+\mathrm{gw}}$ is rainfall plus the terrestrial groundwater discharge component (mm).

We used a group regressions procedure to compare the relationships between LAI and P/E_0 as described by Ellis and Hatton (2008) with the LAI of systems with access to groundwater. The program SMATR (Warton et al., 2006) was used to compare the slopes and intercepts of these relationships. Ordinary least squares regression was used to compare observed ET with estimates of ET predicted using the reformulated Zhang et al. (2004) equation (Eq. 4).

3 Results

We identified 17 water balance studies that included measured ET (with a recognised groundwater discharge component) and LAI and a further six where no groundwater discharge was identified. These latter sites were included for comparative purposes. In total, 30 estimates of groundwater discharge are included in this analysis (Table 1).

The vegetation studied included plantations, trees belts, native forests and the riparian forests associated with the Chowilla floodplain on the Murray River in South Australia. The majority of sites were restricted to southern Australia, and in particular South Australia and Western Australia (Fig. 1). Estimated rates of groundwater discharge varied from 2 mm yr^{-1} to more than 700 mm yr^{-1} and ranged from less than 1 % to 100 % of the measured evapotranspiration.

Actual to potential evapotranspiration ratios (E_a/E_0) for the plot scale water balance studies varied from less than 0.05 to approximately 1.6 (Table 1). Climate wetness indices varied from very arid environments (CWI $<$ 0.05) to the very wet environments (CWI $>$ 7). The relations between E_a/E_0 and CWI of these plot scale studies were conceptually consistent with the Budyko framework, i.e. at water limited sites E_a/E_0 increased linearly and reached a plateau at a CWI of 1. Actual E_a/E_0 ratios of sites with access to groundwater fell above the water limitation line as defined by the Budyko framework (Fig. 2a). However, when the CWI was recalculated to include the discharge of groundwater, ie $(P+g)/E_0$ most sites fell along the water limit line defined by the Budyko framework (Fig. 2b). Similarly, there was a strong and highly significant ($r^2=0.79$, df 1, 30, $P<0.001$) linear correlation between estimates of ET derived using the Budyko equation with discharge included and observed estimates of ET derived from water balance studies (Fig. 3).

Leaf area index data were collated from a range of sites around the country. These estimates varied from 0.2 for overstorey LAI in the *Banskia* communities of south west Western Australia to approximately 5 for sub-tropical rainforest communities in south east Queensland (Table 1). Of the studies identified, not all sites had access to groundwater. However, at all sites detailed plot scale water balance measurements were undertaken. Actual ET ranged from 73 mm yr^{-1} to approximately 1900 mm yr^{-1}. There was a linear increase in LAI with increasing CWI up to a value of 1, after which there was a marked plateau (Fig. 4a). Thus for water limited sites there was a strong linear relationship between LAI and the ratio E_a/E_0 (Fig. 4b).

At sites with access to groundwater there was a significant linear relationship between LAI and CWI (Fig. 4a; LAI and CWI, LAI = 3.606(CWI) + 0.883, $r^2 = 0.48$, $df = 17$, $p = 0.001$). However, this relationship was more variable than that reported by Ellis and Hatton (2008). There was no significant difference between the slope of the relationship between LAI and CWI for sites with access to groundwater and the relationship reported by Ellis and Hatton (2008). However, there was a significant difference in the Y-intercept (Fig. 5a, $p < 0.001$). Sites having access to groundwater had a higher Y-intercept than that reported by Ellis and Hatton (2008). When the CWI was recalculated to incorporate the groundwater discharge component, the differences between the Y-intercepts was significantly reduced, although a small but significant ($P = 0.0499$) difference remained. Despite this, the correlation between CWI and LAI increased from $r^2 = 0.5$ to $r^2 = 0.7$ and the RMSE associated with the regression reduced from 0.85 to 0.66 (Fig. 5b).

4 Discussion

A major limitation to sustainable water resources planning is the lack of reliable estimates of the various components of the water balance. Within Australia estimates of groundwater discharge are relatively few. In contrast, recharge is commonly estimated; a recent paper by Crosbie et al. (2010) reviewed over 4000 estimates of recharge across Australia. Furthermore, although it has long been recognised that the LAI of terrestrial plant communities is strongly related to climate and indices of water availability (Specht, 1972; Baldocchi and Meyers, 1998; Eamus et al., 2001; Ellis and Hatton, 2008), these insights have not been incorporated into water resources planning, neither have these indices recognised that groundwater may provide a water source other than rainfall for evapotranspiration.

In the current analysis we identified strong convergence between terrestrial ecosystems that have access to groundwater with existing ecohydrological concepts, particularly the Budyko framework. The Budyko framework inherently incorporates the biophysical controls on evaporation (Donohue et al., 2007; Zhang et al., 2008), thus it is not surprising that the strong convergence identified here exists. However, it is worth recognising two factors:

Firstly, the strength of convergence with the Budyko framework identified in Figs. 2 and 3 was somewhat surprising given that the data collated were plot-based water balance studies, where estimates of evapotranspiration were constructed from bottom-up measurements of transpiration, interception and understory evaporation. Furthermore, these plot based studies were conducted over relatively short time intervals, typically 1 to 2 yr. In contrast, the Budyko framework was developed from the compilation of catchment based-studies and represents steady state conditions that are unlikely to apply over the short-term, particularly the underlying assumption that changes in soil water content are minimal. Secondly, a priori, for systems that have access to groundwater, we expected E_a/E_0 ratios to converge along the energy-limit line of the Budyko framework. In contrast, when the groundwater component was included (Eq. 3), there was strong convergence with Budyko's theoretical water-limit line (Fig. 2b).

It is difficult to fully attribute this response, but there may be several explanations for this observation. In the studies analysed, groundwater salinities varied from 1 $\mathrm{dSm^{-1}}$ to more than 60 $\mathrm{dSm^{-1}}$. Thus, groundwater may be thermodynamically less available than rainfall or soil water. Furthermore, in arid and semi-arid environments typical of the sites analysed in this paper, high vapour pressure deficits can significantly constrain stomatal conductance and water use (O'Grady et al., 2009) and root distributions tend to be exponentially distributed throughout the soil profile (e.g. O'Grady et al., 2005). Thus not all of the water that is lost via evapotranspiration is derived from groundwater. Furthermore, the hydraulic architecture of plants adapted to arid and semi-arid environments can limit ET (Eamus et al., 2000; Do et al., 2008). Thus, despite having access to groundwater, it appears that these ecosystems remain water-limited.

Leaf area index was strongly related to climate and water availability, as has been observed in previous studies (e.g. Ellis et al., 2005; Ellis and Hatton, 2008). Leaf area index of communities with access to groundwater increased linearly with CWI and there was strong evidence of convergence with the predictions of the Budyko framework. Leaf area index appears to plateau at a CWI > 1 (Fig. 4a), although we acknowledge that there are very few estimates of LAI above a CWI of 1. This in itself it not surprising and highlights the important role of LAI in intercepting incoming energy and partitioning this energy into fluxes of latent and sensible energy (Landsberg and Waring, 1997; Baldocchi and Meyers, 1998). A linear relationship between E_a/E_0 and foliage projective cover, a surrogate of LAI, in water-limited environments has been previously recognised (Specht, 1972). Similarly, Ellis and Hatton, (2008) demonstrated a strong linear relationship between rainfall and LAI. The direct correlation between rainfall and LAI alone is useful, but further insights into the water balance of a system are gained by including the evaporative environment, as this directly relates to water availability in the system. Here we have demonstrated that E_a/E_0 is indeed linearly related to LAI over a wide range of climatic conditions (Fig. 4b). Ratios of E_a/E_0 larger than one reported in the literature are difficult to reconcile. For example, McJannet et al. (2007) reported actual evapotranspiration 1.6 times higher than Penman evaporation for high altitude rainforests in north Queensland. They attributed this to large amounts of advected energy in these mountainous systems situated next to the coast. However, this may also reflect errors in water balance measurements. Despite this, the strong linear agreement over the water-limited spectrum of the relationship provides a simple and powerful empirical method for estimating LAI and ET of terrestrial plant communities.

As hypothesised, the LAI of communities with access to groundwater was higher at any given CWI than that predicted by Ellis and Hatton (2008). One qualification of this statement is that detailed water balance data were not available for the sites presented in the Ellis and Hatton (2008) review. As a result we cannot unequivocally say that none of the sites included in the Ellis and Hatton (2008) review had access to groundwater. Despite this, there were significant differences in the Y-intercept of the slopes of the relationships for sites with access to groundwater and that reported in the Ellis and Hatton (2008) review. When the groundwater discharge component was included in the CWI there was a significant convergence between these two relationships, although a slight but significant ($P = 0.0499$) difference in elevation between the two remained. It is difficult to determine whether this difference in elevation is real or an artefact of the low degrees of freedom in the relationship in this analysis. Either way, this finding does raise the possibility that groundwater discharge from terrestrial ecosystems could be estimated directly using simple empirical models of climate, calibrated using community LAI.

Terrestrial groundwater discharge is a component of the water balance that is often overlooked in water resources planning. Partly this reflects the difficulty and expense associated with quantifying the discharge component. The simple ecohydrological relationships observed in this analysis, potentially provide a valuable tool for estimating discharge in terrestrial ecosystems at large spatial scales as they use insights based on a sound conceptual frameworks (e.g. the Budyko framework) and highlights the value of incorporating biological responses into hydrological frameworks (Donohue et al., 2007). These ecohydrological approaches may be particularly useful in data poor areas, or in areas where detailed investigations of the water balance are not warranted. Many of the required inputs for these types of analyses are available from remotely sensed data, e.g. actual evapotranspiration (Guerschman et al., 2009), evaporation (Donohue et al., 2010) and LAI (Hill et al., 2006) and while questions may remain about the accuracy of some remotely sensed products, this will inevitably improve over time.

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Table 1. Summary of Australian water balance studies that identified groundwater discharge used in the analysis of leaf area index and groundwater discharge relationships.

State	Latitude	Longitude	Forest type	Precipitation (mm yr^{-1})	E_0 (mm yr^{-1})	E_0 Type	LAI	Groundwater discharge (mm)	ET(obs., mm yr^{-1})	E_a/E_0	Reference
SA	−37.37	140.46	plantation	713	980	Areal	3.5	2	713	0.73	Benyon and Doody (2004)
SA	−35.23	138.22	plantation	838	1409	Pan	2.7	52	936	0.66	Holland and Benyon (2011)
SA	−33.98	140.87	riparian	262	2000	Pan	1.0	55	73	0.04	Thorburn et al. (1993)
SA	−33.98	140.87	riparian	261	2000	Pan	1.0	73	73	0.04	Thorburn et al. (1993)
SA	−33.98	140.87	riparian	260	2000	Pan	0.6	94	110	0.06	Thorburn et al. (1993)
SA	−37.43	140.57	plantation	740	970	Areal	3.5	107	847	0.87	Benyon and Doody (2004)
SA	−37.37	140.46	plantation	713	980	Areal	3.7	226	904	0.92	Benyon and Doody (2004)
SA	−37.43	140.57	plantation	666	1250	Point	3.7	413	1059	0.85	Benyon and Doody (2004)
SA	−37.36	140.53	plantation	713	1230	Point	4.1	440	1158	0.94	Benyon and Doody (2004)
SA	−33.98	140.87	riparian	263	2000	Pan	1.5	502	730	0.37	Thorburn et al. (1993)
SA	−37.74	140.78	plantation	567	1180	Point	3.1	636	1193	1.01	Benyon and Doody (2004)
SA	−34.44	140.6	Native woodland	268	1980	Pan		48	195	0.10	Doody et al. (2009)
SA	−34.44	140.6	Native woodland	268	1980	Pan		70	216	0.11	Doody et al. (2009)
SA	−34.44	140.6	Native woodland	268	1980	Pan		315	320	0.16	Doody et al. (2009)
SA			Plantation	633	1124	Penman Monteith		116	712	0.63	Benyon et al. (2006)
SA			Plantation	747	1230	Point		561	1343	1.09	Benyon et al. (2006)
SA			Plantation	362	1340	Penman Monteith		671	1074	0.8	Benyon et al. (2006)
Vic	−36.25	145.00	Plantation	480	1350	Pan	2.1	173	413	0.31	Morris and Collopy (1999)
Vic			Plantation	480	1350	Pan		221	459	0.34	Morris and Collopy (1999)
NSW			Tree belt	627	1385	Pan		22	726	0.52	Crosbie et al. (2008)
NSW	−35.2	145.11	Plantation	619	1280	Penman Monteith		733	1277	0.99	Benyon et al. (2006)
NSW	−35.5	145	Plantation	664	1220	Penman Monteith		377	928	0.76	Benyon et al. (2006)
WA	−33.45	117.27	Tree belt	483	1350	Priestly Taylor	2.5	150	595	0.44	White et al. (2002)
WA	−30.04	116.21	Tree belt	380	1691	Priestly Taylor	2.7	420	1539	0.91	Carter and White unpublished
WA	−30.04	116.21	Tree belt	380	1690	Priestly Taylor	2.7	515	1539	0.91	Carter and White unpublished
WA	−30.09	117.12	Tree belt	319	2200	Pan	1.1	30	274	0.12	Wildy et al. (2004)
WA	−30.09	117.12	Tree belt	319	2200	Pan	2.2	218	391	0.18	Wildy et al. (2004)
WA			Native woodland	750	1843	Pan		64	635	0.34	Dodd and Bell (1993)
WA			Native woodland	772	1843	Pan		67	814	0.44	Farrington et al. (1990)
WA	−31.55	115.41	Native woodland	772	1843	Pan	0.2	0	666	0.36	Farrington et al. (1989)
QLD	−17.16	145.51	Rainforest	8100	1073	Penman	3.3	0	971	0.90	McJannet et al. (2007)
QLD	−17.27	145.29	Rainforest	2983	1237	Penman	4.1	0	1518	1.23	McJannet et al. (2007)
QLD	−16.08	145.26	Rainforest	3952	1269	Penman	4.2	0	1298	1.02	McJannet et al. (2007)
QLD	−16.31	145.16	Rainforest	3040	982	Penman	4.5	0	1533	1.56	McJannet et al. (2007)
QLD	−28.13	152.25	Rainforest	1350	1566	PriestlyTaylor	5.0	0	1259	0.80	Hutley et al. (1997)
NT			Riparian	1157	2300	Pan		143	1300	0.57	O'Grady et al. (2002)

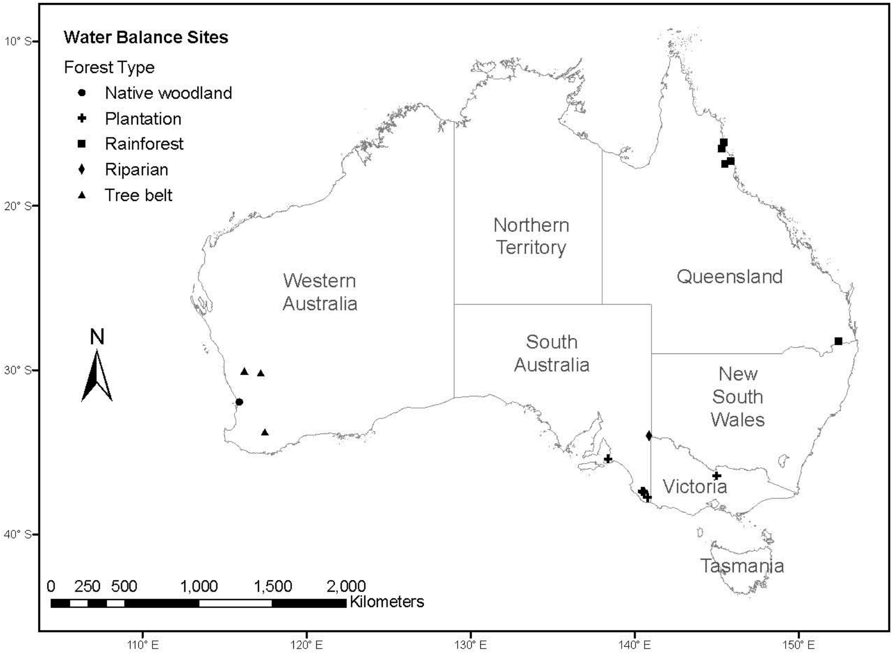

Fig. 1. Location of sites in Australia used in the analysis of the relationship between climate, LAI and groundwater discharge.

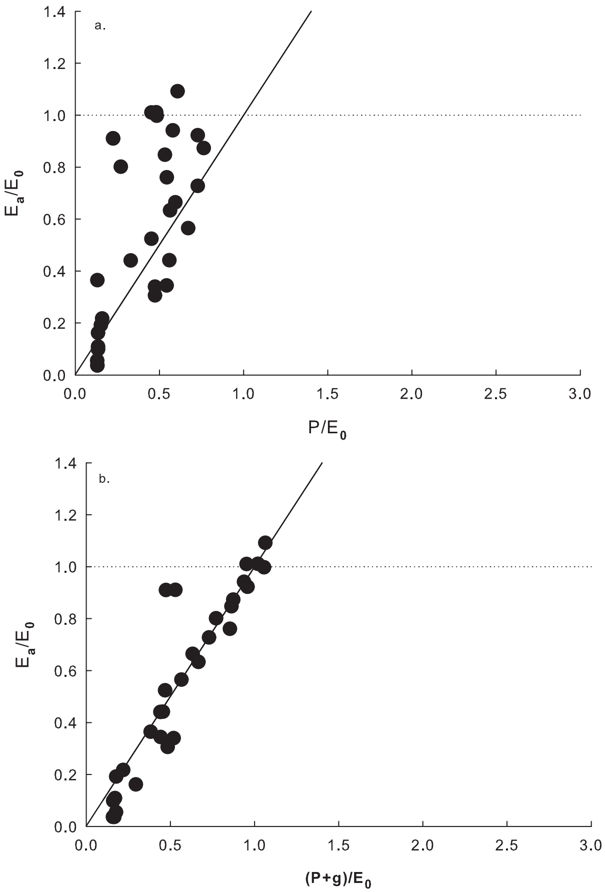

Fig. 2. (a) Relationship between measured E_a/E_0 and climate wetness index (CWI=P/E_0) for sites with access to groundwater. b) Relationship between E_a/E_0 and a recomputed climated wetness index that includes groundwater discharge where: CWI $= (P+g)/E_0$ (Eq. 2).

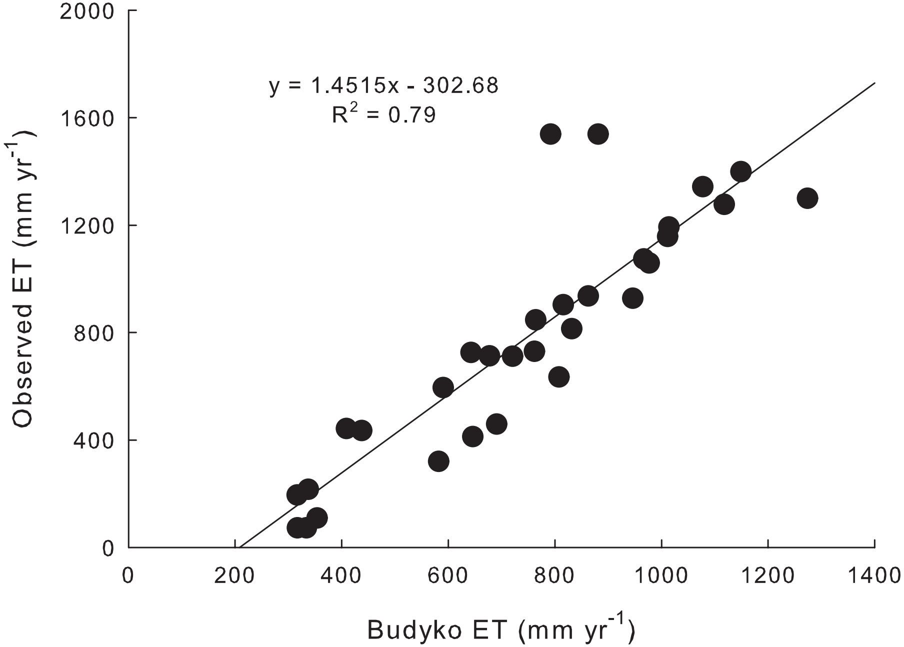

Fig. 3. Relationship between observed ET and ET calculated using the Zhang et al. (2004) version of the Budyko equation modified to include groundwater discharge (calculated using $w = 5$, Eq. 4).

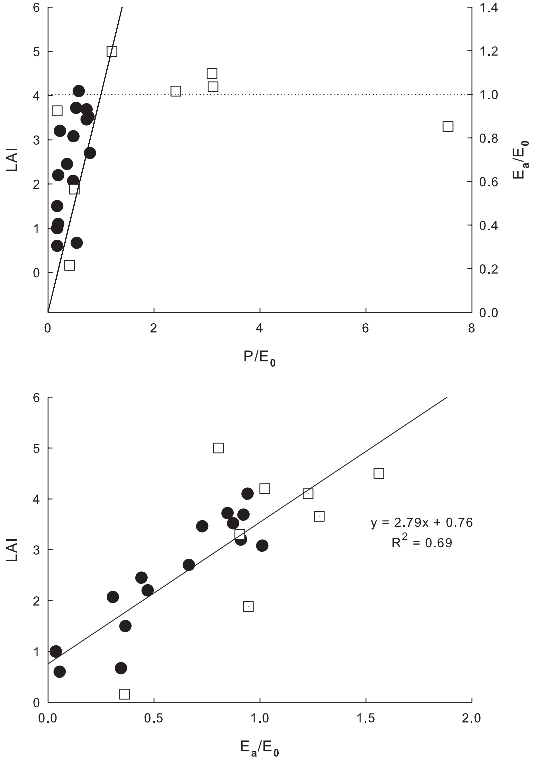

Fig. 4. (a) Relationship between climate wettness index and leaf area index for sites with access to groundwater (solid symbols) and sites without access to groundwater (open symbols). **(b)** Relationship between the ratio of actual evapotranspiration and potential transpiration to leaf area index for sites with and without access to groundwater.

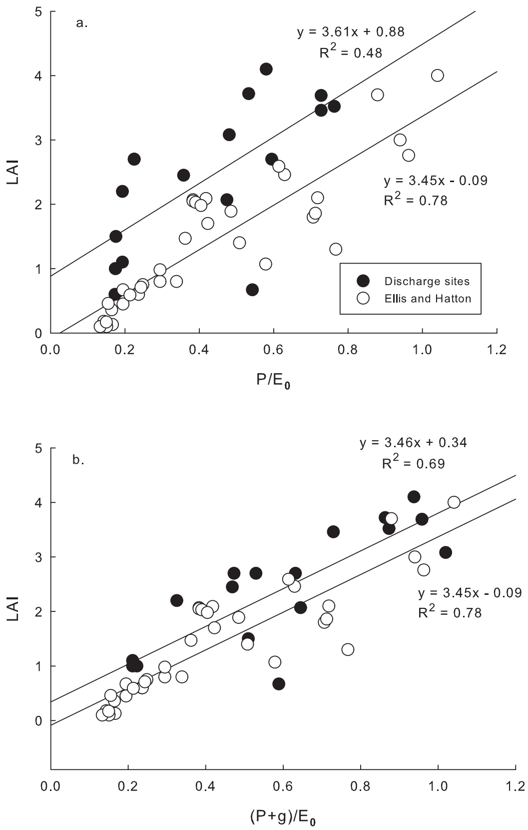

Fig. 5. (a) Relationship between climate wetness index and leaf area index for sites identified as having groundwater dischage as a component of evapotranspiration compared to the Ellis and Hatton (2008) relationship. **(b)** Demonstrates the convergence between the two relationships when the CWI is recalculated to include the groundwater discharge component (CWI = $(P+g)/E_0$, Eq. 2).