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# On the importance of including vegetation dynamics in Budyko's hydrological model

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## Abstract

The Budyko curve describes the relationship between climate, evapotranspiration and run-off and can be used to model catchment energy and water balances. The curve's underlying framework assumes catchments are at steady-state, a condition dependent on the scales of application, such that its reliability is greatest when applied to large catchments ( $>10\,000\text{ km}^2$ ) and using long-term averages ( $\gg 1$  year). At these scales previous experience has shown that the hydrological role of vegetation does not need to be explicitly considered within the framework. By demonstrating how dynamics in the leaf area, photosynthetic capacity and rooting depth of vegetation affect not only annual and seasonal vegetation water use, but also steady-state conditions, we argue that it is necessary to explicitly include vegetation dynamics into the Budyko framework before it is applied at small scales. Such adaptations would extend the framework not only to applications at small timescales and to small catchments but to operational activities relating to vegetation and water management.

## 1 Introduction

Efforts to better understand the components of the catchment water balance have traditionally been the realm of the hydrological community. Investigations have used models predominantly based on physical processes and applications have generally remained in the same arena. This is beginning to change with the recognition by the hydrological community that biological processes play a key role in the catchment water balance (Rodriguez-Iturbe and Porporato, 2005; Montaldo et al., 2005). One key feature of this linkage is that transpiration, a major component of the catchment water balance, and biological productivity are intimately coupled (Berry et al., 2005). The fields of hydrology and ecology will benefit from a more integrated understanding of catchment behaviour. This is the central challenge of ecohydrology.

In order to characterise the components of catchment water balances, Budyko

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(1974) developed what is now one of the most enduring frameworks that links climate to catchment run-off and evapotranspiration. It is simple to interpret and plainly links basic physical principles governing the catchment water balance. The resulting relationship, widely known as the “Budyko curve”, partitions average precipitation into average run-off and average evapotranspiration. Deviations around this relationship are observed and attempts have been made to explain these deviations with differing degrees of success, attributing them to variability and seasonality in climate (Milly, 1994; Koster and Suarez, 1999; Potter et al., 2005), to soil characteristics (Milly, 1994; Zhang et al., 2001; Porporato et al., 2004) and to the scales of analyses (Choudhury, 1999).

It seems likely that the quantitative integration of measures of key vegetation characteristics might enhance the Budyko framework. If true, then the applicability of the framework might be extended to a variety of land management applications. The purpose of this paper is to revisit Budyko’s framework and highlight the sometimes-forgotten assumptions within it. We then argue that the explicit inclusion of vegetation dynamics will enhance the Budyko framework.

**2 The Budyko framework and curve**

In the middle of last century Budyko (Budyko, 1958, 1974) published a framework describing the partitioning of average precipitation into average evapotranspiration and average run-off based on simple physical relationships. This is now known as the “Budyko curve” and is described below.

**2.1 Catchment water and energy balances**

Budyko described the hydrology of a catchment using a supply-demand framework and a simple bucket model where net drainage is assumed to be negligible. The water

balance was defined as:

$$\frac{dS_w}{dt} = P - E - Q \quad (1)$$

where  $E$ ,  $P$  and  $Q$  are catchment-wide estimates of evapotranspiration, precipitation and run-off fluxes, respectively (in SI units, which will be the units used henceforth, these are all  $\text{kg s}^{-1}$ ), and  $S_w$  (kg) is the soil water storage. A catchment is in steady-state when changes in  $S_w$  are zero. Equation (1) can be integrated over some finite time period ( $\tau$ ) as follows:

$$\int_0^\tau \frac{dS_w}{dt} dt = \int_0^\tau P dt - \int_0^\tau E dt - \int_0^\tau Q dt \quad (2)$$

In finite form we have the catchment mass balance:

$$\Delta S_w = \bar{P}\tau - \bar{E}\tau - \bar{Q}\tau \quad (3)$$

or

$$\frac{\Delta S_w}{\tau} = \bar{P} - \bar{E} - \bar{Q} \quad (4)$$

We can convert to the familiar depth units by dividing both sides by the catchment area ( $A_c$ ,  $\text{m}^2$ ) and the density of liquid water ( $\rho_w$ ,  $\text{kg m}^{-3}$ ):

$$\frac{\Delta S_w}{\rho_w A_c \tau} = \frac{\bar{P} - \bar{E} - \bar{Q}}{\rho_w A_c} \quad (5)$$

The framework can be further extended by noting that soil water depends on the volume of the bucket ( $V$ ,  $\text{m}^3$ ) and the mass concentration of water in the bucket ( $[S_w]$ ,  $\text{kg m}^{-3}$ ):

$$S_w = V [S_w] \quad (6)$$

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and the soil water can change because of a change in the volume of the bucket or a change in mass concentration within the volume. To the first order we have:

$$\Delta S_w = [S_w] \Delta V + V \Delta [S_w] \quad (7)$$

The volume of the bucket depends on the catchment area and bucket depth ( $z$ , m):

$$V = A_c z \quad (8)$$

For a given catchment, the area is fixed and the volume of the bucket can only change because of the change in depth ( $\Delta z$ ). With that, and combining Eqs. (5, 7 and 8):

$$\frac{1}{\rho_w} \left( [S_w] \frac{\Delta z}{\tau} + z \frac{\Delta [S_w]}{\tau} \right) = \frac{\bar{P} - \bar{E} - \bar{Q}}{\rho_w A_c} \quad (9)$$

Even though this seems more complicated than Eq. (1) it has the advantage that it makes all the terms, especially  $\tau$ ,  $A_c$  and  $z$ , explicit. Firstly,  $\tau$  determines the timescale of analyses. In developing his framework, Budyko assumed catchments were at steady-state (i.e. the left-hand side of Eq. (9)→0). Budyko therefore a priori selected a value of  $\tau$  to ensure that the steady-state assumptions would be reasonable. In doing that, Budyko found that  $\Delta S_w$  can be as large as  $\bar{E}$  or  $\bar{Q}$  over a single year, and so set  $\tau$  to be much greater than 1 year by using long-term averages. Secondly,  $A_c$  determines the spatial scale of analyses. Budyko only examined catchments with  $A_c$  well over 1000 km<sup>2</sup>, partly to minimise the effect of any groundwater flow (i.e. to ensure the validity of the bucket model) as he assumed this to be negligible, and partly to minimise the effect of “local conditions” on  $\bar{E}$  (see Sect. 2.2). Lastly,  $z$  controls total possible  $S_w$ . However, under the assumption that groundwater flow is negligible, water loss from the bucket is via soil evaporation or plant transpiration. Thus rooting depth,  $z_r$  (m), determines the water potentially available to plants and therefore the effective bucket depth.

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Fluxes of both mass and energy are involved in evapotranspiration and this provides a critical link between the water and energy balances. The catchment-wide energy balance is given by:

$$\Delta S_e = R_n - \lambda E - H \quad (10)$$

where the change in energy storage ( $S_e$ ) is the balance between net radiation ( $R_n$ ) and the fluxes of latent ( $\lambda E$ ) and sensible ( $H$ ) heat (all in  $\text{J s}^{-1}$ ) where  $\lambda$  ( $\text{J kg}^{-1}$ ) is the latent heat of vaporisation. Note that the sign convention used in Eq. (10) assumes that  $\lambda E$  and  $H$  are positive away from the surface while  $R_n$  is positive into the surface. Using the same form as Eq. (9) gives:

$$[S_e] \frac{\Delta z_e}{\tau} + z_e \frac{\Delta [S_e]}{\tau} = \frac{\overline{R_n} - \lambda \overline{E} - \overline{H}}{A_c} \quad (11)$$

where  $z_e$  (m) is the depth to which energy can be stored. Over annual timescales energy storage can usually be omitted from the energy balance.

## 2.2 The framework and curve

Evapotranspiration is limited by the supply of either water or energy. At steady-state, when water is limiting ( $\overline{R_n}/\lambda > \overline{P}$ ), the maximum possible  $\overline{E}$  is  $\overline{P}$ , at which  $\overline{Q}=0$  (Eq. 9). Similarly, the maximum possible  $\overline{E}$  when energy is limiting is  $\overline{R_n}/\lambda$  at which  $\overline{H}=0$  (Eq. 11). Evapotranspiration approaches one of these two limits as water or energy, respectively, become increasingly limiting. This framework of mass and energy balances and supply and demand-limited evapotranspiration is the key component of Budyko's work. The type and degree of limitation is determined by the radiative index of dryness ( $\Phi$ ) which is the ratio of  $\overline{R_n}/\lambda$  to  $\overline{P}$ . Values of  $\Phi < 1$  represent energy-limited environments, and  $> 1$  water-limited. Intermediate environments occur where  $\Phi \sim 1$ .

If all available energy is converted to  $\lambda \overline{E}$ , then  $\overline{E} = \overline{R_n}/\lambda$ . Budyko considered this to represent "the greatest possible value of evaporation under given conditions" (Budyko,

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1974, pp. 323). To avoid the need to define the widely used notion of “potential evaporation” (Granger, 1989), subsequent discussion will refer to the available energy simply as  $\overline{R}_n/\lambda$ . This seems like a reasonable simplification as Budyko found that, averaged over a year or longer,  $\overline{H}$  is always positive (i.e. provides no net energy input) and that  $\overline{R}_n$  alone is a good approximation of the available energy.

Catchment-scale annual (or longer) evapotranspiration is usually estimated for gauged catchments by assuming that  $\Delta S_w$  is 0 and hence  $\overline{E}$  is the difference between measured values of  $\overline{P}$  and  $\overline{Q}$  (Eq. 9). The need for a simple means of estimating  $\overline{E}$  from ungauged catchments prompted Budyko to develop the “equation of relationship” that describes the dependency of  $\overline{E}$  on the variables  $\overline{P}$  and  $\overline{R}_n/\lambda$ :

$$\overline{E} = \left( \frac{\overline{R}_n \overline{P}}{\lambda} \tanh \frac{1}{\Phi} (1 - \cosh \Phi + \sinh \Phi) \right)^{1/2} \quad (12)$$

This curvilinear relationship has become known as the Budyko curve (Fig. 1). Budyko often used the evaporative index ( $\varepsilon$ ; which is  $\overline{E}/\overline{P}$ ) to describe the partitioning of  $\overline{P}$  into  $\overline{E}$  and  $\overline{Q}$ . The curve approaches the water and energy limits as values of  $\Phi$  become more extreme.  $\overline{Q}$  is proportional to the vertical distance between the curve and the water limit and  $\overline{H}$  is proportional to the vertical distance between the curve and the energy limit.

Budyko tested this relationship using measured values of  $\overline{E}$  from 1200 moderate sized ( $A_c > 1000 \text{ km}^2$ ) catchments and found that it explained about 90% of the variation in observed values. When limited to very large catchments ( $A_c > 10\,000 \text{ km}^2$ ) the relation was even better. This improvement with catchment area was attributed to the (macro-) climate being the principle determinant of  $\overline{E}$  over large areas. As  $A_c$  diminishes (i.e. as catchment size decreases),  $\overline{E}$  “may vary appreciably under the influence of local conditions of a non-climatic character” such as topography and vegetation (Budyko, 1974, pp. 318 and 330). The availability of energy, as described by  $\overline{R}_n$ , is a

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micro-climatic variable (e.g. depends on albedo and surface temperature) (Oke, 1987). Hence, we take Budyko's statement to mean that, the larger the catchment area, the more  $\overline{R_n}$  behaves as if it were a macro-climatic variable.

### 3 Understanding deviations from the Budyko curve

5 Budyko did note that systematic deviations occurred between actual and expected values and that it was most pronounced in intermediate climates (Fig. 2) and that these deviations were, in part, related to the seasonal cycles of  $P$  and  $R_n/\lambda$  (Budyko, 1974, pp. 326). When these are in phase, measured values of  $\varepsilon$  are slightly higher than expected and, when out of phase, are slightly lower. Budyko did not comment in any  
10 detail about the underlying processes. A better understanding of these processes would enable the Budyko framework to be used to estimate  $\overline{Q}$  and  $\overline{E}$  with greater reliability. It may even allow the framework to be used with small  $\tau$  and  $A_c$  without violating its inherent assumptions.

#### 3.1 Previous studies

15 A number of studies have examined the Budyko curve to find out what causes the deviations (e.g. Milly, 1994; Choudhury, 1999; Koster and Suarez, 1999; Zhang et al., 2001; Porporato et al., 2004). Most, however, have focused on climatic and physical processes with very few focusing on biological processes. Milly (1994) set out to explore reasons why Budyko's curve plots below the energy and water limits and what  
20 causes the deviations. Using a stochastic model, Milly found that, when the supplies of energy and water varied seasonally, the phase differences between  $R_n/\lambda$  and  $P$  where important. For example, when the supplies of  $R_n/\lambda$  and  $P$  were seasonal and out of phase there was proportionally less  $\overline{E}$  (and more  $\overline{Q}$ ) than when they were either non-seasonal or when seasonal and in phase. The ability of soil to store water provides a buffer against this seasonal climate variability. In times of surplus, water can  
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be stored in situ and is available to vegetation for use at a later time of deficit. Thus, Milly also found that  $\bar{E}$  increases (and  $\bar{Q}$  decreases) as potential  $S_w$  increases. Milly's analysis was grid-based, with a resolution of  $0.5^\circ$  ( $A_c \sim 2500 \text{ km}^2$  at  $35^\circ$  latitude). When compared to observed values (represented as interpolated surfaces of equivalent res-  
 5 olution) the model explained 88% and 85% of the variation in  $\bar{Q}$  and  $\bar{E}$ , respectively. Even though the model used allowed for a dynamic  $z_r$ , Milly held this constant in the analyses.

Choudhury (1999) tested the effects of spatial scales of analysis, or  $A_c$ , on predic-  
 10 tions of  $\bar{E}$ . Choudhury used Pike's (1964) equation which is numerically similar to Budyko's curve, except that it had an adjustable parameter,  $\alpha$ :

$$\bar{E} = \frac{\bar{P}}{\left(1 + \left(\bar{P}\lambda/\bar{R}_n\right)^\alpha\right)^{1/\alpha}} \quad (13)$$

This relationship was tested using observations of  $\bar{P}$ ,  $\bar{R}_n$  and  $\bar{E}$  derived from mass balances and micro-meteorology at field sites ( $A_c \sim 1 \text{ km}^2$ ), and derived from a biophysical process model (Choudhury and DiGirolamo, 1998) for large basins  
 15 ( $A_c > 1\,000\,000 \text{ km}^2$ ). It was found that the dependence of  $\bar{E}$  on  $\bar{P}$  and  $\bar{R}_n$  changes with  $A_c$  ( $\alpha=2.6$  for site based observations [ $r^2=0.99$ ] and 1.8 for basins [ $r^2=0.97$ ]). That is, the larger the basin area, the lower the  $\alpha$  and the less evapotranspiration for a given  $\Phi$  (Fig. 3). Choudhury did not stipulate exactly what physical processes were involved in this scale-dependence in  $\alpha$ .

Zhang et al. (2001) focused on the role vegetation plays within the Budyko frame-  
 20 work, acknowledging that a number of key vegetation characteristics affect evapotran-  
 spiration rates. Their aim was to adapt the Budyko framework so that it could be used to quantify the effect of long-term vegetation change on  $\bar{E}$ . They developed an equa-  
 tion similar to Budyko's and Choudhury's, also with an adjustable parameter,  $w$ , that

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they called the “plant available water coefficient”. This equation is defined by:

$$\varepsilon = \frac{1 + w\Phi}{1 + w\Phi + \frac{1}{\Phi}} \quad (14)$$

They hypothesised that this parameter should reflect the role of vegetation, particularly  $z_r$ , on  $\bar{E}$ . In fitting this curve to mass balance data from forested and non-forested catchments, the best-fit values of  $w$  were found to be 2.0 [ $r^2=0.93$ ] and 0.5 [ $r^2=0.90$ ], respectively (Fig. 3). Hence, forested catchments (high  $w$ ) have higher  $\bar{E}$  and lower  $\bar{Q}$  for a given  $\Phi$  compared to grassed catchments (low  $w$ ). Catchment sizes varied between 1 and 600 000 km<sup>2</sup>. Whilst showing that  $\bar{E}$  was related to vegetation, no quantitative link was made between these two variables. Zhang et al. (2004) noted that  $w$  represents the integrated effect of multiple catchment processes on evapotranspiration, of which vegetation is one, and that a priori estimations of  $w$  for a catchment are very difficult. An important point made by these authors (based on the work on Fu, 1981) was that evapotranspiration is most sensitive to variation in  $w$  under intermediate climates ( $\Phi \sim 1$ ).

Building on the work of Milly (1994) and Rodriguez-Iturbe et al. (2001), Porporato et al. (2004) used a simple stochastic model to explore the effect that changes in both  $z_r$  and the temporal distribution of rainfall have on the soil water balance and associated ecological processes. Using the Budyko framework, they showed that  $\Delta S_w$  has the inverse effect on  $\varepsilon$  as a change in average storm depth. That is, an increase in  $z_r$  shifts the Budyko curve up (increases  $\varepsilon$ ) as does a decrease in average storm depth, holding all else constant. These results provide some confirmation of Zhang et al.’s (2001) hypothesis of the relationship between  $w$  and  $z_r$ . Porporato et al. (2004) then demonstrated how their reformulation of Budyko could be used to estimate the effect of long-term changes in average storm depth (for a given  $\bar{P}$ ) on vegetation productivity, and changes in vegetation on evapotranspiration.

Koster and Suarez (1999) looked specifically at the relationships between  $\bar{P}$  and

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$\overline{R_n}/\lambda$  and the inter-annual variability in  $\overline{E}$ . They developed the “evaporation deviation ratio” as being the ratio between the standard deviation of annual evapotranspiration to that of annual precipitation calculated using long-term data records. It was found that this ratio could be reasonably well predicted from  $\Phi$  [ $r^2=0.86$ ]. These results are based on 20 years of simulated data from a GCM with a resolution of  $4^\circ \times 5^\circ$  which, at latitudes below  $66.5^\circ$ , means an  $A_c > 6500 \text{ km}^2$ . A key assumption in this analysis was that at  $\tau=1$  year,  $\Delta S_w$  approaches 0.

### 3.2 Interactions between analysis scale, vegetation and Budyko deviations

Whilst the importance of the role of vegetation in the water balance is generally acknowledged, few of these studies explicitly incorporate any plant functional attributes. Most commonly considered is  $z_r$ , but only in theory – it is usually held constant in applications. Porporato et al. (2004) are an exception as they quantitatively included temporal variations in  $z_r$  in their model. Holding  $z_r$  constant is currently a reasonable approach as it is difficult to measure. Ultimately, as long as catchment mass balance models, such as Budyko’s, continue to omit measures of vegetation, they will remain limited in their ability to address important ecological and hydrological issues.

The dependence of  $\overline{E}$  on the long-term climatic parameters  $\overline{P}$  and  $\overline{R_n}/\lambda$  has been demonstrated by several authors using a variety of equations that represent variations of the Budyko curve. According to Budyko (1974), the numerical similarity of equations describing this relationship is inevitable. The advantage of the Choudhury (1999) and Zhang et al. (2001) equations is computational simplicity and the flexibility afforded by the adjustable parameters. These two adjustable parameters appear also to be functionally similar, possibly indicating a link between vegetation,  $A_c$  and variation in  $\overline{E}$  and that such a link is most pronounced under intermediate climates.

Choudhury’s (1999) work emphasised the importance of  $A_c$  in describing the dynamics of  $\overline{E}$ . As Budyko’s curve considers only macro-climatic processes, its reliability is greatest where  $A_c$  exceeds  $1000 \text{ km}^2$ . This is confirmed by Budyko (1974), Milly (1994)

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and Koster and Suarez (1999) who, working at large scales, concluded that most variation in  $\bar{E}$  was explained by  $\Phi$ . Alternatively, over half the catchments used by Zhang et al. (2001) were under 1000 km<sup>2</sup>, and these authors concluded that vegetation does play an important role in partitioning  $\bar{P}$  into  $\bar{E}$  and  $\bar{Q}$  at these scales. Integration of vegetation into the Budyko framework is expected to increase its reliability in predicting  $\bar{E}$  and  $\bar{Q}$  when  $A_c$  is small and render it more useful at typical management scales.

The assumption that between individual years  $\Delta S_w$  is insignificant needs to be made with caution as vegetation dynamics, and particularly vegetation change, can result in large  $\Delta S_w$  even when  $\tau$  is around 1 year. Several examples will illustrate this. Talsma and Gardner (1986) showed that some *Eucalyptus* species drew more heavily on stored water during the summer of a drought year than the summers of years with average rainfall, using 200 mm more soil water than average. Another example is given in Fig. 4, which shows evapotranspiration for the Upper Cotter catchment in the Australian Capital Territory (148°50', 35°40' S, 148 km<sup>2</sup>) calculated using Eq. (9) with  $\tau=1$  year. Several years show evapotranspiration values above the energy limit. These years had unexpectedly low  $\bar{Q}$  given the high  $\bar{P}$  and were each preceded by moderately dry years. This catchment contains *Sphagnum* bogs with large water holding capacities. The observed pattern implies that recharge/discharge of these bogs results in relatively large changes in  $S_w$ . When measured  $\bar{P}$  and  $\bar{Q}$  are used to estimate  $\bar{E}$  using Eq. (9) in a non-steady-state catchment, the estimate of  $\bar{E}$  inherently includes  $\Delta S_w$ . Finally, Calder et al. (1997) reported that *Eucalyptus* plantations established on former croplands exploited substantial stored soil water resulting in unusually high  $\bar{E}$  and that  $\Delta S_w$  could be up to 50% of  $\bar{P}$  for several years after planting (the opposite  $\Delta S_w$  would be expected in the years following clearing of the same plantations). These examples demonstrate that vegetation dynamics can result in non-steady-state conditions, especially after vegetation change, over periods of up to several years. The longer the period needed for steady-state conditions, the less useful the approach for catchment and land management applications.

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Despite the importance of Budyko's work and the attention it has received since publication, the equation of relationship remains restricted to analyses of long-term averages. Such averages remove short to medium-term variability to establish steady-state conditions and consequently the reliability of Budyko's curve is diminished when used to address issues of short-term changes in the water balance. This is particularly pertinent to vegetated landscapes as the hydrological role of vegetation can be highly dynamic. It would be of great practical value to apply a Budyko-type framework to inter-annual (and even intra-annual) timeframes and therefore be able to use it to address landscape change.

Besides affecting the spatial and temporal scales to which Budyko can be applied, quantitative incorporation of hydrologically important vegetation characteristics into Budyko's model is also expected to open its scope to more ecologically-oriented applications such as vegetation productivity modelling (e.g. Porporato, 2004), to integrated vegetation and water management and to assessing possible impacts of climate change on catchment processes. A crucial aspect of achieving this is to ensure that the vegetation characteristics have relevance at catchment scales and be readily measured, preferably by some form of remote sensing.

**4 The dynamic role of vegetation in the water balance**

It is well established that vegetation plays an important role in the water balance (e.g. Jones, 1992; Calder, 1993; Arora, 2002; Lee et al., 2005) and that changes in vegetation extent and type are accompanied by changes in catchment evapotranspiration and run-off (Sharma, 1984; Vertessy et al., 2003). This was recently highlighted by Farley et al. (2005) and Jackson et al. (2005) in the context of the hydrological consequences of proposed afforestation for carbon sequestration. The total evapotranspiration from catchments can be viewed as the sum of distinct components, for example, transpiration ( $\overline{E}_t$ ), evaporation from plant surfaces of intercepted rainfall ( $\overline{E}_i$ ) and evaporation

from soil and other non-vegetated surfaces ( $\overline{E}_s$ , all in  $\text{kg s}^{-1}$ ):

$$\overline{E} = \overline{E}_t + \overline{E}_i + \overline{E}_s \quad (15)$$

There are three vegetation characteristics which are particularly important in determining  $\overline{E}$ : leaf area, photosynthetic rate and rooting depth. Significantly, all are highly dynamic across space and through time. Understanding of these characteristics, however, has rarely been incorporated into catchment-scale hydrological models (Arora, 2002), especially in ways that have practical significance.

#### 4.1 Three key vegetation attributes

Although many plant physiological and structural characteristics affect  $\overline{E}$ , the three that dominate catchment-scale water use are: 1) leaf area; 2) photosynthetic rate; and 3) rooting depth (Pierce et al., 1993; Zhang et al., 2001; Arora, 2002; Eamus, 2003). The leaf area index ( $L$ ) is the total projected leaf area per unit ground area:

$$L = \frac{\text{leaf area}}{\text{ground area}} \quad (16)$$

$L$  is an important plant structural attribute that relates to both the energy and water fluxes (Nemani and Running, 1989; Pierce et al., 1993; Hatton and Wu, 1995).  $L$  is related to photosynthesis as it determines the fraction of Photosynthetically Active Radiation absorbed by foliage (fPAR, 0–1). It alters albedo, and therefore net radiation, as well as surface roughness which influences evapotranspiration rates (Arora, 2002). At low values of  $L$  common in drier environments ( $\leq 3$ –5)  $L$  is often linearly related to  $\overline{E}_t$  (Jones, 1992; Law et al., 2002) and is similarly related to fPAR over this range. As the climate becomes wetter the relationship between  $\overline{E}_i$  and  $L$  becomes important, such that  $\overline{E}_i$  can comprise 40–50% of  $\overline{E}$  in energy-limited environments (Hutley et al., 1997; Barbour et al., 2005). Considering these relations,  $L$  should bear a general relationship to  $\overline{E}$  over most climates.

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Leaf area is a highly dynamic vegetation characteristic. It varies with resource availability (Field et al., 1992; Whitehead and Beadle, 2004) being higher where conditions are more favourable for growth. Significant temporal variation occurs due to vegetation type, climate dynamics and age. Annual and deciduous species have extreme cyclical variation in  $L$  whilst evergreen species have more moderate values with medium-low seasonal variability.  $L$  can change inter-annually as a function of vegetation age: young vegetation quickly increases its leaf area which peaks before dropping to a lower and more constant value as it matures (Arora, 2002). Vegetation age is altered by the frequency of major disturbances (e.g. fires, storms, diseases) and management actions (e.g. destructive harvesting, crop establishment).

Photosynthetic rate ( $A_g$ , mol CO<sub>2</sub> s<sup>-1</sup>) refers to the net carbon assimilation rate per unit ground area (Salisbury and Ross, 1992; Larcher, 1995).  $A_g$  can be related to  $E_t$  as:

$$E_t = 0.018 \left( \frac{A_g}{W_{ph}} \right) \tag{17}$$

where  $W_{ph}$  is the water use efficiency of photosynthesis and is the ratio of the number of moles CO<sub>2</sub> gained in photosynthesis to the number of moles H<sub>2</sub>O lost in transpiration, expressed per unit ground area. It can be seen from Eq. (17) that, at a given  $W_{ph}$ , high  $A_g$  is accompanied by high rates of transpiration. McVicar et al. (2002) provide relevant units for expressing  $W_{ph}$  for small spatial-temporal scales (e.g. leaves, days) to large spatial-temporal scales (e.g. catchments, years).  $A_g$  is highly dynamic, varying within and across species and vegetation types, with location and plant age. Highly fertile sites support plants with higher  $A_g$  than resource poor sites (Larcher, 1995; Eamus et al., 2001). There is a general relationship between  $A_g$ , the ratio of leaf area to leaf volume ( $\Lambda$ ) and leaf longevity (Reich et al., 1997; Roderick et al., 2000). Short-lived, thin leaves (high  $\Lambda$ ) typical of annual and deciduous species and the young foliage of evergreens, have high  $A_g$  compared with long-lived, thick leaves (low  $\Lambda$ ) of mature evergreens, all else being equal.

Rooting depth ( $z_r$ ) is an extremely important plant characteristic as it determines the soil water potentially available for transpiration. In the absence of roots (vegetation), little buffering of rainfall variability occurs and, considering that evaporation from bare soil rapidly diminishes after rainfall (Ritchie, 1972), the majority of precipitation eventually becomes run-off (Milly, 1994; Porporato et al., 2004). Roots extend down some proportion of total soil depth. Even though soil depth at a site may be invariant (over typical timescales of interest, e.g. 100 years),  $z_r$  is not. It can vary inter-annually due to fluctuations in climate (Field et al., 1992), and even seasonally in concert with water table fluctuations (Knight, 1999; Pate and Bell, 1999). Of significance is the potentially rapid changes in  $z_r$ , and therefore in  $S_w$  (Eq. 9), due to vegetation change. Disturbances such as deforestation can almost instantly reduce the effective  $z_r$  (roots may remain but are generally inactive) whilst regeneration and revegetation can increase it over time. This not only affects  $\overline{E_t}$  but also alters the value of  $\tau$  required to achieve steady-state conditions.

#### 4.2 Seasonal vegetation dynamics

Budyko (1974) and Milly (1994) both noted that phase differences between the seasonal dynamics of  $R_n/\lambda$  and  $P$  are associated with differences that can occur in  $E$  and  $Q$  under a given climate. Such differences result in vertical deviations from the Budyko curve where, for a given  $\Phi$ , a variety of values in  $\varepsilon$  can occur (Fig. 5a). As Zhang et al. (2001) and Porporato et al. (2004) have shown, these vertical deviations also relate to seasonal water use dynamics of different vegetation types. Further, seasonal vegetation dynamics and seasonal climate dynamics are coupled (Berry et al., 2005) – except where the vegetation has been heavily modified – such that it would be difficult to ascertain which of the two dynamics are most directly responsible for these deviations.

A useful functional classification of vegetation which captures these seasonal water use differences is evergreen and raingreen functional types. This approach is useful because the functional types can be distinguished in time-series satellite imagery (De-

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Fries et al., 1995; Roderick et al., 1999; Lu et al., 2003). Evergreen vegetation is comprised of non-deciduous perennial species and raingreen is comprised of deciduous and annual species. These two types are characterised by differences in the seasonal dynamics of  $L$  and  $A_g$ . Also, if deciduous species are uncommon in a catchment, then the useful generalisation can be made that evergreens have high and reasonably static  $z_r$  and raingreens have low  $z_r$  and this for only part of the year. One consequence of these dynamics is that, for a given climate,  $\bar{E}$  from a catchment supporting mostly evergreen vegetation should be relatively high and  $\bar{Q}$  relatively low compared to that from a catchment with mostly raingreen vegetation (Hatton and Nulsen, 1999; Berry et al., 2005). On the Budyko curve, an evergreen catchment is likely to plot above the curve and a raingreen catchment below the curve (Figs. 5a and b), as per Zhang et al. (2001). Describing vegetation simply as annual averages will not fully capture these important differences in  $\bar{E}$  and  $\bar{Q}$  associated with seasonal vegetation dynamics. Instead, some indication of the relative contributions of raingreen and evergreen vegetation types to a catchment's water balance (e.g. Fig. 5b) will most likely explain more of the vertical deviations that occur around the Budyko curve.

### 4.3 Annual vegetation dynamics

Catchments experiencing net vegetation change between years will experience changes in catchment evapotranspiration. The position that such catchments plot on the Budyko curve can change over time even in the absence of changes in the macroclimate. For example, clearing of evergreen vegetation means an instant reduction in  $z_r$ ,  $A_g$  and  $L$  and, for a given  $\Phi$ , is followed by a decrease in  $\bar{E}$  and an increase in  $\bar{Q}$ . A change in  $S_w$  occurs as the soil profile fills in the absence of soil water extraction by deep roots. A new steady-state eventually re-establishes at a lower  $\bar{E}$  associated with the replacement vegetation type typically being raingreen (Fig. 6a). This is the typical hydrological impact of clearing for agriculture (Calder, 1993; Pierce et al., 1993; Walker et al., 1993). These changes mean a catchment will progressively plot lower

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on the Budyko curve. The opposite vegetation change – the replacement of raingreen with evergreen vegetation – initially produces a marked increase in  $\bar{E}$  and drop in  $\bar{Q}$  (Fig. 6b) due to the high  $L$ ,  $A_g$  and rapid increases in  $z_r$  (up to 2.5 m/yr (Calder et al., 1997)) associated with young evergreen vegetation. Rapid extraction of  $S_w$  often occurs. As the vegetation ages,  $\bar{E}$  moderates and a new steady-state establishes with higher overall  $\bar{E}$  and lower  $\bar{Q}$  than that of the original steady-state condition, which eventually locates the catchment higher on the Budyko curve. This is the typical hydrological pattern following afforestation (Van Lill et al., 1980; Vertessy et al., 2003; Farley et al., 2005). Both these cycles are observed when evergreen vegetation regenerates after disturbance (Fig. 6c) such as after fire (Vertessy, 1998) or after timber harvesting (Cornish and Vertessy, 2001). These examples demonstrate that dramatic vegetation change can disrupt steady-state conditions within catchments and alter the relative proportions of  $\bar{Q}$  and  $\bar{E}$  for years, and even decades, after large disturbances, ultimately changing a catchment's position within the Budyko framework.

In summary, the implications of the dynamics of vegetation water use on catchment water balances have been highlighted. When both  $\tau$  and  $A_c$  are large, it has been found that it is not necessary to explicitly include vegetation in Budyko's framework to achieve reasonable predictions of catchment behaviour. However, as  $\tau$  and  $A_c$  become smaller it becomes increasingly important to incorporate both the inter- and intra-annual vegetation dynamics into the framework. This is expected to result in a more practical and a more reliable predictor of catchment hydrological behaviour at small scales.

## 5 Using vegetation information in ecohydrology

### 5.1 Vegetation – the great landscape integrator

Vegetation directly affects the energy and water balances. However, vegetation grows in response to the combined affect of all conditions that limit growth (Odum, 1993),

such as light, temperature, nutrients and disturbances. In environments where the dominant limitation is water, vegetation grows in response to the multiple processes that affect the availability of water (Specht, 1972; Zhang et al., 2004) and may provide a shortcut to quantifying the local, micro-climatic factors affecting  $\bar{E}$ . As Nemani and Running (1989) suggested, vegetation is the great landscape integrator.

## 5.2 Ecohydrological equilibrium

In water-limited environments strong relationships have been found between water availability and mature, perennial vegetation, most particularly vegetation structure (Specht, 1972; Woodward, 1987). Perennial vegetation supports leaf areas that can be predicted from moisture availability and which vary in concert with it. This suggests an ecohydrological equilibrium, or steady-state (Nemani and Running, 1989; Pierce et al., 1993; Hatton and Nulsen, 1999), a dynamic condition that fluctuates with micro-climatic variations and only occurs in relatively undisturbed vegetation. Measures of such vegetation are expected to be correlated to the net effect of all processes affecting water availability and may bypass the need to measure each process individually (Zhang et al., 2004). Since  $L$  is an above-ground, structural characteristic and is therefore relatively easy to measure compared to  $z_r$  and  $A_g$ , it is the most useful of the three vegetation characteristics to incorporate into the Budyko model. As  $L$  fluctuates according to ecohydrological equilibrium theory, in some circumstances incorporation of  $L$  will account for the effects of  $z_r$ , and even changes in  $z_r$  (Specht, 1972), and may provide a surrogate measure of  $z_r$ . Additionally,  $L$  provides a link to land management as  $L$  is manipulated by management practices such as planting, harvesting and thinning of vegetation and by modifying site fertility.

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### 5.3 Remotely-sensed measures of leaf area index and the fraction of absorbed Photosynthetically Available Radiation

The easiest means of measuring  $L$  across large areas, and repeatedly through time, is by satellite-based remote sensing. Vegetation has a unique spectral signature (Jones, 1992) which forms the basis of a variety of remotely sensed vegetation indices, including the Simple Ratio (SR) and the more common Normalised Difference Vegetation Index (NDVI). Theory and measurements have shown that  $L$  is linearly related to SR (Lu et al., 2003) whilst NDVI is near-linearly related to fPAR (Kumar and Monteith, 1981; Asrar et al., 1984). fPAR can be related to  $A_g$  and  $E_t$  through Monteith's light use efficiency model (Monteith, 1981; Roderick et al., 2001; Berry and Roderick, 2004). From a remote sensing point of view, fPAR itself is a key measure for describing the hydrological role of vegetation.

In applications, integrals of NDVI are often used (e.g. Prince, 1991; McVicar and Jupp, 1998). Annual NDVI has been found to be linearly related to annual catchment  $\bar{E}$  from both an energy-limited environment (Szilagyi, 2000) and a water-limited environment (Mora and Iverson, 1998). For more detailed work, the seasonal dynamics of the NDVI signal can be processed to estimate the evergreen and raingreen vegetation types (Fig. 5b) (Roderick et al., 1999; Lu et al., 2003) which can then be used to estimate primary productivity and  $\bar{E}$  of the separate types (Berry and Roderick, 2004). It is worth noting that before using NDVI data in applications, it is important to ensure potential sources of signal contamination are accounted for, such as the effects of satellite calibration, atmospheric and cloud interference, and Sun-target-sensor geometry (Gutman, 1999).

## 6 Conclusion

The assumptions inherent in Budyko's hydrological model have been highlighted by restating the Budyko framework in such a way as to explicitly include the temporal ( $\tau$ )

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and spatial ( $A_c$ ) scales of analysis. The first assumption is that catchments are at steady-state (that is,  $\Delta S_w \approx 0$ ). This condition depends on both  $\tau$  and  $A_c$ . The second is that, at large spatial scales ( $A_c \gg 1000 \text{ km}^2$ ), net catchment drainage is negligible and that only macro-climatic variables are required to describe catchment water balances.

5 Application of Budyko's model to small catchments and over small timeframes can violate the assumptions inherent in the framework, contributing to the deviations of observed values from the Budyko curve.

Vegetation is known to play a significant and highly dynamic role in determining catchment evapotranspiration. Vegetation accesses stored soil water, the potential volume of which is determined by  $z_r$ , and evaporates this water into the atmosphere at rates dependent on  $L$  and  $A_g$  amongst other things. The role of vegetation in the water balance is continually changing as  $z_r$ ,  $L$  and  $A_g$  all vary with climatic conditions and with the type and age of vegetation. At small spatial and temporal scales ( $A_c \leq 1000 \text{ km}^2$  and  $\tau \leq 1-5$  years), which are scales arguably more relevant to management activities than those originally used by Budyko, vegetation becomes an important explanatory variable of catchment hydrological behaviour. This is particularly true for catchments experiencing vegetation change as this means the relative proportions of  $\bar{E}$  and  $\bar{Q}$  are shifting and, because of changes in  $z_r$ , steady-state conditions are unlikely to exist in these catchments.

20 The theory of ecohydrological equilibrium is based on the idea that, in water-limited environments, vegetation is the integrated response to all processes affecting the availability of water. Consequently, incorporation of some key measure of vegetation into Budyko's model is expected to extend the model's ability to describe catchment behaviour to small scale analyses.  $L$  is one such measure as it has been shown to vary with water availability according to ecohydrological equilibrium theory. The most practical way of measuring  $L$  across large areas and repeatedly through time is with remotely sensed vegetation indices. fPAR is an alternative measure and one that is closely related to the commonly used NDVI. We expect that the integration of the temporally dynamic raingreen and evergreen components of fPAR into the Budyko framework will

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extend the framework to be a reliable predictor of  $\bar{E}$  and  $\bar{Q}$  over small timescales and in small catchments, even when those catchments are experiencing significant vegetation change.

As far as we are aware, this proposal has not yet been tested. If such a modified Budyko framework can be developed, its use is expected to extend not only to applica-  
5 tion at small scales but also to practical applications such as predicting the hydrological effects of vegetation management activities. It is also expected to be a powerful tool for exploring the possible effects of short and long-term climate change on both vegetation and hydrology.

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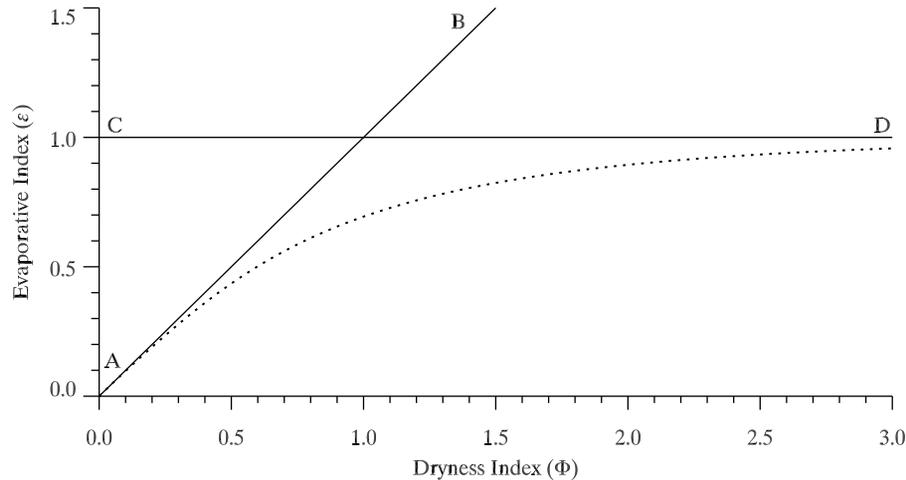
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**Fig. 1.** Budyko's framework and curve. The curve (dotted line), defined by Eq. (12), describes the relationship between the dryness index ( $\Phi$ ;  $\overline{R_n}/\lambda\overline{P}$ ) and the evaporative index ( $\epsilon$ ;  $\overline{E}/\overline{P}$ ). Line A–B defines the energy-limit to evapotranspiration, and line C–D defines the water-limit.

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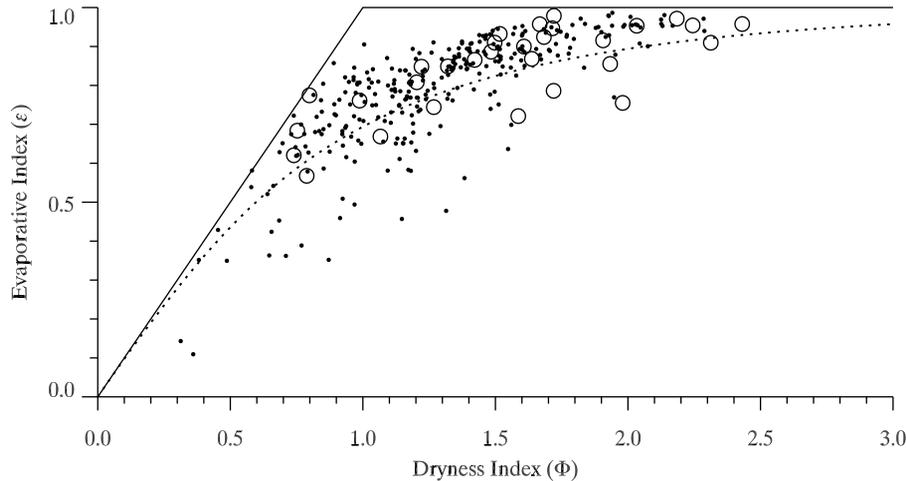
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**Fig. 2.** Plot of mass balance data from 331 Australian catchments showing the deviations of values around the Budyko curve. Large, hollow circles denote the 30 moderate-sized catchments ( $A_c \geq 1000 \text{ km}^2$ ) and small circles denote the remaining 301 smaller catchments ( $< 1000 \text{ km}^2$ ). Data are from Peel et al. (2000) and Raupach et al. (2001) calculated using Eq. (9) with  $\tau \geq 8$  years.

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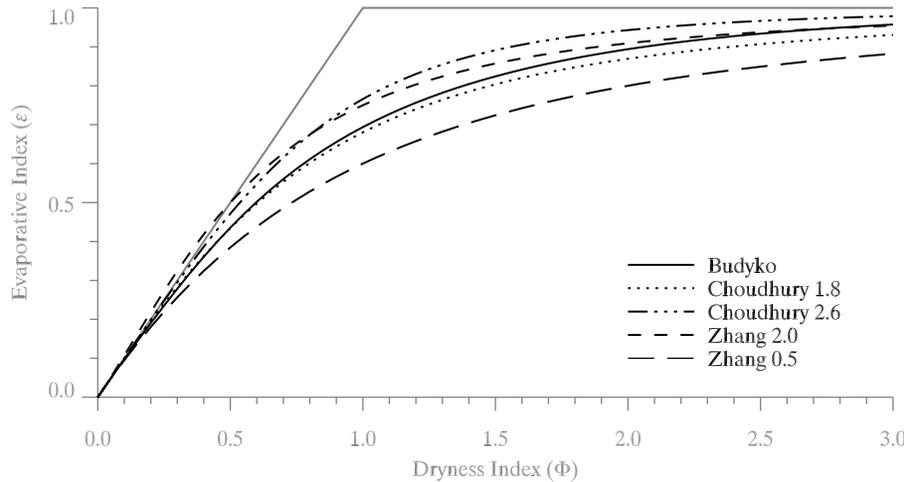
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**Fig. 3.** Comparison of the Budyko curve (Eq. 12) with the curves of Choudhury (1999) (Eq. 13) and Zhang et al. (2001) (Eq. 14). Choudhury 1.8 calculated using  $\alpha=1.8$  and describes  $\varepsilon$  from large catchments ( $A_c > 1 \times 10^6 \text{ km}^2$ ). Choudhury 2.6 uses  $\alpha=2.6$  and describes field plots ( $A_c \sim 1 \text{ km}^2$ ). Zhang 2.0 and Zhang 0.5 use  $w=2.0$  and  $0.5$ , respectively, and describe  $\varepsilon$  from forested and non-forested catchments, respectively.

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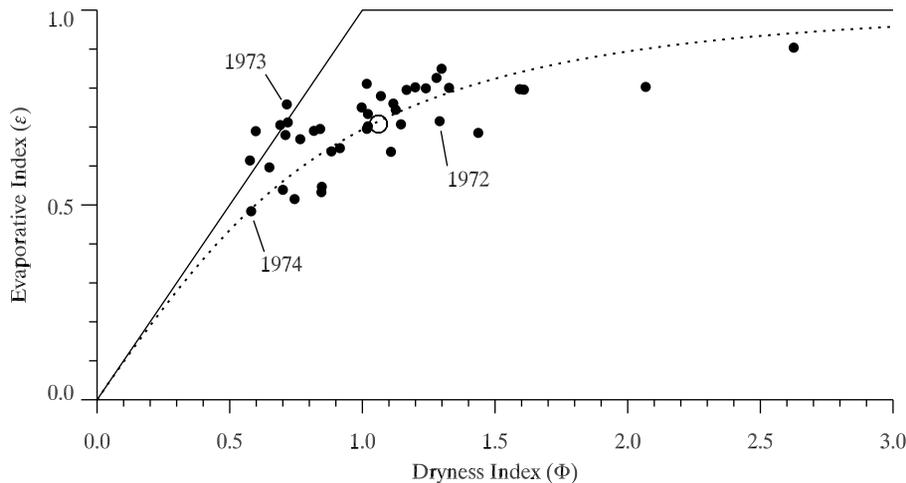
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**Fig. 4.** Inter-annual mass balance data for the Upper Cotter catchment, showing several years with values of  $\epsilon$  above the energy-limit. Values derived with Eq. (9) with  $A_c=148 \text{ km}^2$  and  $\tau=1$  year. The progression of  $\epsilon$  and  $\Phi$  from 1972 to 1974 is shown to highlight the  $\Delta S_w$  between a dry year (1972;  $\bar{P}=780 \text{ mm}$ ,  $\bar{Q}=220 \text{ mm}$ ) and a very wet year (1973;  $\bar{P}=1320 \text{ mm}$ ,  $\bar{Q}=320 \text{ mm}$ ) and two very wet years (1973) and (1974;  $\bar{P}=1460 \text{ mm}$ ,  $\bar{Q}=750 \text{ mm}$ ). The hollow circle denotes the long-term ( $\tau=39$  years) value of  $\epsilon$ . Data courtesy of Ecowise Services (Australia), Pty. Ltd.

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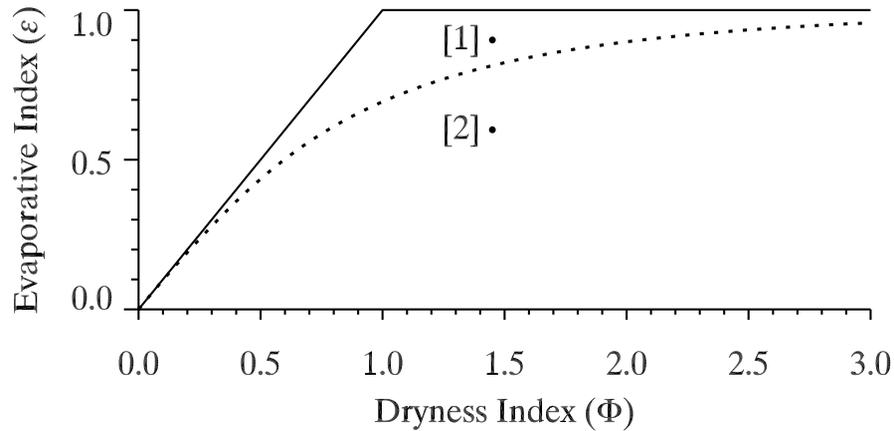
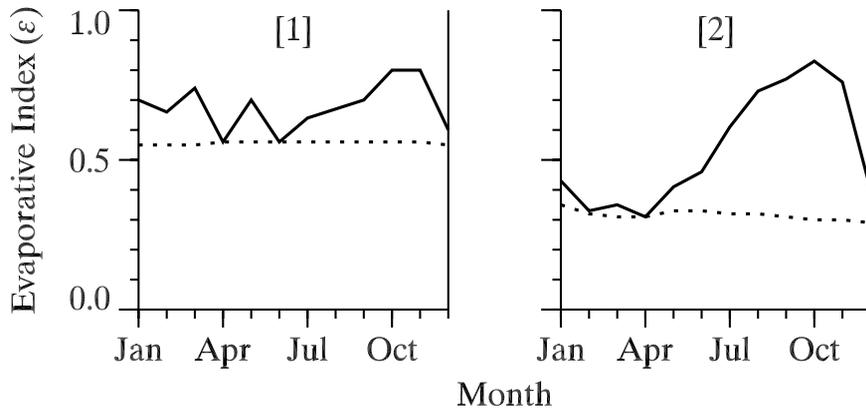
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**A****B****Fig. 5.**

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**Fig. 5.** The effect of seasonal vegetation dynamics on catchment evapotranspiration and run-off. For a given dryness index, catchments with a high proportion of evergreen vegetation (e.g. [1]) have greater evapotranspiration fluxes and smaller run-off fluxes (and therefore plot higher on the Budyko curve) than catchments with a high proportion of raingreen vegetation (e.g. [2]).

**(A):** Indicative values of the evaporative index for catchments [1] and [2], both with  $\Phi \sim 1.45$ , demonstrating vertical deviations that are possible within the Budyko framework.

**(B):** Profiles of catchment fPAR showing seasonal vegetation dynamics. Catchment [1] has a higher total fPAR (solid line) and higher proportion of evergreen fPAR (dotted line) compared to catchment [2]. Raingreen fPAR is the difference between total and evergreen. Catchment [1] supports mostly open Eucalypt forest (149.725° E, 34.070° S). Catchment [2] supports agricultural pastures with patches of Eucalypt forest (147.369° E, 35.443° S). Derivations of fPAR and the evergreen/raingreen components based on Roderick et al. (1999) using AVHRR Global Area Coverage NDVI data.

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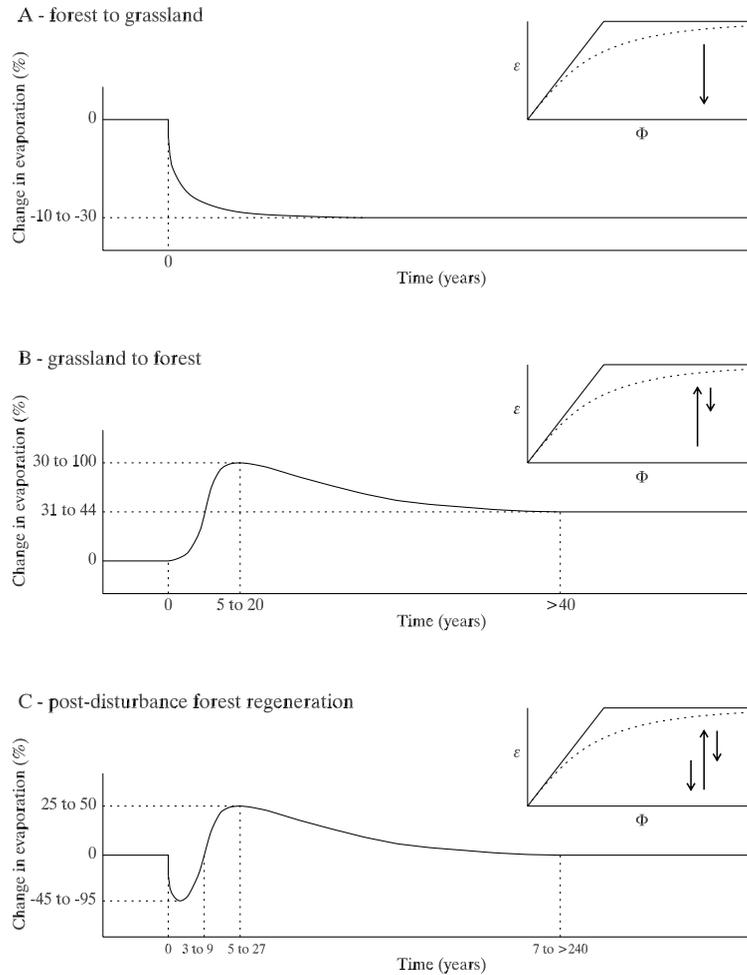
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Fig. 6.

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**Fig. 6.** Changes in catchment evapotranspiration following major vegetation changes.

**(A):** Conversion of forest to grassland. **(B):** Conversion of grassland to forest. **(C):** Forest disturbance and subsequent regeneration. Values given are predominantly based on Eucalypt forests and plantations in water-limited catchments (Langford, 1976; Van Lill et al., 1980; Kuczera, 1987; Pierce et al., 1993; Costa and Foley, 1997; Vertessy, 1998; Cornish and Vertessy, 2001; Gordon et al., 2003; Vertessy et al., 2003; Farley et al., 2005). The timing and magnitude of changes in evapotranspiration vary with annual average precipitation, species and the proportion of catchment undergoing change. Insets indicate vertical changes ( $\Delta\varepsilon$  for a given  $\Phi$ ) in a catchment's location within the Budyko framework associated with each type of vegetation change.

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