A general predictive model for estimating monthly ecosystem evapotranspiration

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ABSTRACT

Accurately quantifying evapotranspiration (ET) is essential for modelling regional-scale ecosystem water balances. This study assembled an ET data set estimated from eddy flux and sapflow measurements for 13 ecosystems across a large climatic and management gradient from the United States, China, and Australia. Our objectives were to determine the relationships among monthly measured actual ET (ET), calculated FAO-56 grass reference ET (ETₒ), measured precipitation (P), and leaf area index (LAI)—one associated key parameter of ecosystem structure. Results showed that the growing season ET from wet forests was generally higher than ETₒ, while those from grasslands or woodlands in the arid and semi-arid regions were lower than ETₒ. Second, growing season ET was found to be converged to within ±10% of P for most of the ecosystems examined. Therefore, our study suggested that soil water storage in the nongrowing season was important in influencing ET and water yield during the growing season. Lastly, monthly LAI, P, and ET, together explained about 85% of the variability of monthly ET. We concluded that the three variables LAI, P, and ETₒ, which were increasingly available from remote sensing products and weather station networks, could be used for estimating monthly regional ET dynamics with a reasonable accuracy. Such an empirical model has the potential to project the effects of climate and land management on water resources and carbon sequestration when integrated with ecosystem models. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS climate change; ET; eddy flux; modelling; sapflow; water balance

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INTRODUCTION

Evapotranspiration (ET) accounts for over half of the total water loss from most terrestrial vegetated ecosystems (Zhang et al., 2001; Lu et al., 2003). For example, in water-limited semi-arid and arid regions, ET can comprise an even greater percentage of the total water loss (Wang et al., 2010) and can equal precipitation. Changes in land use/land cover and climate can also directly impact water supply and demand and the regional hydrological cycle (DeWalle et al., 2000; Jackson et al., 2001; Foley et al., 2005; Liu et al., 2008; Sun et al., 2008a) by altering the ET processes. Although ET is a key variable that links hydrological and biological processes in most ecosystem models (Hanson et al., 2004), ET is one of the most difficult water budget components to quantify (Allen, 2008; Shuttleworth, 2008). Worldwide high temporal scale ET measurements based on soil water balance, sapflow, and eddy covariance methods offered new insights in ecohydrological sciences and helped to advance our understanding of the ET processes. Several techniques for quantifying ET exist; for example, the watershed water balance method of precipitation (P) inputs minus streamflow outputs (Q), or ET = P − Q, is typically limited to long-term average, when the change in water storage component is negligible (Wilson et al., 2001; Ford et al., 2007). At the other temporal extreme, sapflow- and eddy covariance-based ET estimates agree well with other techniques for uniform stands with large footprints (i.e. continuous coverage), but are less reliable in complex stands and small or nonuniform footprints (i.e. canopy gaps) (Wullschleger et al., 1998; Wilson et al., 2001; Ewers et al., 2002; Law et al., 2002; Arain et al., 2003; Paw U, 2006; Ford et al., 2007; Sun et al., 2008a, 2009, 2010; Barker et al., 2009). Eddy covariance and sapflow methods have gained popularity for simultaneously measuring both water and carbon fluxes because of their ability to resolve fluxes on a short time-step, offering high temporal resolution. This is largely
due to performance improvements and reduced costs of fast-response monitoring equipment in recent years. A general predictive model of ET at a monthly scale could help land managers to maximize the ecosystem services because ET is highly coupled with carbon gain (Law et al., 2002; Jackson et al., 2005; Noormets et al., 2006) and other ecosystem services such as biodiversity (Currie, 1991).

Biophysical modelling has been the most popular approach for estimating the regional ET using mass- and energy balance theories and empirical relationships among potential ET, precipitation or soil moisture status, and/or land cover type (Zhang et al., 2001; Lu et al., 2003; Amatya and Trettin, 2007; Zhou et al., 2008). Energy and water balances of terrestrial ecosystems are tightly coupled through the ET processes at multiple scales. The long-term ET for a large area is mainly controlled by water and energy availability and by land surface characteristics to a minor extent (Milly, 1994; Zhang et al., 2001, 2004). Although a comparison of Budyko-type models that describe such energy–water relationships is found in Zhang et al. (2004), quantifying ET of vegetated surfaces at a fine spatial and temporal scale (e.g. watershed, daily, monthly) remains challenging. For example, the process-based Penman-Monteith ET model requires several climatic variables that are often not available, nor can the parameters be derived for large areas. Even the widely used FAO-56 grass reference ET (ET0) method (Allen et al., 1994), a simplified version of the Penman-Monteith equation, needs substantial corrections to provide ET estimates for certain landscapes (e.g. forests) at a daily or monthly scale (Sun et al., 2010). Generally, because in situ ET measurements are rarely available at the watershed scale, most hydrological models are validated with run-off rates measured at the watershed outlets only; thus, those models have large uncertainties in describing the full hydrological cycle (Sun et al., 2008b). However, tree sapflow and eddy flux measurements from many types of ecosystems around the globe offer an opportunity to derive ET and water balance models at a higher temporal resolution than were previously possible.

Our overall goal in this study was to develop a simple monthly ET model that can be used for regional applications in modelling ecosystem services (i.e. predicting water yield, carbon sequestration, and biodiversity). Our hypothesis was that monthly ET could be estimated from three environmental controls that include available energy (i.e. ET0), water (i.e. precipitation, P), and seasonal vegetation dynamics (i.e. leaf area index, LAI). We assembled data from ten United States-China Carbon Consortium (Sun et al., 2009) sites and three forested sites with intensive sapflow measurements in the United States and Australia. Our specific objectives of this synthesis study were to: (1) contrast monthly ET and environmental controls (P, LAI, and ET0) among the 13 sites, and (2) develop an empirical monthly ET model that can be readily used to estimate ET at the site or over a large region.

**METHODS**

### Monthly ET, P, and LAI

We assembled a database from 13 research sites that represent a range of biomes. Sites span a large climatic gradient, ranging from subtropical rain forests (CWWP) to the humid Appalachiens in the southeastern United States, to the hot dry woodlands in eastern Australia (AUWS, AUQA), and from forested wetlands (NCLP, NCCC) on the Atlantic coastal plain in the southeastern United States to the grasslands (DLSP, XLDS, XLFC) and shrub lands (KBSB) and cultivated croplands (DLCP) in the semi-arid Inner Mongolia region in northern China (Figure 1; Table I). Management practices also vary widely. The data set includes two loblolly pine plantations (NCLP, NCCC) on a drained wetland landscape and two poplar plantation sites (BJPL, KBPL) that were subject to brief irrigation during the growing seasons. For the same grassland ecosystem type, the data set consists of an ecosystem that was under annual grazing (XLDS) and one under protection (XLFC) from human disturbances (i.e. fenced, no grazing). The geographic range of the sites varies in latitude from 43.5°N to 33.7°S and in longitude from 83.8°W to 150°E. The annual mean air temperature ranges from 0–6 to 17.6°C and mean annual precipitation from 300 to over 1800 mm year−1. Details of the physical characteristics, site codes, research methods, and key references that have published the ET data for each site are listed in Table I.

Monthly total ET from each site was scaled from half-hour measurements using either the standard eddy covariance methods or the sapflow and interception methods (Table I). Although most of the ET data had been published, ancillary data, such as monthly averaged LAI, P, and climatic variables, were assembled from various sources.

To be consistent, we defined the growing season in the northern hemisphere to be May–September and October–April in the southern hemisphere. We acknowledge that there was no distinct growing season for the two Australian forests used here and the tree growth was generally limited to water availability. As some sites did not have year-round measurements, therefore, this study focused on growing season ET when cross-site comparisons were made.

**Calculated grass reference evapotranspiration (ET0)**

Potential evapotranspiration (PET) is a nebulous term and can evoke confusion because PET does not clearly specify what land surface it refers to. For example, the 'potential' amount of water that a forest could evaporate and transpire would be much higher than a grassland ecosystem could under the same 'water unlimited' conditions due to the larger leaf area of the forest compared to the grassland. Thus, forest PET values should be much higher than grassland PET under the same climate. When the differences of PET methods are ignored and a general PET method for grassland or crops is used for a forest-dominated landscape, serious
A MODEL FOR ESTIMATING ECOSYSTEM EVAPOTRANSPIRATION

underestimation of actual forest ET is expected (Sun et al., 2010). To allay this confusion and normalize the vegetated land surface to which PET refers to, the term grass reference ET (ETo) has gradually been replacing the PET term as a standard way to represent the energy conditions for a particular region and makes PET estimates comparable worldwide (Allen et al., 1994). Using the process-based Penman-Monteith ET equation, actual daily ET of a hypothetical well-watered grass (i.e. ETo) that has a 0-12 m canopy height, a leaf area of 4-8, a bulk surface resistance of 70 s m⁻¹¹, and an albedo of 0.23 is estimated as follows:

\[
ET_o = \frac{0.408 \Delta (R_n - G) + \gamma (C/(T + 273)) u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)},
\]

where \( ET_o \) = grass reference ET (mm);
\( \Delta \) = slope of the saturation water vapour pressure at air temperature \( T \) (kPa °C⁻¹);
\( R_n \) = net radiation (MJ m⁻²);
\( G \) = soil heat flux (MJ m⁻²);
\( \gamma \) = the psychrometric constant (kPa °C⁻¹);
\( e_s \) = saturation vapour pressure (kPa);
\( e_a \) = actual vapour pressure (kPa);
\( u_2 \) = mean wind speed (m s⁻¹) at 2 m height;
\( C \) = unit conversion factor with a value of 900.

Details of the computation procedures are found in Allen et al. (1994). Monthly ETo rates were calculated as the sum of daily values in this study.

**Empirical ET model development**

We pooled all published data of monthly ET, \( P \), and LAI that were measured onsite using various methods (Table I), and the monthly ETo estimated by Equation (1) as described above. The observation time length varied from one full growing season to 3 years (Table I). This database contains 270 records (i.e. 270 site-months). All data analyses were performed using the SAS 9.2 software (SAS Institute Inc., 2008). Regression models that relate ET, ETo, \( P \), and LAI for the entire data set were developed using the SAS’s regression procedure. Different combinations of the independent variables (\( P \), LAI, and ETo) were tested to derive the best fit of observed data. Influences of ETo, \( P \), and LAI on ET for each site were determined by the Pearson correlation coefficients with significant level at \( \alpha = 0.05 \).

**RESULTS**

**ETo, P, and ET in the growing season**

The 13 sites covered a large range of climatic regimes as indicated by average air temperature and annual total precipitation (Table I), resulting in a large difference in ecosystem structures (i.e. LAI) and water balance patterns. For example, the Coweeta site (CWWP) in the

Table I. Characteristics of 13 experimental sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Site code</th>
<th>Plant community and dominant species</th>
<th>Location and elevation (m)</th>
<th>Mean annual P (mm)</th>
<th>Annual ET (mm)</th>
<th>Annual ETa (mm)</th>
<th>Soils</th>
<th>Management</th>
<th>Observation period</th>
<th>Measurement methods (SF, sapflow; EF, eddy flux) and references</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooleechagh, Western Sydney,</td>
<td>AUWS</td>
<td>Open woodlands (Anoploa barkeri (narrow-leaved apple) and Eucalyptus acrophylla (scribbly gum))</td>
<td>33°04'S, 150°47'E; 30 m</td>
<td>163</td>
<td>782±</td>
<td>538</td>
<td>Sandy soil (0–80 cm) overlay on deep clay soils</td>
<td>No management; remnant woodlands</td>
<td>2006–2007 (September to August; incomplete data from July to August in 2007)</td>
<td>SF (Zeppel et al., 2008a, b)</td>
</tr>
<tr>
<td>Liverpool Plains, NSW, Australia</td>
<td>AUPA</td>
<td>Eucalyptus bridges (Eucalyptus crebra; Callitris glaucophylla)</td>
<td>31°30'S, 150°42'E; 390 m</td>
<td>17.5</td>
<td>528–1062±</td>
<td>685±(2003 data)</td>
<td>Shallow sandy soils (15–50 cm)</td>
<td>No management; remnant woodlands</td>
<td>2003, 2004</td>
<td>SF (Zeppel et al., 2008a; Zeppel et al., 2008b)</td>
</tr>
<tr>
<td>Castlereagh, Western Sydney,</td>
<td>AUWS</td>
<td>Populus populosa bruyniana</td>
<td>35°03'N, 82°25'W; 760–1021 m</td>
<td>13.0</td>
<td>2160–232±</td>
<td>169–1169</td>
<td>Sandy loam, deep soils (&gt;200 cm) on steep slopes</td>
<td>Planted in 1956</td>
<td>2004, 2005</td>
<td>SF (Foidl et al., 2007)</td>
</tr>
<tr>
<td>Daxing, Beijing, China</td>
<td>BJPL</td>
<td>Populus populosa verrucosa</td>
<td>42°03'N, 116°17'E; 1350 m</td>
<td>3.3</td>
<td>178–395µ</td>
<td>40±</td>
<td>Sandy soils (bulk density = 1.24 g cm⁻³)</td>
<td>Converted from steppe in 1981; wheat seeded in mid-May, harvest end of mid-September</td>
<td>2006, 2007 growing season (May–September)</td>
<td>EF (Miao et al., 2009)</td>
</tr>
<tr>
<td>Coonea Hydrologic Lab, NC, USA</td>
<td>CWWP</td>
<td>White pine (Pinus strobus) plantations</td>
<td>40°32'18'N, 108°41'37'E; 1020 m</td>
<td>6.3</td>
<td>148±±</td>
<td>300±</td>
<td>Sandy soils (bulk density = 1.38 g cm⁻³)</td>
<td>Fenced</td>
<td>2006, 2007 growing season (May–September)</td>
<td>EF (Miao et al., 2009)</td>
</tr>
<tr>
<td>dualun, Inner Mongolia, China</td>
<td>DLCP</td>
<td>agricultural crops (Triticum aestivum, Avena nuda, Fallopia capillata)</td>
<td>42°03'N, 116°17'E; 1350 m</td>
<td>3.3</td>
<td>178–395µ</td>
<td>40±</td>
<td>Sandy soils (bulk density = 1.24 g cm⁻³)</td>
<td>Fenced</td>
<td>2006, 2007 growing season (May–September)</td>
<td>EF (Miao et al., 2009)</td>
</tr>
<tr>
<td>dualun, Inner Mongolia, China</td>
<td>DLSP</td>
<td>Steppe grasslands (Stipa kessleri, Artemisia frigida)</td>
<td>40°22'N, 108°35'E; 1160 m</td>
<td>6.3</td>
<td>220±±</td>
<td>300±</td>
<td>Sandy soils (bulk density = 1.38 g cm⁻³)</td>
<td>Planned in 2003 on floodplains in the desert; minor drip irrigation applied</td>
<td>2006 growing season (May–September)</td>
<td>EF (La., 2009; Wilcke et al., 2009)</td>
</tr>
<tr>
<td>Kubuqi, Inner Mongolia, China</td>
<td>KBPL</td>
<td>Populus (Populus sp.)</td>
<td>40°32'18'N, 108°41'37'E; 1020 m</td>
<td>6.3</td>
<td>148±±</td>
<td>300±</td>
<td>Sandy soils (bulk density = 1.38 g cm⁻³)</td>
<td>Fenced</td>
<td>2006, 2007 growing season (May–September)</td>
<td>EF (Miao et al., 2009)</td>
</tr>
<tr>
<td>Kubuqi, Inner Mongolia, China</td>
<td>KBRS</td>
<td>Populus (Populus sp.)</td>
<td>40°32'18'N, 108°41'37'E; 1020 m</td>
<td>6.3</td>
<td>220±±</td>
<td>300±</td>
<td>Sandy soils (bulk density = 1.38 g cm⁻³)</td>
<td>Fenced</td>
<td>2006, 2007 growing season (May–September)</td>
<td>EF (Miao et al., 2009)</td>
</tr>
<tr>
<td>Parker Track, NC, USA</td>
<td>NCCC</td>
<td>Loblolly pine (Pinus taeda L.), dog fennel (Eupatorium capillifolium) and greenbrier (Smilax retinodifolius)</td>
<td>35°48'N, 76°40'W; 2 m</td>
<td>15.5</td>
<td>907–1467±</td>
<td>1320±</td>
<td>Sandy clay</td>
<td>Loblolly pine planted in 2002 after clearing cutting native hardwoods</td>
<td>2005, 2006, 2007</td>
<td>EF (Noormets et al., 2009; Sun et al., in press)</td>
</tr>
<tr>
<td>Parker Track, NC, USA</td>
<td>NCLP</td>
<td>Loblolly pine (Pinus taeda L.)</td>
<td>35°48'N, 76°40'W; 5 m</td>
<td>15.5</td>
<td>892–1467±</td>
<td>1320±</td>
<td>Organic soil (0–50 cm) sands (&gt;50 cm)</td>
<td>Loblolly pine planted in 1992</td>
<td>2005, 2006, 2007</td>
<td>EF (Noormets et al., 2009; Sun et al., 2010)</td>
</tr>
<tr>
<td>Oak Opening, OH, USA</td>
<td>OHOO</td>
<td>Oak (Quercus sp.), Maple (Acer sp.)</td>
<td>41°34'N, 83°51'W; 200 m</td>
<td>9.2</td>
<td>584–1008±</td>
<td>84±</td>
<td>Sandy, fine till</td>
<td>No management; 5-year-old oaks; 15-year-old maples</td>
<td>2004, 2005, 2006, 2007</td>
<td>EF (Noormets et al., 2008)</td>
</tr>
</tbody>
</table>

Note: ± indicates the use of data from references.
southeastern United States had the highest annual precipitation (>2000 mm) with a temperate climate, thus supported a plantation conifer forest with the highest LAI (peak LAI = 7.1) among all sites examined. In contrast, The Kubuqi shrub (KUSB) and poplar plantation (KUPL) sites in a desert environment of western China’s Inner Mongolia had an annual precipitation of <300 mm and low air temperature of 6.3 °C (Table I). Thus, those two sites supported plant communities with a low LAI (LAI < 0.4). The Paringa site on the Liverpool Plain in eastern Australia had the highest annual ETo (~1070 mm) and moderate annual precipitation (P = 680 mm) with a rather high seasonal and annual variability. A combination of high ETo and uneven distribution of rainfall might explain the periodic water stress that resulted in low LAI (maximum LAI < 1.3) for this water-limited ecosystem (Zeppel et al., 2006).

In addition to the contrasting differences in annual averaged climate, the 13 sites had contrasting patterns of P and ETo during the growing seasons (Figure 2). The CWWP had the highest precipitation (1153 mm) but the lowest ETo (482 mm), while the KBPL received the lowest precipitation (228 mm) and the AUPA had the highest ETo (1070 mm) (Figure 2a). Across the 13 sites, it appears that the 400 mm precipitation line separated the grassland ecosystems from temperate forests and water-stressed open woodlands in eastern Australia (Figure 2a). Energy received by the grassland regions on the Mongolian Plateau and other drier forest sites (Beijing and Toledo) were comparable to the forest sites in the southeastern United States, suggesting that the arid and semi-humid ecosystems were not energy limited for ET during the growing season, but rather limited by P.

The total growing season ET was linearly correlated with P ($R^2 = 0.96$, $p < 0.001$) with a slope of 0.99, with CWWP being an exception (Figure 2b) to the overall relationship as a group. Among the 13 sites, except for the wettest (CWWP) and driest (KUPL) sites, ET was within 10% of P (Figure 2c). Precipitation barely matched the ET demand at BJPL, AUWS, AUPA, DLSP, and KUSB and was less than ET at the NCLP, NCCC, OHOO, KUPL, XLDS, XLFC sites during the growing season. In contrast, the CWWP had the lowest ETo, but the highest ET (Figures 2a–b). The CWWP received 50% more P (1153 mm) than needed for ET consumption during the growing season. Thus, severe droughts were not likely for this site, and a perennial stream existed at this relatively wet site (ETo/P < 0.5) (Ford et al., 2007). Therefore, unlike the other 12 sites that were somewhat water-limited as indicated by the aridity index (ETo/P), the CWWP was an energy-limited system. The groundwater table, an indicator of soil water storage, declined dramatically during the growing season at the NCLP, NCCC (Sun et al., 2010), and OHOO sites (Figure 3).

**Monthly ETo, P, and ET**

Monthly ET values varied from less than 10 mm month$^{-1}$ to as high as 170 mm month$^{-1}$, reflecting the biophysical
controls of LAI (Figure 4) and other environmental factors such as available energy and water as represented by ET₀ and P. Overall, LAI explained most of the variability in ET, but ET₀ and P were also important factors, especially for forests and dry regions, respectively (Table II). The poplar plantation site (BJPL), for example, had a rather high ET₀ during the summer months, and because water was relatively nonlimiting, BJPL had the highest ET during the peak growing season when LAI reached its maximum (3-0). In contrast, the water-limited sites, such as AUPA and the ecosystems in Inner Mongolia (DLCP, DLSP, KBPL, KBSP, XLDS, and XLFC), had low ET despite high ET₀. Monthly ET exceeded P during the peak growing season for several forested sites, including NCLP, NCCC, and OHOO. In contrast, monthly P exceeded ET even during the peak growing seasons at the extremely wet CWWP site (Figure 4a).

The monthly ET for each individual site was controlled by different biophysical variables that were largely regulated by climate (Table II). For example, ET from the water-limited ecosystems in Inner Mongolia (i.e. DLCP, DLSP, KBPL, KBSP, XLDS, and XLFC) was mostly controlled by P and LAI, while ET₀ did not significantly (p > 0.05) correlate with ET. Unlike forest ecosystems that showed a clear, tight linear relation between ET and ET₀, the estimated ET₀ values from the two grassland sites (DLCP, DLSP) reached maxima in May, well ahead of the peak ET months of July and August. The relationship between ET and ET₀ appears to be nonlinear (Figure 4b). The LAI values for the two Australian sites in a high ET₀ environment had a narrow range (0-9–1.55) (Figure 4c), and LAI did not respond greatly to annual and inter-annual variability of P.

The ET/ET₀ ratio-ecosystem ‘Crop Coefficients’

Monthly and growing season ET/ET₀ ratios varied among ecosystem types and throughout the year (Figures 5 and 6). Overall, the water-limited grasslands or open woodlands had the lowest ET/ET₀ (<0.5) and forests that experienced low water stress had the highest values.
(0.5–2.0). As expected, when water was not limiting, conifer forests (CWWP, NCLP, and NCCC) in a humid warm environment had the higher ET than the deciduous forests (BJPL and OHOO) in the dormant season when ET₀ was low. However, the conifer forests, except for CWWP, had similar ET/ET₀ to the deciduous forests during summer months. The AUWS had the highest ET/ET₀ ratios of wet mature forests (i.e. NCPL and CWWP) exceeded 1.0 during the growing season (Figure 5), i.e. these two forests used more water than a ‘well-watered’ grass land. The ratios were even higher (up to 2.0) during the fall and winter seasons when the conifer trees continued transpiring and intercepting water and ET₀ declined dramatically (Figure 6). However, ET/ET₀ ratios fell below 1.0 during drier months of March–May and October.

A general monthly ET model

When pooling all data, monthly ET was significantly correlated with LAI, ET₀, and P, and the combination of the variables. The terms, ET₀ × LAI and ET₀ × P, explained 67 and 17% of the variability of observed ET, respectively. Our final regression model was expressed as:

\[
ET = 11.94 + 4.76 \text{ LAI} + ET₀ (0.032 \text{ LAI} + 0.0026 \text{ P} + 0.15)
\]

where \( R^2 = 0.85 \), RMSE = 15 mm month\(^{-1} \), \( n = 222 \). All variables and the intercept in the above equation were highly significant (\( p < 0.001 \)) except for ET₀ (\( p = 0.02 \)). A comparison between measured and estimated ET values as derived from the regression model resulted in
DISCUSSION

Relationships between ET, P, ET_o, and LAI

At a long time scale, ecosystem ET is mainly controlled by the availability of evaporative energy (ET_o) and water inputs (P) and, to a minor extent, by vegetation types (Zhang et al., 2001, 2004; Lu et al., 2003; Oudin et al., 2008). The general relationships among ET, P, and ET_o for average climatic conditions have been well described by Budyko-type of models (Zhang et al., 2004). Budyko curves show the relationship of E/P versus PET/P (i.e. aridity index). Theoretically, in energy-limited systems these two variables are linearly related to one another with a slope of 1.0. In extremely water-limited systems, E/P approaches the limit of 1.0 over a long term. This suggests that ET/PET ratios for most ecosystems should fall below the theoretical curve (Zhang et al., 2004), and ET can be estimated from the site level aridity index (PET/P). However, finer temporal resolution (i.e. monthly or seasonal) information is required to aid in the water resource management decisions such as water allocation during droughts or flooding mitigation. Ecosystem and water stresses on human water supply occur most often during periods with high water demand and low water supply, both supply and demand fluctuate seasonally, but normally reach the extremes during the growing season (Sun et al., 2008a).

This multiple-ecosystem synthesis study shows that the general relationships among terrestrial water loss, energy, and water availability as outlined by Zhang et al. (2004) hold true. However, our study offers new insights on the intricate relationships among precipitation, availability of evaporative energy, and vegetation dynamics at a finer temporal scale (i.e. monthly)—a scale that most regional-scale hydrological models use for global change studies (Vörösmarty et al., 1998; McNulty et al., 2010). By examining the empirical relations between ET and LAI across a range of ecosystems and temporal scales, this study confirmed that besides energy and water availability, LAI is a critical variable for understanding and modelling regional ET at a seasonal basis. LAI has been well known to be a good integrator of many biological and physiological controls on ET processes (Chapin et al., 2004); thus, this finding was not surprising. LAI dynamics affect land surface albedo (Betts, 2000; Sun et al., 2010), stand canopy total conductance (Zeppel et al., 2008b; Ford et al., 2010), canopy interception rates (Helvey, 1967; McCarthy et al., 1992), root biomass and distribution (O’Grady et al., 2006), and the partitioning between evaporation and transpiration (Scott et al., 2006; Zhou et al., 2008). In fact, most process-based forest hydrological models (i.e. MIKE SHE) consider LAI as a major control on daily or sub-daily ET (Lu et al., 2009). Plants respond to water stress through reducing stomatal conductance and/or LAI (Limousin et al., 2009). Zeppel et al. (2008b) suggested that tree water use at the Australian sites responded to water availability through...
adjusting stomatal conductance, not LAI. A large portion (>50%) of the total ET loss for these types of woodlands was by understory ET and canopy interception (Zeppel et al., 2008b).

Jackson et al. (2009) emphasized the hydrological significance of vegetation change due to human activities such as afforestation or deforestation, especially in arid and semi-arid regions where ecohydrology is sensitive to human disturbances and climatic change. Our study offered new evidence of the delicate balances between water use, water yield, and vegetation structure for a wide range of climatic and management regimes. Water loss (ET) from most ecosystems examined in this study converged more or less around the amount of precipitation (P) received during the growing season. The growing season ET of the young poplar plantation at the KUPL site exceeded more than 50% of precipitation under an extremely dry environment (ETo/P > 4). Therefore, drip irrigation using groundwater as additional water sources was needed to support stand development (Lu et al., 2009; Wilske et al., 2009). For those sites where ET was about 10% higher than P, shallow groundwater was essential for NCLP, NCCC, and OHOO (Sun et al., 2010) and soil moisture was essential for XLDS and XLFC (Chen et al., 2009; Miao et al., 2009). Both sources of water represent water accumulated prior to the growing season. Therefore, groundwater or soil storage systems likely served as important reservoirs to meet peak ET demand during the growing season for those systems.

The tight coupling between P and ET during the growing season, and the fact that ET could slightly exceed P, even in forested wetlands (e.g. NCLP, NCCC) have important implications for the ecosystem water balance and its response to climatic variability. Both growing season precipitation and soil water recharge in the nongrowing season were necessary for ecosystems to meet water demand in the growing season. Therefore, shifting seasonal precipitation patterns due to climate change could profoundly affect ecosystem water use patterns during the growing season, thus affecting the sustainability of some managed ecosystems. For example, a slight reduction in precipitation or increase in atmospheric evaporative demand (e.g. climatic warming) could severely impact ecosystems such as BJPL, KUSB, DLSP, SUPA, AUPA, and AUWS that were on the threshold of being under chronic seasonal water stress. While our synthesis study suggests that rates of water loss from ecosystems converges on growing season precipitation, a larger sample size and representation of vegetation types would be necessary to rigorously address this hypothesis.

Applications of the ET model

The accuracy of the ET model derived from this study is sufficient for monthly hydrological forecasting at a regional scale as judged by the high R² value (0.85) and moderate estimation error. However, future studies should include more diverse ecosystems to make the empirical model more applicable. For example, there was a large data gap in terms of growing season precipitation regime between 650 and 1150 mm, and beyond 1150 mm in wet tropical regions (Figure 2). As a result of the data gaps, it is unclear if the maximum growing seasonal ET found from this study (about 700 mm during May–September) is the ET limit of terrestrial forested ecosystems.

Although much advancement in the fields of remote sensing, global hydrological and climatic monitoring, and flux measurements has been made, accurately estimating ET for a large area remains challenging (Mu et al., 2007). The empirical ET model developed from our study has the potential to estimate regional ET using hybrid data sets that can be acquired from a combination of remote sensing and ground monitoring. For example, LAI, a key input to our model, is readily available at a relatively high resolution (8 days, 500 m × 500 m) from the Moderate Resolution Imaging Spectroradiometer remote sensing products. Both ETo and P can be derived from interpolated products from a network of weather stations or projected climate change scenarios from Global Circulation Models. When climatic variables such as radiation, humidity, or wind speed are not available, ETo in our model should be estimated by the modified simpler PET models (Lu et al., 2005) based on the relationship between ETo and PET.

Uncertainties

Estimating monthly ET is an imprecise science (Allen, 2008) regardless of the estimation methods. For example, a ±10% measurement error for energy fluxes as quantified by energy balance ratio (sum of latent heat and sensible heat divided by total available energy, i.e. net radiation minus soil heat flux) was not uncommon among the FLUXNET sites (Wilson et al., 2002). The energy closure for our study sites ranged from 62% at the BJPL to 110% at the Inner Mongolia grassland sites. Likewise, the tree-based sapflow + canopy interception method for estimating ecosystem-level ET could contribute 7–14% of error when compared to watershed-scale water balance method at the CWWP site (Ford et al., 2007). The canopy interception rate was high at this site, approximately 45% of total ET. This component was not measured directly but was rather modelled using an empirical canopy interception model (Ford et al., 2007). Up to 10% disparity between modelled tree transpiration and scaled up sapflux estimates were found for the AUPA in an analysis by Zeppel et al. (2008b). For such sparsely vegetated sites such as AUPA and AUWS, soil evaporation was likely a large component of total ET, and canopy interception estimates were uncertain (Zeppel et al., 2008b). In addition, measurement errors were possible in even basic landscape-scale hydrological and energy components, such as precipitation and net radiation. Errors for these components can range as high as 9–20% (Barker et al., 2009). Such measurement errors could result in a large uncertainty in estimated monthly P and ETo. We recognize that the current study may include some of
the above errors, as well as errors associated with multiple site syntheses. Variations in instrumentation type and data processing methodology (e.g. gap filling and scaling from 30-min measurements to daily and monthly values) may all contribute to the uncertainty of reported ET data. These errors may have contributed to the estimation errors of the regression model that included 15% unexplained elements other than $P$, ET$_0$, and LAI. In addition, the six sites in Inner Mongolia had measurements only during the growing seasons. Thus, the incomplete measurement cycles might cause bias towards the growing seasons and might miss important information regarding the interactions of water and energy balances between the nongrowing season and growing seasons that were artificially set.

CONCLUSIONS

This synthesis study concludes that most of the variability of monthly ecosystem ET across a diverse climatic and management gradient could be explained by leaf area (LAI), precipitation, and the availability of evaporative energy. The empirical ET model developed from this study has the potential to be used for studying the regional impacts of climate and land cover change on seasonal ET and ecosystem water balances.

For most ecosystems examined, water use was close to precipitation received during the growing season. Therefore, growing season precipitation is critical to meeting plant water demand. This implies that deviations from the 'norm' in hydrological fluxes due to either precipitation reduction or increase in plant water consumption could tip the water balances and result in the alteration of onsite and offsite water flow and downstream water availability. Nongrowing season precipitation and water storage in soils and aquifers would affect streamflow and water availability in the growing season because precipitation was roughly balanced by ET during the growing season. Future studies should include more eddy flux sites, such as the FLUXNET that covers a wider climatic regime (i.e. wet tropics), to test the proposed hypotheses (i.e. growing season ET convergence phenomena) and to refine the empirical model for wider applications.

The ET/ET$_0$ ratios varied seasonally and annually, and across ecosystem types due to climatic variability and plant phenology. The 'Crop Coefficient' values offered a convenient way to empirically estimate ET when climatic data are available from local weather stations. This study offered additional evidence to show that temperate forests could use more water than 'potential ET' of grass ecosystems in a humid environment. The traditional hydrological modelling approach that sets an ET limit using potential ET (defined as the well-watered grass reference ET) may cause large estimation errors, especially for modelling ET for a forest-dominated landscape. More research is needed to develop standardized forest versions of FAO Penman-Monteith models to account for the complexity of forest ecosystems in contrast to annual crops or grasslands.
A MODEL FOR ESTIMATING ECOSYSTEM EVAPOTRANSPIRATION


