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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 (ET_o), 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 ET_o while those from grasslands or woodlands in the arid and semi-arid regions were lower than ET_o. Second, growing season ET was found to be converged to within $\pm 10\%$ 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_o together explained about 85% of the variability of monthly ET. We concluded that the three variables LAI, P, and ET_o, 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

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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 (ET_o) 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. ET_o), 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 ET_o) 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) in the humid Appalachians in the southeastern United States, to the hot dry woodlands in eastern Australia (AUWS, AUPA), 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 150·8 °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 (ET_o)

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

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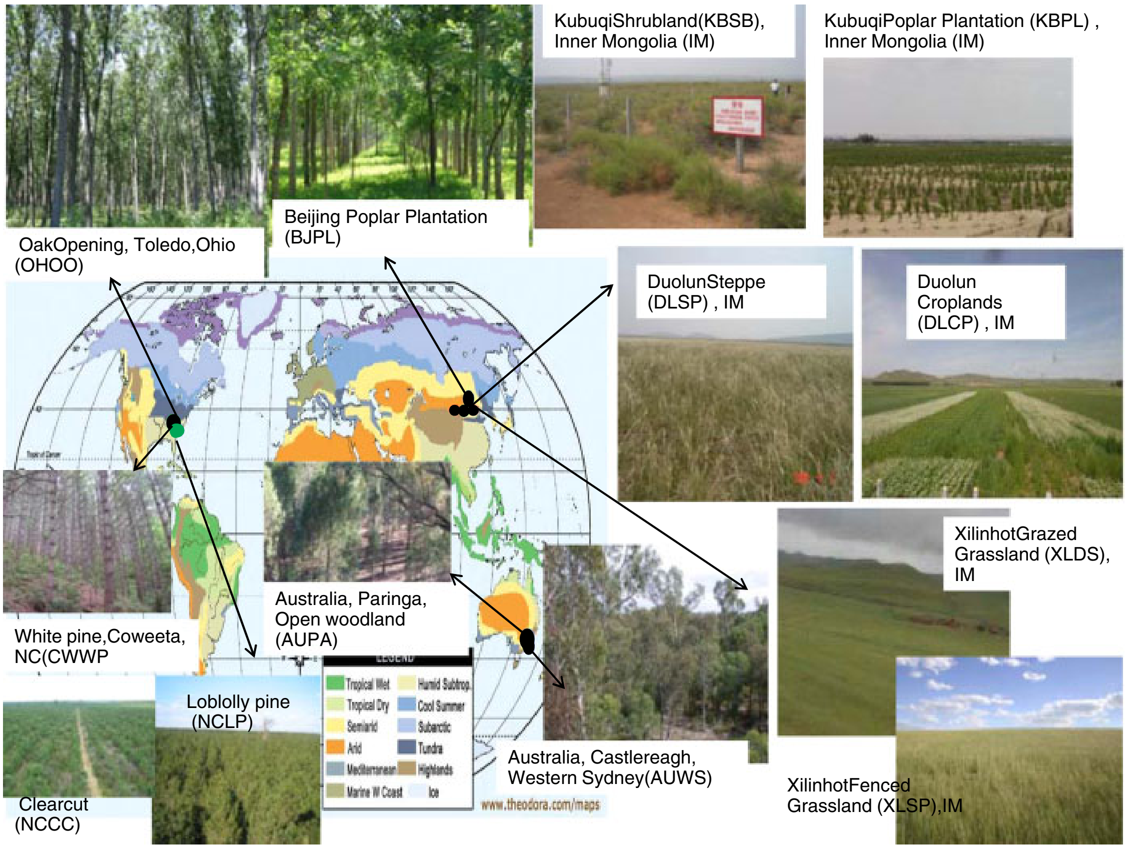

Figure 1. Geographic distribution and characteristics of 13 ecosystems across a climatic and management gradient.

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 (ET_o) 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. ET_o) that has a 0·12-m canopy height, a leaf area of 4·8, a bulk surface resistance of 70 s m^{-1}, and an albedo of 0·23 is estimated as follows:

$$ET_o = \frac{0{\cdot}408\Delta(R_n - G) + \gamma(C/(T+273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0{\cdot}34u_2)}, \quad (1)$$

where ET_o = grass reference ET (mm)

Δ = slope of the saturation water vapour pressure at air temperature T (kPa °C^{-1})

$$\Delta = 2503\frac{e^{17{\cdot}27T/(T+237{\cdot}3)}}{(T+237{\cdot}3)^2}$$

R_n = net radiation (MJ m^{-2});
G = soil heat flux (MJ m^{-2});
γ = 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 ET_o 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 ET_o 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, ET_o, 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 ET_o) were tested to derive the best fit of observed data. Influences of ET_o, P, and LAI on ET for each site were determined by the Pearson correlation coefficients with significant level at $\alpha = 0{\cdot}05$.

RESULTS

ET_o, 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

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Table I. Characteristics of 13 experimental sites.

Site	Site code	Plant community and dominant species	Location and elevation (m)	Mean annual air temperature (°C)	Annual P (mm)	Annual ET (mm)	Annual ET_o (mm)	Soils	Management	Observation period	Measurement methods (SF, sapflow; EF, eddy flux) and references
Castlereagh, Western Sydney, Cumberland Plains, NSW, Australia	AUWS	Open woodlands *Angophora bakeri* (narrow-leaved apple) and *Eucalyptus sclerophylla;* (scribbly gum)	33°40′S, 150°47′E; 30 m	16·3	782[a]	538	914	Sandy soil (0–80 cm) overlay on deep clay soils	No management; remnant woodlands	2006–2007 (September to August; incomplete data from July to August in 2007)	SF (Zeppel *et al*., 2008a, b)
Paringa, Liverpool Plains, NSW, Australia	AUPA	Eucalypts Evergreen broadleaf (*Eucalyptus crebra; Callitris glaucophylla*)	31°30′S, 150°42′E; 390 m	17·5	528–1062[a] 680[b]	685(2003 data)	1592–1563	Shallow sandy soils (15–50 cm)	No management; remnant woodlands	2003, 2004	SF(Zeppel *et al*., 2008a; Zeppel *et al*., 2008b)
Daxing, Beijing, China	BJPL	Poplars *Populus euramericana*	39°32′N, 116°15′E; 30 m	11·5	447–645[a] 569[b]	524–664	704–1005	Deep sandy soils (>200 cm) on fluvial plains	Planted in 2002; minor irrigation	2006, 2007, 2008	EF(Liu *et al*., 2009)
Coweeta Hydrologic Lab, NC, USA	CWWP	White pine (*Pinus strobus*) plantations	35°03′N, 82°25′W; 760–1021 m	13·0	2160–2321[a] 1836[b]	1169–1161	913–896	Sandy loam, deep soils (>200 cm) on steep slops	Planted in 1956	2004, 2005	SF(Ford *et al*., 2007)
Duolun, Inner Mongolia, China	DLCP	Agricultural crops Wheat (*Triticum aestivum, Avena nuda, Fagopyrum esculentum*)	42°03′N, 116°17′E; 1350 m	3·3	178–395[a,c] 400[b]	191–292[c]	510–574[c]	Sandy soils (bulk density = 1·24 g cm^{-3})	Converted from steppe in 1981; wheat seeded in mid-May, harvest end of mid-September	2006, 2007 growing season (May–September)	EF(Miao *et al*., 2009)
Duolun, Inner Mongolia, China	DLSP	Steppe grasslands (*Stipa krylovii, Artemisia frigid*)	42°03′N, 116°17′E; 1350 m	3·3	178–395[a,c] 400[b]	204–344[c]	505–577[c]	Sandy soils (bulk density = 1·38 g cm^{-3})	Fenced	2006,2007 growing season (May–September)	EF(Miao *et al*., 2009)
Kubuqi, Inner Mongolia, China	KBPL	Poplars (*Populus* sp.)	40°32′18″N, 108°41′37″E; 1020 m	6·3	148[a,c] 300	228[c]	626[c]	Sands	Planned in 2003 on floodplains in the desert; minor drip irrigation applied	2006 growing season (May–September)	EF (Lu, 2009; Wilske *et al*., 2009)
Kubuqi, Inner Mongolia, China	KBSB	Shrubs (*Artemisia ordosica*)	40°22′N, 108°35′E; 1160 m	6·3	220[a,c] 300[b]	223[c]	608[c]	Sandy soils	Undisturbed shrublands	2006 growing season (May–September)	EF (Lu, 2009; Wilske *et al*., 2009)
Parker Track, NC, USA	NCCC	Loblolly pine (*Pinus taeda* L.), dog fennel (*Eupatorium capillofolium*) and greenbrier (*Smilax rotundifolia*)	35°48′N, 76°40′W; 5 m	15·5	907–1467[a] 1320[b]	755–885	885–1024	Sandy clay	Loblolly pine planted in 2002 after clearing cutting native hardwoods	2005, 2006, 2007	EF (Noormets *et al*., 2009; Sun *et al*., in press)
Parker Track, NC, USA	NCLP	Loblolly pine (*Pinus taeda* L.)	35°48′N, 76°40′W; 5 m	15·5	892–1467[a] 1320[b]	1011–1226	885–1024	Organic soil (0–50 cm), sands (>50 cm)	Loblolly pine planted in 1992	2005, 2006, 2007	EF (Noormets *et al*., 2009; Sun *et al*., 2010)
Oak Opening, OH, USA	OHOO	Oak (*Quercus* spp.), Maple (*Acer* spp.)	41°34′N, 83°51′W; 200 m	9·2	584–1008[a] 840[b]	651–685	882–908	Sandy, fine till	No management, 5-year-old oaks; 15-year-old maples	2004, 2005, 2006, 2007	EF (Noormets *et al*., 2008)

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Table I. (*Continued*).

Site	Site code	Plant community and dominant species	Location and elevation (m)	Mean annual air temperature (°C)	Annual P (mm)	Annual ET (mm)	Annual ET_o (mm)	Soils	Management	Observation period	Measurement methods (SF, sapflow; EF, eddy flux) and references
Xilinhot, Inner Mongolia, China	XLDS	Degraded Steppe grasslands (*Leymus chinensis, Stipa krylovii, Artemisia frigid*)	43°33′N, 116°40′E; 1250 m	0·6	154–184^{a,c} 350^{b}	~192^{c}	608–699^{c}	Sandy soils (bulk density = 1·33 g cm^{-3})	Under long-term grazing	2006,2007 growing season (May–September)	EF (Miao *et al.*, 2009)
Xilinhot, Inner Mongolia, China	XLFC	Steppe grasslands (*Leymus chinensis, Stipa grandis, Artemisia frigid*)	43°33′N, 116°40′E; 1250 m	0·6	154–184^{a,c} 350^{b}	~190^{c}	662–708^{c}	Sandy soils (bulk density = 1·22 g cm^{-3})	Fenced in 2005 after long-term grazing	2006, 2007 growing season (May–September)	EF (Miao *et al.*, 2009)

[a] Precipitation listed denotes the range or total during the study period.
[b] Precipitation listed denotes the range or total during the long-term mean.
[c] Growing season (May–September) measurements only.

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 ET_o (~1070 mm) and moderate annual precipitation (P = 680 mm) with a rather high seasonal and annual variability. A combination of high ET_o 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 ET_o during the growing seasons (Figure 2). The CWWP had the highest precipitation (1153 mm) but the lowest ET_o (482 mm), while the KBPL received the lowest precipitation (228 mm) and the AUPA had the highest ET_o (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 ($R^2 = 0{\cdot}96$, $p < 0{\cdot}001$) 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 ET_o, 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 ($ET_o/P < 0{\cdot}5$) (Ford *et al.*, 2007). Therefore, unlike the other 12 sites that were somewhat water-limited as indicated by the aridity index (ET_o/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 ET_o, 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

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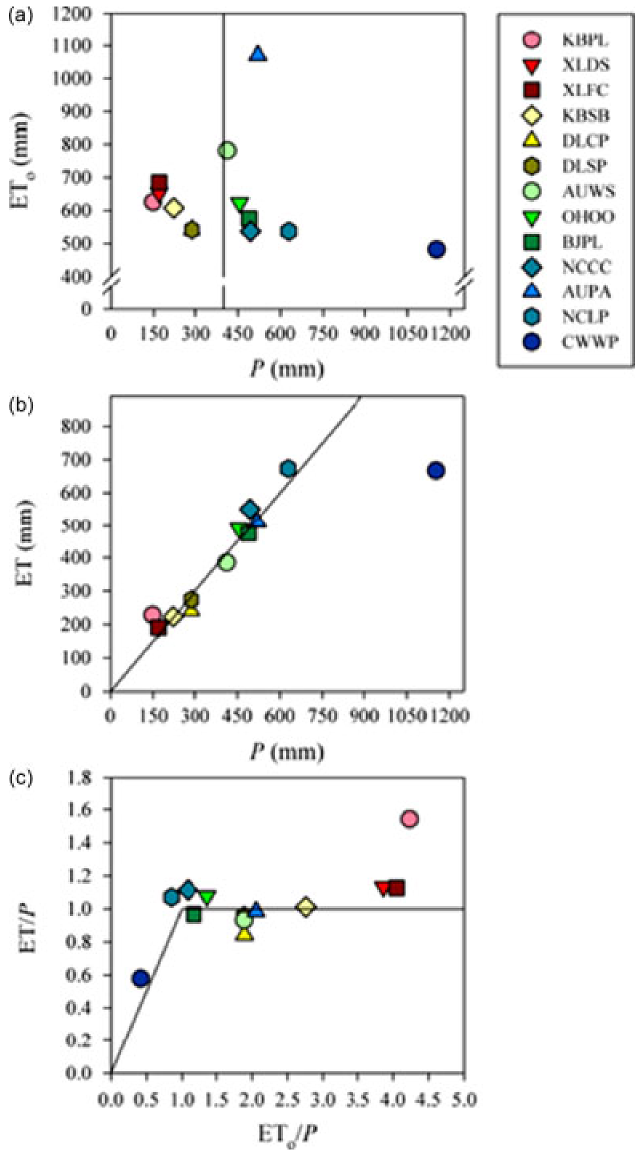

Figure 2. Growing season (May–Sep) (Oct–April for AUWS and AUPA) (a) grass reference evapotranspiration (ET_o) and (b) actual evapotranspiration (ET) for 13 experimental sites with varying precipitation (*P*) regimes. Lines shown for reference are $x = 400$ mm in (a) and $y = x$ in (b). Ratio of (c) ET and *P* compared with ET_o and *P*. Line shown for reference is $y = x$ $\{x \leq 1\}$ and $y = 1$ $\{x > 1\}$. Site codes as in Table I.

controls of LAI (Figure 4) and other environmental factors such as available energy and water as represented by ET_o and *P*. Overall, LAI explained most of the variability in ET, but ET_o 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 ET_o 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 ET_o. 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 ET_o did not significantly ($p > 0{\cdot}05$) correlate with ET. Unlike forest ecosystems that showed a clear, tight linear relation between ET and ET_o, the estimated ET_o 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 ET_o appears to be nonlinear (Figure 4b). The LAI values for the two Australian sites in a high ET_o 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/ET_o ratio-ecosystem 'Crop Coefficients'

Monthly and growing season ET/ET_o 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/ET_o (<0·5) and forests that experienced low water stress had the highest values

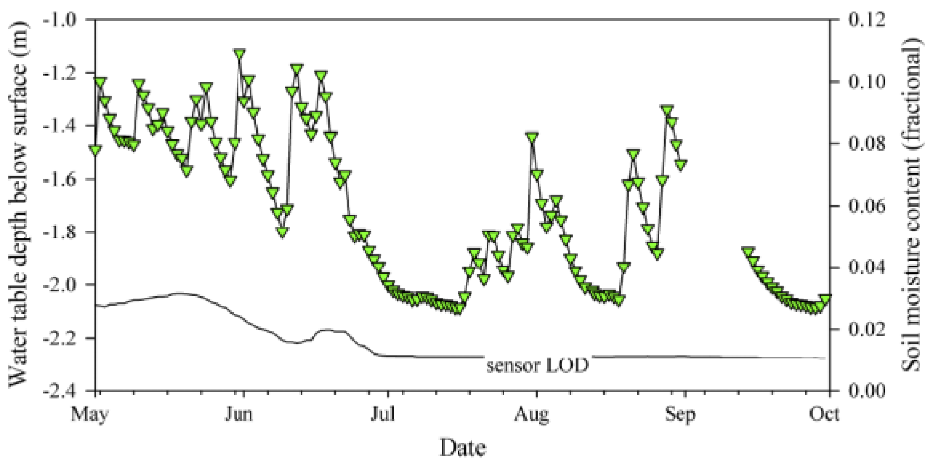

Figure 3. Soil water storage (fractional soil moisture content in top 20 cm soil depth, symbols and line, and groundwater table level, line only) decreased during the 2004 growing season at OHOO site (Table I for sites codes). LOD is limit of detection of groundwater table sensor.

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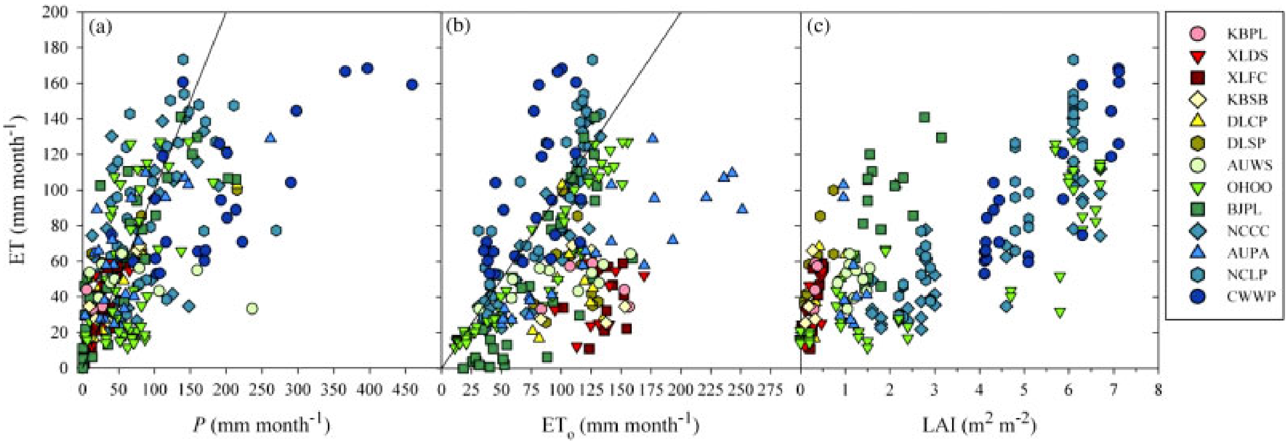

Figure 4. Mean monthly actual evapotranspiration (ET) as a function of (a) mean monthly precipitation (*P*), (b) mean monthly reference grass evapotranspiration (ET_o), and (c) leaf area index (LAI) for 13 ecosystems. Lines shown for reference are $y = x$ in (a) and (b). Site codes as in Table I.

Table II. Pearson correlation coefficients between monthly actual evapotranspiration (ET), and grass reference ET (ET_o) and precipitation (*P*) for each of the 13 sites across a climatic and management gradient.

Site code	ET_o	*P*	LAI
AUPA	**0·86 (*n* = 21)**	**0·72 (*n* = 21)**	0·36 (*n* = 9)
AUWS	**0·72 (*n* = 10)**	−0·46 (*n* = 10)	0·05 (*n* = 10)
BJPL	**0·81 (*n* = 33)**	**0·82 (*n* = 30)**	**0·65 (*n* = 17)**
CWWP	**0·54 (*n* = 24)**	**0·73 (*n* = 24)**	**0·83 (*n* = 24)**
DLCP[a]	0·15 (*n* = 10)	**0·89 (*n* = 10)**	**0·84 (*n* = 7)**
DLSP[a]	0·0 (*n* = 10)	**0·83 (*n* = 10)**	**0·73 (*n* = 10)**
KBPL[a]	0·0 (*n* = 5)	0·58 (*n* = 5)	**0·71 (*n* = 5)**
KBSB[a]	−0·08(*n* = 5)	**0·89 (*n* = 5)**	0·31 (*n* = 4)
NCCC	**0·89 (*n* = 34)**	**0·54 (*n* = 36)**	**0·86 (*n* = 33)**
NCLP	**0·88 (*n* = 34)**	**0·53 (*n* = 36)**	**0·91 (*n* = 36)**
OHOO	**0·94 (*n* = 51)**	**0·52 (*n* = 51)**	**0·85 (*n* = 51)**
XLDS[a]	0·4 (*n* = 10)	0·46 (*n* = 10)	0·61 (*n* = 10)
XLFC[a]	0·24 (*n* = 10)	**0·64 (*n* = 10)**	**0·73 (*n* = 10)**

[a] All correlations performed on growing season data instead of monthly. Bold values denote significant at $\alpha = 0.05$ level.

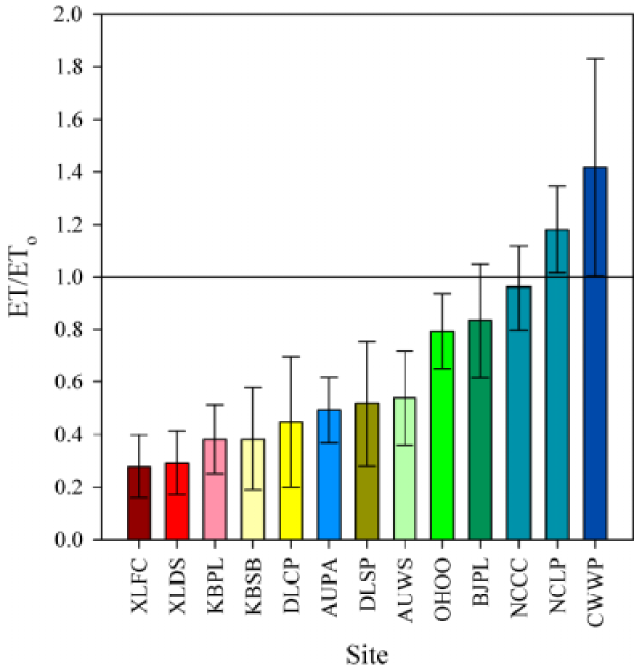

Figure 5. Mean growing season (October–April for AUPA and AUWS; May–September for other sites) ET/ET_o ratios for 13 sites. Error bars show 1 SD. Site codes as in Table I.

(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 ET_o was low. However, the conifer forests, except for CWWP, had similar ET/ET_o to the deciduous forests during summer months. The AUWS had the highest ET/ET_o during June–July when ET_o was low. In contrast, the dry and hot AUPA site had a rather stable ET/ET_o (Table II).

The ET/ET_o 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 ET_o declined dramatically (Figure 6). However, ET/ET_o 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, ET_o, and *P*, and the combination of the variables. The terms, $ET_o \times$ LAI and $ET_o \times P$, explained 67 and 17% of the variability of observed ET, respectively. Our final regression model was expressed as:

$$ET = 11.94 + 4.76\ LAI + ET_o(0.032\ LAI + 0.0026\ P + 0.15) \quad (2)$$

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 ET_o ($p = 0.02$). A comparison between measured and estimated ET values as derived from the regression model resulted in

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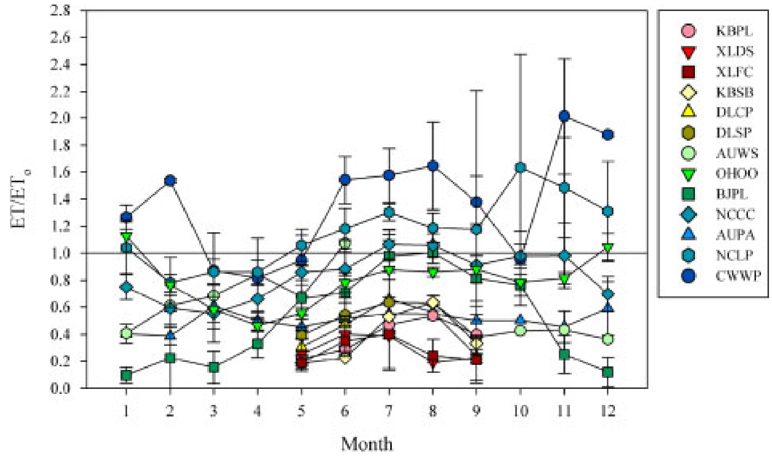

Figure 6. Mean monthly ratio of evapotranspiration (ET) to a grass reference evapotranspiration (ET_o) for 13 sites. Error bars are 1 SD. Site codes as in Table I.

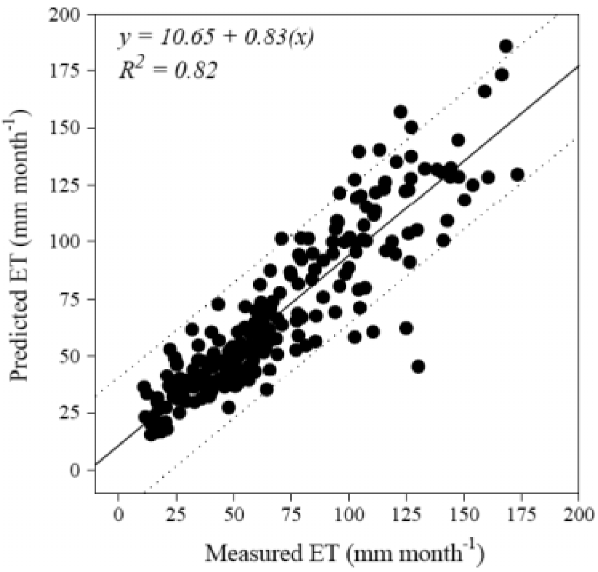

Figure 7. Predicted and measured monthly evapotranspiration (ET). Lines shown are modelled mean (solid) and prediction intervals for the mean (dotted).

an overall RMSE of 15·1 mm month^{-1}, representing an relative error of 23% (Figure 7).

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

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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 ($ET_o/P > 4$). 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 R^2 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 ET_o 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, ET_o in our model should be estimated by the modified simpler PET models (Lu *et al*., 2005) based on the relationship between ET_o 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 ET_o. We recognize that the current study may include some of

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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_o, 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_o 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.

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