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Global estimates of evapotranspiration and gross primary production based on MODIS and global meteorology data

Wenping Yuan Beijing Normal University, wenpingyuancn@yahoo.com

Shuguang Liu U.S. Geological Survey, sliu@usgs.gov

Guirui Yu Chinese Academy of Sciences, yugr@igsnrr.ac.cn

Jean-Marc Bonnefond INRA

Jiquan Chen University of Toledo, jiquan.chen@utoledo.edu

See next page for additional authors

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Authors

Wenping Yuan, Shuguang Liu, Guirui Yu, Jean-Marc Bonnefond, Jiquan Chen, Ken Davis, Ankur R. Desai, Allen H. Goldstein, Damiano Gianelle, Federica Rossi, Andrew E. Suyker, and Shashi B. Verma



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Wenping Yuan ^{a,*}, Shuguang Liu ^{b,c}, Guirui Yu ^{d,*}, Jean-Marc Bonnefond ^e, Jiquan Chen ^f, Ken Davis ^g, Ankur R. Desai ^h, Allen H. Goldstein ⁱ, Damiano Gianelle ^j, Federica Rossi ^k, Andrew E. Suyker ¹, Shashi B. Verma ¹

^a College of Global Change and Earth System Science, Beijing Normal University, Beijing 100875, China

- ^b U.S. Geological Survey (USCS), Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota 57198, USA
- ^c Geographic Information Science Center of Excellence, South Dakota State University, Brookings, South Dakota 57007, USA
- ^d Key Laboratory of Ecosystem Network Observation and Modeling, Synthesis Research Center of Chinese Ecosystem Research Network, Institute of Geographic Sciences and Natural Resources Research,
- Chinese Academy of Sciences, Beijing 100101, China

- ^g Earth System Science Center, Pennsylvania State University, University Park, PA 16802, USA
- ^h Atmospheric and Oceanic Sciences Department, University of Wisconsin Madison, Madison, WI 53706, USA
- ¹ Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA 94720, USA
- ^j Fdn Edmund Mach, IASMA Research and Innovation Centre, I-38100 Trento, Italy

^k IBIMET-CNR, Via Gobetti,101-40129 Bologna, Italy

¹ School of Natural Resources, University of Nebraska – Lincoln, 807 Hardin Hall, 3310 Holdrege Street, Lincoln, NE 68583-0978, USA

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ABSTRACT

The simulation of gross primary production (GPP) at various spatial and temporal scales remains a major challenge for quantifying the global carbon cycle. We developed a light use efficiency model, called EC-LUE, driven by only four variables: normalized difference vegetation index (NDVI), photosynthetically active radiation (PAR), air temperature, and the Bowen ratio of sensible to latent heat flux. The EC-LUE model may have the most potential to adequately address the spatial and temporal dynamics of GPP because its parameters (i.e., the potential light use efficiency and optimal plant growth temperature) are invariant across the various land cover types. However, the application of the previous EC-LUE model was hampered by poor prediction of Bowen ratio at the large spatial scale. In this study, we substituted the Bowen ratio with the ratio of evapotranspiration (ET) to net radiation, and revised the RS-PM (Remote Sensing-Penman Monteith) model for quantifying ET. Fifty-four eddy covariance towers, including various ecosystem types, were selected to calibrate and validate the revised RS-PM and EC-LUE models. The revised RS-PM model explained 82% and 68% of the observed variations of ET for all the calibration and validation sites. respectively. Using estimated ET as input, the EC-LUE model performed well in calibration and validation sites, explaining 75% and 61% of the observed GPP variation for calibration and validation sites respectively. Global patterns of ET and GPP at a spatial resolution of 0.5° latitude by 0.6° longitude during the years 2000– 2003 were determined using the global MERRA dataset (Modern Era Retrospective-Analysis for Research and Applications) and MODIS (Moderate Resolution Imaging Spectroradiometer). The global estimates of ET and GPP agreed well with the other global models from the literature, with the highest ET and GPP over tropical forests and the lowest values in dry and high latitude areas. However, comparisons with observed GPP at eddy flux towers showed significant underestimation of ET and GPP due to lower net radiation of MERRA dataset. Applying a procedure to correct the systematic errors of global meteorological data would improve global estimates of GPP and ET. The revised RS-PM and EC-LUE models will provide the alternative approaches making it possible to map ET and GPP over large areas because (1) the model parameters are invariant across various land cover types and (2) all driving forces of the models may be derived from remote sensing data or existing climate observation networks.

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* Corresponding author. E-mail addresses: wenpingyuancn@yahoo.com (W. Yuan), yugr@igsnrr.ac.cn (G. Yu).

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^e INRA, EPHYSE, F-33883 Villenave Dornon, France

^f Department of Environmental Sciences, University of Toledo, Toledo, OH 43606, USA

1. Introduction

Terrestrial ecosystems drive most of the seasonal and interannual variations in atmospheric carbon dioxide (CO_2) concentration and have taken up about 20–30% annual total anthropogenic CO_2 emission over the last two and half decades (Canadell et al., 2007). However, the geographic locations of this absorption are not well known (Friend et al., 2007). Moreover, atmospheric measurements and inverse modeling suggest that net terrestrial carbon uptake substantially increased from the 1980s to the 1990s (Battle et al., 2006; Bousquet et al., 2000), but the causes of these increases are not well understood (Schimel et al., 2001). Vegetation gross primary production (GPP) quantifies the gross carbon fixed by vegetation in terrestrial ecosystems; in effect, it is the beginning of the carbon biogeochemical cycle and the principal indicator of biosphere carbon fluxes. Therefore, GPP is of great importance to the processes and factors regulating the terrestrial carbon sink.

A number of ecosystem models have been widely applied as a means of quantifying spatio-temporal variations in GPP at large scales (Cao & Woodward, 1998; Cramer et al., 1999; Yuan et al., 2007). However, different ecosystem models are inconclusive regarding the magnitude and spatial distribution of GPP at the regional and global scales. For example, Cramer et al. (1999) compared 16 dynamic global vegetation models and suggested the lowest estimation of global NPP (39.9 Pg C) by the Hybrid model was approximately 50% smaller compared to what was estimated by the TURC model (Terrestrial Uptake and Release of Carbon) (80.5 Pg C). Model outputs were indicated by low confidence at regional and global scales due to several major limitations: (1) spatial and temporal heterogeneity of ecosystem processes used by models; (2) nonlinearity of the functional responses of ecosystem processes to environmental variables; (3) requirement of both physiological or site-specific parameters; and (4) inadequate validation against observation (Baldocchi et al., 1996; Friend et al., 2007).

The Light Use Efficiency (LUE) model may have the most potential to adequately address the spatial and temporal dynamics of GPP because it presents the consistent ecosystem processes across the various vegetation types (Running et al., 2000), avoiding the problems on responsive nonlinearity of ecosystem processes to environmental variables. The LUE model is built upon two fundamental assumptions (Running et al., 2004): (1) that ecosystem GPP is directly related to Absorbed Photosynthetically Active Radiation (APAR) through LUE, where LUE is defined as the amount of carbon produced per unit of APAR and (2) that realized LUE may be reduced below its theoretical potential value by environmental stresses such as low temperatures or water shortages (Landsberg, 1986). The general form of the LUE model is:

$$GPP = PAR \times fPAR \times \varepsilon_{max} \times f \tag{1}$$

where *PAR* is the incident photosynthetically active radiation (MJ m⁻²) per time period (e.g., day or month), *fPAR* is the fraction of *PAR* absorbed by the vegetation canopy, ε_{max} is the potential *LUE* (g C m⁻² MJ⁻¹ APAR) without environment stress, and *f* is a scalar varying from 0 to 1 and represents the effects of temperature, moisture, and other environmental conditions on LUE.

We have developed a LUE model for simulating daily GPP, named the EC-LUE (Eddy Covariance Light Use Efficiency) model, derived by satellite data and eddy covariance measurements (Yuan et al., 2007). The EC-LUE model was calibrated and validated using estimated GPP from eddy covariance towers at the AmeriFlux and EuroFlux networks, covering a variety of forests, grasslands, and savannas. More importantly, parameters of the EC-LUE model are invariant across various vegetation types, which make it possible to map daily GPP over large areas. The EC-LUE model uses the Bowen ratio of sensible to latent heat flux to present the moisture constraint to LUE, which hampers its applications due to the poor simulation of sensible and latent heat flux at large spatial scales. In addition, EC-LUE has not been validated at cropland ecosystems as a major ecosystem type impacting the regional and global carbon budgets.

Besides driving the EC-LUE model for simulating GPP, evapotranspiration (ET, equivalent of latent heat) over land is a key component of the climate system as it links the hydrological, energy, and carbon cycles (Dirmeyer, 1994; Betts & Ball, 1997; Pielke et al., 1998). Accurate knowledge on temporal and spatial variations of ET is critical for understanding the interactions between land surfaces and the atmosphere, improving water and land resource management (Meyer, 1999; Raupach, 2001), drought detection and assessment (McVicar & Jupp, 1998), and regional hydrological applications (Kustas & Norman, 1996; Keane et al., 2002). However, ET remains the most problematic component of the water cycle because of the heterogeneity of the landscape and the large number of controlling factors involved, including climate, plant biophysics, soil properties, and topography (Gash, 1987; Friedl, 1996; Lettenmaier & Famiglietti, 2006). Remotely sensed data provides us with temporally and spatially continuous information over vegetated surfaces and is useful for accurately parameterizing surface biophysical variables, such as leaf area index (LAI), and vegetation cover, which can be used to develop a remotely sensed ET model.

Eddy covariance (EC) measurements recorded by the increasing number of EC towers offer the best opportunity for estimating vegetation productivity and calibrating or validating ecosystem models. The concurrent measurements of meteorological variables such as temperature and vapor pressure, as well as water balance variables including evapotranspiration and soil water statue, provide unprecedented datasets for investigating the dynamics and driving variables of GPP. The CO₂ EC flux data now play a growing role in evaluating process- and satellite-based models (Law et al., 2000). The network of EC towers (e.g., AmeriFlux) now covers a wide range of biomes in contrast to most previous efforts, which focused on individual sites or biomes. The overarching goals of this study are to (1) refine GPP and ET models for mapping GPP and ET across the regional scales, and (2) investigate the spatial patterns of GPP and ET.

2. Models and data

2.1. Revised Remote Sensing-Penman Monteith (RS-PM) model

The RS-PM model was originally proposed by Cleugh et al. (2007). Mu et al. (2007) revised it by adding a soil evaporation component, using moisture and temperature constraints on stomatal conductance, and upscaling canopy conductance with leaf area index. In this study, we revised the equations dealing with temperature constraint for stomatal conductance and energy allocation between vegetation canopy and soil surface.

Mu et al. (2007) calculated the temperature and moisture constraints for stomatal conductance (m_{VPD} and m_{TM}) as:

$$m_{\rm VPD} = \begin{cases} 1.0 & \rm VPD \leq \rm VPD_{open} \\ \frac{\rm VPD_{close} - \rm VPD}{\rm VPD_{close} - \rm VPD_{open}} & \rm VPD_{open} < \rm VPD < \rm VPD_{close} & (2) \\ 0.1 & \rm VPD \geq \rm VPD_{close} & \\ 1.0 & \rm TM \geq \rm TM_{open} & \\ \frac{\rm TM - \rm TM_{close}}{\rm TM_{open} - \rm TM_{close}} & \rm TM_{close} < \rm TM < \rm TM_{open} & (3) \\ 0.1 & \rm TM \leq \rm TM_{close} & \\ \end{cases}$$

where *close* indicates nearly complete inhibition (full stomatal closure) and *open* indicates no inhibition to transpiration, *TM* is minimum air temperature (°C), and *VPD* is vapor pressure deficit

(kPa). Studies have demonstrated, however, that high air temperature significantly decreases leaf stomatal conductance by closing stomata and causing structure defects (Schreiber et al., 2001). In our revised RS-PM algorithm, the temperature constraint for stomatal conductance follows the equation detailed by June et al. (2004) and Fisher et al. (2008) with an optimum T_{opt} set as 25 °C.

$$m_T = \exp\left(-\left(\frac{T - T_{\text{opt}}}{T_{\text{opt}}}\right)^2\right) \tag{4}$$

where *T* is air temperature.

Net radiation (R_n) is linearly partitioned between the canopy and the soil surface using vegetation cover fraction (F_c) in the study of Mu et al. (2007), such that:

$$\begin{aligned} A_{\rm c} &= F_{\rm c} \times R_{\rm n} \\ A_{\rm soil} &= (1 - F_{\rm c}) \times R_{\rm n} \end{aligned} \tag{5}$$

where A_c and A_{soil} are the total net incoming radiation partitioned to the canopy and soil, respectively. F_c is defined as the fraction of ground surface covered by the maximum extent of the vegetation canopy (varies between 0 and 1). Mu et al. (2007) calculated F_c using *EVI*:

$$F_{\rm c} = \frac{\rm EVI - \rm EVI_{min}}{\rm EVI_{max} - \rm EVI_{min}} \tag{6}$$

where EVI_{min} and EVI_{max} are the signals from bare soil (LAI \rightarrow 0) and dense green vegetation (LAI $\rightarrow \infty$),which are set as seasonally and geographically invariant constants 0.05 and 0.95, respectively. However, a number of studies have shown that irradiance decrease exponentially with increasing canopy depth (Foroutan-Pour et al., 2001; Gholz et al., 1991; Monsi & Saeki, 1953; Vose et al., 1995). In our revised RS-PM algorithm, we used the Beer–Lambert law to exponentially partition net radiation between the canopy and the soil surface (Ruimy et al., 1999):

$$A_{\text{soil}} = R_{\text{n}} \times \exp\left(-k \times \text{LAI}\right) \tag{7}$$
$$A_{\text{c}} = R_{\text{n}} - A_{\text{soil}}$$

where *LAI* is leaf area index, and k is extinction coefficient (0.5).

In addition, Mu et al. (2007) used a biome properties look-up table to determine the parameters: TMopen, TMclose, VPDclose, and VPDopen in the Eqs. (2) and (3). We conducted two sensitivity experiments in order to examine the necessity of varying parameters with ecosystem types: (1) setting *TM*_{open} and *VPD*_{close} as the maximum value (12 °C and 3.9 kPa) and TM_{close} and VPD_{open} as minimum value (-8 °C and 0.65 kPa) in the study of Mu et al. (2007) for all study sites (see Table 1 of Mu et al. (2007)); and (2) setting *TM*_{open} and *VPD*_{close} as the minimum value (8.31 °C and 2.5 kPa) and TM_{close} and VPD_{open} as maximum value $(-6 \degree C \text{ and } 0.93 \text{ kPa})$ for all study sites, respectively. There were not much differences of model simulations between the two model experiments among various ecosystem types. The maximum difference of RPE (relative predictive errors, see Eq. (12)) occurred at deciduous broadleaf forest with 2.9% and average value was 2.4% in all the ecosystem types. The maximum difference in coefficient of determination was 0.04 at evergreen broadleaf forest, and average difference was 0.02 at all ecosystem types. Therefore, it is possible to set invariant model parameters across the various vegetation types. We calibrated three parameters in the revised RS-PM model: VPD_{close}, total aerodynamic conductance to vapor transport (Ctot, the sum of soil surface conductance and the aerodynamic conductance for vapor transport), and mean potential stomatal conductance (C_1) using observed ET from all eddy flux towers in order to set constant parameters for all vegetation types.

2.2. EC-LUE model

The EC-LUE model is driven by only four variables: normalized difference vegetation index (NDVI), photosynthetically active radiation (PAR), air temperature, and the Bowen ratio of sensible to latent heat flux. However, previous applications of the EC-LUE model were hampered by poor simulation of the Bowen ratio of sensible to latent heat flux at large spatial scales, which was used to present the moisture constraint on light use efficiency:

$$W_{\rm s} = \frac{1}{\beta + 1} = \frac{\rm LE}{\rm LE + H} \tag{8}$$

where β is the Bowen ratio, and *LE* and *H* are ecosystem latent (MJ m⁻²) and sensible heat flux (MJ m⁻²). In this study, we used R_n to substitute the sum of *LE* and *H*, and revised downward-regulation scalar for moisture on *LUE* as:

$$W_{\rm s} = \frac{\rm LE}{R_{\rm n}} \tag{9}$$

LE is equivalence of ET, which could be estimated by the revised RS-PM model across the large spatial scales. R_n can be derived from existing climate observation networks (Zhang et al., 2004).

2.3. Data at the EC sites

The EC data were used in this study to calibrate and validate the revised RS-PM and EC-LUE model from the AmeriFLUX (http://public. ornl.gov/ameriflux) and EuroFLUX internet Web pages (http://www.fluxnet.ornl.gov/fluxnet/index.cfm; Valentini, 2003). Fifty-four EC sites were included in this study (Table 1), covering six major terrestrial biomes: deciduous broadleaf forests, mixed forests, evergreen needleleaf forests, grasslands, savannas, and croplands. Supplementary information on the vegetation, climate, and soil at each site is available on-line. Half-hourly or hourly averaged global radiation (R_g), photosynthetically active radiation (PAR), air temperature (T_a), and friction velocity (u^*) were used together with net ecosystem exchange of CO₂ (NEE) in this study. When available, datasets that were gap-filled by site PIs were used for this study. For other sites, data filtering and gap-filling were conducted according to the following procedures.

An outlier ("spike") detection technique was applied, and the spikes were removed, following Papale et al. (2006). Because nighttime CO_2 flux can be underestimated by eddy covariance measurements under stable conditions (Falge et al., 2001), nighttime data with nonturbulent conditions were removed based on a u^* -threshold criterion (site-specific 99% threshold criterion following Papale et al., 2006, and Reichstein et al., 2005).

Nonlinear regression methods were used for filling NEE data gaps (Falge et al., 2001). Nonlinear regression relationships between measured fluxes and environmental factors were fit using a 15-day moving window. The *Vant Hoff* ("Q₁₀"; see Lloyd & Taylor, 1994) equation was used to fill the missing nighttime fluxes (NEE_{night}):

$$NEE_{night} = Ae^{(BT)}$$
(10)

where, *A* and *B* are fit model parameters, *T* is air temperature (°C). A Michaelis–Menten light response equation was used to fill the missing daytime fluxes (NEE_{day}) (Falge et al., 2001):

$$NEE_{day} = \frac{\alpha \times PAR \times F_{GPP,sat}}{F_{GPP,sat} + \alpha \times PAR} - Re_{day}$$
(11)

where $F_{\text{GPP,sat}}$ (gross primary productivity at saturating light) and α (initial slope of the light response function) are fit parameters, and

Table 1

Name, location, vegetation type and available years of the study sites used for model calibration and validation.

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Blackspruce 53.8F NU/58.4F W ENF 2000-2005 Griffis et al. (2007) Dakeprine 33.57 NV 7095 W ENF 2000-2004 Dum et al. (2007) Dakeprine 53.57 NV 7095 W ENF 2000-2003 Griffis et al. (2008) Jackpine 53.91 NV 104.697 W ENF 2000-2003 Griffis et al. (2006) Jackpine 53.91 NV 104.697 W ENF 2000-2005 / Ucit989 53.91 NV 98.967 W ENF 2000-2005 / Vindriver 43.52 NV 12.155 W ENF 2000-2005 / Vindriver 43.52 NV 12.155 W ENF 2000-2005 Novick et al. (2006) Ucit989 53.91 NV 98.96 W ENF 2000-2002 Flora and Coscuti (2006) Ucit980 53.91 NV 12.05 W MIX 2000-2002 Flora and Coscuti (2005) Valiatriver 37.52 NS658 W GRS 2001-2004 Verme et al. (2005) Valiatriver 40.00 N 88.20 W MIX 2002-2006 Posat et al. (2005) Valiatriver 40.00 N 88.20 W MIX	Puechabon	43.73°N,3.58°E	EBF	2000-2003	Rambal et al. (2004)
Bockspine 55.87 NS948'W ENF 2008-2004 Dunn et al. (2007) Howland 45.20 NS847'W ENF 2000-2005 Style et al. (2008) Howland 45.20 NS87'W ENF 2000-2003 Critinavial and Berholer (2007) Lindsed 55.91 NS838'W ENF 2000-2003 Critinavial and Berholer (2007) Unit 964 55.91 NS838'W ENF 2000-2005 / / Windriver 45.82 N1.21.95'W ENF 2001-2005 Novick et al. (2004) Walhuttiver 37.52 NS685'W GRS 2001-2004 Song et al. (2005) Vindriver 45.95'N1.126'F MIX 2000-2005 Posit et al. (2005) Vinanta 46.62 NS.93'W GRS 2001-2004 Song et al. (2005) Vinanta 46.62 NS.93'W CRP 2001-2004 Verma et al. (2005) Meadirrotat 41.16 NS.64 T'W CRP 2001-2004 Verma et al. (2005) Meadirrotat 41.16 NS.64 T'W CRP 2001-2004 Verma et al. (2005) Meadirrotat 31.07 NS.64 T'W	Blackspruce	53.98°N,105.12°W	ENF	2000-2005	Griffis et al. (2003)
Dukepine 35.97%,73.09'W ENF 2000-2005 Stoy et al. (2008) Howland 45.20%,85.47W ENF 2000-2003 Griffis et al. (2004) Jackpine 53.31%,104.69'W ENF 2000-2003 Griffis et al. (2005) Uc1959 55.51%,98.83'W ENF 2000-2005 Coulden et al. (2006) Uc1959 55.51%,98.85'W ENF 2001-2005 Nork et al. (2004) Dukegrass 35.97%,79.09'W GRS 2001-2005 Nork et al. (2004) Valuary 2.53%,78.96.85'W GRS 2001-2005 Nork et al. (2005) Valuary 2.53%,78.96.85'W GRS 2001-2004 Song et al. (2005) Valuary 2.002-2006 Dest et al. (2005) Valuary Valuary 2004 Valuary Valuary WIX 2002-2006 Meyers and Holinger (2004) Meyers and Holinger (2004) Valuary Valuary CRP 2001-2004 Verma et al. (2005) Valuary 46.37%,91.09'W GRP 2001-2004 Verma et al. (2005) Valuary 41.	Boeas_nsa	55.87°N,98.48°W	ENF	2000-2004	Dunn et al. (2007)
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jackpine 53.91*N.104.69*W ENF 2003 Griffs et al. (2005) Thanandt 50.95*N.13.55*E ENF 2001-2005 Goulden et al. (2006) Uci1969 55.91*N.98.95*W ENF 2003-2005 / Windriver 45.82*N.121.95*W ENF 2003-2005 // Windriver 45.82*N.121.95*W ENF 2001-2005 Norket et al. (2004) Dukegrass 55.97*N.9309*W GRS 2001-2004 Song et al. (2005) Valutriver 37.52*N.96.85*W GRS 2000-2002 Fiora and Cescatt (2006) Sylvania 46.37*N.91.09*W MIX 2002-2006 Meyers and Hollinger (2004) Valutation ster Winashard 46.63*N.91.09*W GRP 2001-2004 Verma et al. (2005) Meadiringtated 41.16*N.96.47*W GRP 2001-2004 Verma et al. (2005) Meadiringtate 41.16*N.96.47*W GRP 2001-2004 Verma et al. (2005) Indealaringtate 41.16*N.96.47*W GRP 2001-2004 Verma et al. (2005) Meadirinotate 41	Howland	45.20°N,68.74°W	ENF	2000-2004	Hollinger et al. (2004)
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Uci1890 55.9T N98.96"W ENF 2004-2005 / Vindriver 45.82" N12.155"W ENF 2004-2005 Novick et al. (2004) Valuatriver 37.52" N65.85"W GRS 2001-2004 Song et al. (2005) Lavarone 45.95" N11.26"E MIX 2000-2002 Fiora and Cescatti (2005) Sylvania 46.63" N.91.09"W MIX 2004 / Validation sites	Uci1964	55.91°N,98.38°W	ENF	2001-2005	Goulden et al. (2006)
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Dukegrass 35.97N.79.09"W CRS 2001-2005 Novick et al. (2004) Wahntriver 3.75.27N.96.857W CRS 2001-2004 Song et al. (2005) Lavarone 45.637N.11.26'E MIX 2000-2002 Fiora and Cescatti (2006) Sylvania 46.637N.91.97W MIX 2004 / Validation sites Beadirrigated 41.16'N.96.47'W CRP 2001-2004 Verma et al. (2005) Meadirrigated 41.16'N.96.47'W CRP 2001-2004 Verma et al. (2005) Meadrinotate 51.06'N.10.45'E DBF 2001-2004 Verma et al. (2003) Indianammsf 3.932'N.86.41'W DBF 2001-2005 Pataki and Oren (2003) Indianammsf 3.932'N.86.41'W DBF 2000-2003 Kmohl et al. (2000) Valkerbrach 3.932'N.86.41'W DBF 2000-2001, 2004 Wilson and Baloochi (2000) Valkerbrach 3.932'N.86.41'W DBF 2000-2001, 2004 Wilson and Cark (2002) Valkerbrach 3.932'N.86.41'W DBF <td>Windriver</td> <td>45.82°N,121.95°W</td> <td>ENF</td> <td>2004-2006</td> <td>Paw et al. (2004)</td>	Windriver	45.82°N,121.95°W	ENF	2004-2006	Paw et al. (2004)
Walm Inverse 37.52 YN 56.85 'W GRS 2001-2004 Song et al. (2005) Sylkania 46.53 'N.91.09 'W MIX 2000-2006 Desai et al. (2005) Sylkania 46.63 'N.91.09 'W MIX 2002-2006 Desai et al. (2005) Viimmahard 46.63 'N.91.09 'W MIX 2002-2006 Meyers and Hollinger (2004) Meadirrigated 41.16 'N.96.47 'W CRP 2002-2006 Meyers and Hollinger (2004) Meadirrigated 41.16 'N.96.47 'W CRP 2011-2004 Verma et al. (2005) Meadirrigated 41.16 'N.96.47 'W CRP 2011-2004 Verma et al. (2005) Mukarbinod 51.06 'N.10.45 'E DBF 2010-2003 Knihl et al. (2003) Hainich 51.06 'N.10.45 'E DBF 2000-2003 Schnihl et al. (2000) Malkerbach 53.55 'N.84.28 'W DBF 2000-2003 Schnihl et al. (2000) Valkerbach 53.55 'N.84.28 'W DBF 2000-2003 Schnid et al. (2000) Valkerbach 53.55 'N.84.28 'W DBF 2001-2004 Uilson ad Cark (2002)	Dukegrass	35.97°N.79.09°W	GRS	2001-2005	Novick et al. (2004)
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Sylvania 46.24"N,89.34"W MIX 2002-2006 Desai et al. (2005) Winmahard 46.37N,91.09"W MIX 2004 / Validation sites Bondville 40.00"N,88.29"W CRP 2001-2006 Meyers and Hollinger (2004) Meadirrigated 41.16"N,96.47"W CRP 2001-2004 Verma et al. (2005) Meadirrigated 41.16"N,96.43"W CRP 2001-2004 Verma et al. (2005) Dukehardwood 35.9"N,910"W DBF 2000-2003 Knohl et al. (2003) Hainich 51.06"N,10.45"E DBF 2000-2003 Schmid et al. (2000) Walkerbrach 35.95"N,84.28"W DBF 2000-2003 Schmid et al. (2000) Walkerbrach 35.95"N,84.28"W DBF 2003-2006 Gholz and Cark (2002) Matchinary 29.37"N,82.1"W EBF 2004-2003 Kindiacca et al. (2009) Austincary 29.37"N,82.1"W EBF 2004-2006 / Blackhill 44.15"N,103.65"W ENF 2004-2006 /	Lavarone	45 95°N 11 26°E	MIX	2000-2002	Fiora and Cescatti (2006)
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Validation sites Jose Jose Jose Validation sites	Winmahard	46.63°N 91.09°W	MIX	2002 2000	/
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Hamich 51.05 'N,10.45'E DBF 2000-2003 Knohl et al. (2003) Hesse 45.65 'N,70.57'E DBF 2000-2003 Grainer et al. (2000) Walkerbrach 35.95 'N,84.48'W DBF 2000-2001, 2004 Wilson and Baldocchi (2000) ParcoTicino 45.20 'N,9.05'E DBF 2003 Miginavcca et al. (2009) Austincary 29.73 'N,82.21 'W EBF 2005-2006 Cholz and Clark (2002) Blackhill 44.15 'N,10.365'W ENF 2001-2004 Coldstein et al. (2009) Control 63.89 'N,120.63'W ENF 2000-2003 Cholz and Clark (2002) Leikray 44.71 'N,0.76'E ENF 2000-2003 Cholz and Clark (2002) Leikray 44.45 'N,121.55'W ENF 2000-2003 Cholz and Clark (2002) Metoliusoldyoung 44.45 'N,121.56'W ENF 2000-2002 Law et al. (2006) Nivotridge 40.03 'N,105.54'W ENF 2001-2004 Monson et al. (2006) Uci1930 55.90 'N,98.25'W ENF 2002-2003 Goulden et al. (2006) Uci1938<	Dukehardwood	35.97°N,79.10°W	DBF	2001-2005	Pataki and Oren (2003)
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Tonzi Ranch 38.43°N,120.96°W SAV 2002–2006 Ma et al. (2007)	Umichigan	45.55°N,84.71°W	MIX	2000-2006	Curtis et al. (2005)
	Tonzi Ranch	38.43°N,120.96°W	SAV	2002-2006	Ma et al. (2007)

DBF: deciduous broadleaf fores; EBF: evergreen broadleaf forest; ENF: evergreen needleleaf forest; GRS: grassland; MIX: mixed forest; CRP: cropland; SAV: savanna.

 Re_{day} (ecosystem respiration during the day) was estimated by extrapolation of Eq. (10) using the daytime air temperature.

Daily NEE, Re, and meteorological variables were synthesized based on half-hourly or hourly values and the daily values were indicated as missing when missing data was more than 20% of entire data at a given day, otherwise daily values were calculated by multiplying averaged hourly rate by 24 (hours). GPP was calculated as the sum of NEE and Re. Based on the daily dataset, yearly values of various variables can be calculated by multiplying averaged daily rate by 365 (days). If missing daily data was more than 20% of entire year data, the value of this year was indicated as missing.

Normalized difference vegetation index (NDVI) and leaf area index (LAI) for the sites were determined from the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS ASCII subset data were used in this study and generated from MODIS Collection 5 data, which was downloaded directly from the Oak Ridge National Laboratory Distributed Active Center (ORNL DAAC) Web site. The 8-day MODIS LAI (MOD15A2) and 16-day MODIS NDVI (MOD13A2) data at 1-km spatial resolution were the basis for models verification in the flux sites. Only the NDVI and LAI values of the pixel containing the tower were used. Quality control (QC) flags, which signal cloud contamination in each pixel, were examined to screen and reject NDVI and LAI data of insufficient quality.

2.4. Data at the global scale

For global estimates of ET and GPP, we used input datasets for net radiation (R_n), air temperature (T), relative humidity (R_h) and photosynthetically active radiation (PAR) from the MERRA (Modern Era Retrospective-Analysis for Research and Applications) archive for 2000–2003 (Global Modeling and Assimilation Office, 2004). MERRA is a NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). MERRA uses data from all available surface weather observations globally every 3 h, and GEOS-5 was used to interpolate and grid these point data on a short time sequence, and produces an estimate of climatic conditions for the world, at 10 meters above the land surface (approximating canopy height conditions) and at a resolution of 0.5° latitude by 0.6° longitude. MERRA reanalyses dataset has been validated carefully at the global scale using surface meteorological data sets to evaluate the uncertainty of various meteorological factors (e.g. temperature, radiation, humidity, energy balance), which showed MERRA considerably reduced the energy and water imbalance. Detailed information on the MERRA dataset is available at the website (http://gmao.gsfc.nasa. gov/research/merra/).

The global 8-day MODIS LAI (MOD15A2) and 16-day MODIS NDVI (MOD13A2) data were used in this study. Quality control (QC) flags were examined to screen and reject NDVI and LAI data of insufficient quality. We temporally filled the missing or unreliable LAI and NDVI at each 1-km MODIS pixel based on their corresponding quality assessment data fields as proposed by Zhao et al. (2005). If the first (or last) 8-day LAI (16-day NDVI) data are unreliable or missing, they will be replaced by the closest reliable 8-day (16-day) values.



Fig. 1. Variation in 8-day mean value of predicted and observed ET at model calibration sites. The black solid lines represent the predicted ET, and the open circle dots represent observed ET.

2.5. Nonlinear optimization and statistical analysis

The nonlinear regression procedure (Proc NLIN) in the Statistical Analysis System (SAS, SAS Institute Inc., Cary, NC, USA) was applied to two calculations: (1) to determine the parameter values in the equation filling NEE data gaps and calculating daytime ecosystem respiration (i.e., Eqs. (10) and (11)), and (2) to optimize the values for VPD_{close}, R_{tot} and C_l in the revised RS-PM model (see Mu et al., 2007), and T_{opt} and ε_{max} (see Yuan et al., 2007) in the EC-LUE model across all the calibration sites.



Fig. 2. Variation in 8-day mean value of predicted ET and observed ET at model validation sites. The black solid lines represent the predicted ET, and the open circle dots represent observed ET.

Three metrics were used to evaluate the performance of the revised RS-PM and EC-LUE model in this study:

- (1) The coefficient of determination, R^2 , representing how much variation in the observations was explained by the models.
- (2) Absolute predictive error (PE), quantifying the difference between simulated and observed values:

$$PE = \overline{S} - \overline{O} \tag{12}$$

where \overline{S} and \overline{O} are mean simulated and mean observed values, respectively.

(3) Relative predictive error (RPE), computed as:

$$RPE = \frac{\overline{S} - \overline{O}}{\overline{O}} \times 100\%$$
(13)

3. Results

3.1. Calibration and validation of the revised RS-PM model

Twenty-one sites were selected to calibrate the revised RS-PM model, and other thirty-three sites were to validate the model (Table 1). Both calibration and validation sites covered several dominant natural and agricultural ecosystem types, including: evergreen needleleaf forests, mixed forests, deciduous broadleaf forests, grasslands, savannas, and croplands.

The calibrated values for C_{tot} , C_{I} and VPD_{close} were 0.008 m s⁻¹, 0.003 m s⁻¹, and 2.79 kPa in the revised RS-PM model, respectively. Fig. 1 shows the range of predicted ET and observed ET at the 21 calibration sites (Fig. 1). The model also successfully predicted the magnitudes and seasonal variations of the observed ET at the validation sites (Fig. 2). Collectively, the revised RS-PM model explained about 82% of the variation of 8-day ET at all calibration sites (Fig. 3a). Model performance was similar to that at the calibration sites and explained 68% of the ET variations at these new sites (Fig. 3b).

However, large differences between predicted and observed ET still existed in a few sites. Predicted ET values were higher than observed ET at Aspen, Jackpine, and Tonzi Ranch with RPE values of 41%, 30%, and 93%, respectively (Table 2). The model underestimated the ET at Bondville, Monte Bondone, and Canaanvalley with the RPE varying from 31% to 39%. At the other 48 sites, the RPE values were lower than 30%.

Our revised RS-PM algorithm improved the ET estimates at most of the 54 flux towers compared with these estimated using the original RS-PM algorithm, and reduced RPE at 36 of the 54 flux tower sites (data not shown). The average absolute value of RPE of the 8-day latent heat fluxes over the 54 flux towers was decreased using the revised RS-PM algorithm to 15% compared with the 22% of the original algorithm. The coefficient of determination (R^2) between the ET estimates and observations for the 8-day results are higher at 48 sites, averaging 0.78 using revised RS-PM algorithm and 0.67 using the original version.

Fig. 4 showed the model performance of our revised RS-PM model driven by tower-specific meteorology and the global MERRA meteorology dataset, respectively. The model driven by tower-specific meteorology data explained 83% variations of annual mean ET across 54 flux sites (Fig. 4a), and provided no systematic errors in model predictions. In contrast, using the MERRA dataset significantly decreased model performance, and explained 67% of the variations of ET and underestimated ET at the most sites (Fig. 4b).

3.2. Calibration and validation of EC-LUE model

Using ET simulated by the revised RS-PM model, the calibrated values for optimal temperature and potential LUE were 21 °C and 2.25 g C MI⁻¹. The EC-LUE model successfully predicted the magnitudes and seasonal variations of the estimated GPP from EC measurements at calibration and validation sites (Figs. 5, 6). The model explained about 75% and 61% of the variation of 8-day GPP estimated at calibration and validation sites, respectively (Fig. 7). There were no significant systematic errors in model predictions. Although the EC-LUE model explained significant amounts of GPP variability at the individual sites, large differences between predicted GPP and estimated GPP values from EC measurements still existed at a few sites. The model underestimated GPP at several European sites (e.g., Hesse, MonteBondone and Nonantola) with RPE higher than 40% (Table 2). Predictions were higher than observed for GPP at several high latitude sites (Uci 1989, Uci1930, Uci1998 and Burn99) and at Tonzi Ranch PE values varied from 0.41 g C m⁻² day⁻¹ to 1.25 g C m⁻² day⁻¹ and RPE values from 35% to 63%, respectively. At the other 37 sites, the EC-LUE model gave accurate predictions with RPE values lower than 30% (Table 2).

Using net radiation to substitute the sum of H and LE, the revised EC-LUE algorithm generally performed worse than the original GPP algorithm at most of the 54 flux sites. The revised EC-LUE model produced higher predictive errors at 35 of the 54 flux towers, and the absolute RPE of the 8-day GPP increased from 18% of the original EC-LUE algorithm to 24% using the revised algorithm. The coefficient of determination (R^2) between the GPP estimates and observations for the 8-day results decreases from 0.89 of original EC-LUE to 0.73 of revised version. Predictive errors of ET significantly induced the biases



Fig. 3. Observed and predicted ET at the model calibration (a) and validation (b) sites in Table 1. The short dash lines are 1:1 line and the solid lines are linear regression line.

Table 2

Predicted results of the revised RS-PM and EC-LUE model at calibration and validation sites.

	Site	Revised F	RS-PM model					Revised EC-LUE model			
Collimation size Collimation size Collimation size Collimation size Burn87 2.03 2.01 0.89 -0.03 -0.01 1.79 1.83 0.80 0.04 0.00 Condwincreek 4.69 4.46 0.85 -0.01 3.99 4.48 0.71 0.49 0.11 Condwincreek 4.69 4.46 0.85 -0.04 -0.01 3.99 4.48 0.71 0.49 0.11 Toledo 4.85 4.47 0.81 0.10 0.00 5.63 5.69 0.78 0.06 0.01 Patchalon 3.15 2.47 0.05 0.05 0.24 4.71 0.05 -0.05 -0.05 -0.04 -0.04 -0.04 -0.01 0.00 1.04 2.02 0.03 -0.02 -0.03 -0.13 5.12 3.64 0.02 0.02 -0.03 -0.13 5.12 3.64 0.08 -0.02 0.02 1.12 1.25 0.50 0.07 -1.18		ETo ^a	ETp ^b	R^2	PE	RPE	GPP _o ^c	GPP _p ^d	R^2	PE	RPE
Appen 181 2.58 0.84 -0.75 0.41 3.23 3.22 0.83 -0.01 0.00 Chestmut 2.78 3.14 0.93 -0.01 1.39 1.83 0.80 0.04 0.02 Coordwince 4.69 4.64 0.93 0.03 0.13 3.20 4.02 0.93 0.04 0.01 1.83 0.80 0.04 0.01 1.83 0.44 0.07 0.448 0.01 0.448 0.01 0.448 0.01 0.448 0.01 0.448 0.03 0.00 0.03 0.04 0.03 0.04 0.03 0.04 0.03 0.04 0.03 0.04 0.03 0.04 0.03 0.04 0.03 0.05 0.03 0.01 0.05 0.04 0.03 0.03 0.01 0.03 0.03 0.01 0.03 0.03 0.03 0.01 0.03 0.03 0.01 0.03 0.01 0.03 0.01 0.03 0.01 0.03	Calibration sites										
BirmR7 2.03 2.01 0.88 -0.03 -0.01 1.79 1.83 0.80 0.04 0.02 Construit 2.83 1.44 0.03 0.35 0.11 3.50 4.02 0.80 0.51 0.11 Code 4.86 4.87 0.33 0.01 0.00 5.35 9.00 0.53 0.60 0.01 Willowrreak 2.80 2.77 0.81 0.01 0.00 5.35 4.48 0.77 0.49 -0.11 Backspruce 1.84 1.92 0.87 -0.31 0.10 2.46 1.42 0.86 -0.24 Dukepine 1.22 0.87 0.03 2.01 2.46 1.42 0.88 0.04 2.46 1.60 0.09 Licklaspruce 1.22 2.25 0.07 0.33 0.07 0.17 0.03 0.03 0.01 0.61 1.82 0.44 0.16 0.09 0.17 0.03 0.03 0.01 0.	Aspen	1.81	2.58	0.84	0.75	0.41	3.23	3.22	0.83	-0.01	0.00
Chestmut 2.78 3.14 0.93 0.35 0.13 3.50 4.48 0.90 0.52 0.13 Codwincred 4.86 4.87 0.83 0.04 0.00 5.63 5.69 0.78 0.06 0.01 Parchabon 3.15 2.97 0.74 -0.17 -0.05 3.75 2.88 0.40 -0.88 -0.31 Backspurz 1.82 0.72 0.74 -0.05 5.24 4.72 0.75 -0.45 -0.05 Iowland 2.77 0.34 0.86 0.02 0.01 4.29 4.57 0.88 0.28 0.06 Jackpine 1.72 2.25 0.67 0.52 0.30 2.07 2.35 0.84 -0.48 -0.10 Ucit989 1.79 0.80 -0.32 -0.07 3.57 3.50 0.57 -0.17 -0.50 Ucit989 1.79 2.00 0.83 0.21 0.12 1.25 2.50 0.31	Burn87	2.03	2.01	0.89	-0.03	-0.01	1.79	1.83	0.80	0.04	0.02
Good Multicreck 4.69 4.64 0.02 -0.04 -0.01 3.99 4.48 0.71 0.49 0.11 Willowcreck 2.60 2.79 0.81 0.19 0.07 4.88 4.12 0.76 -0.76 -0.18 Puechabon 3.15 2.97 0.81 0.13 0.17 2.37 2.07 0.82 -0.38 -0.14 Bocar, na 1.84 1.92 0.85 -0.64 -0.028 -0.01 0.02 4.97 0.80 0.28 0.01 Unitipite 4.52 4.57 0.79 -0.25 -0.03 5.24 4.97 0.80 0.28 0.01 0.01 1.66 1.82 0.84 0.16 0.09 0.13 5.12 3.64 0.83 -0.13 5.12 3.64 0.83 0.17 -0.05 0.56 0.31 0.72 -0.13 0.71 -0.05 0.56 0.31 0.72 0.13 0.20 0.21 0.26 0.80 0.21 </td <td>Chestnut</td> <td>2.78</td> <td>3.14</td> <td>0.93</td> <td>0.35</td> <td>0.13</td> <td>3.50</td> <td>4.02</td> <td>0.90</td> <td>0.52</td> <td>0.13</td>	Chestnut	2.78	3.14	0.93	0.35	0.13	3.50	4.02	0.90	0.52	0.13
Teledo 4.86 4.87 0.81 0.01 0.00 5.63 5.69 0.78 0.06 0.01 Villowreek 2.60 2.79 0.74 -0.17 -0.05 3.76 2.88 0.40 -0.68 -0.31 Backspruc 1.80 2.10 0.87 0.31 0.17 2.37 2.07 0.82 -0.30 -0.31 Durpme 4.77 0.34 0.83 0.04 2.46 1.32 0.86 -0.34 Durpme 4.77 0.34 0.86 -0.32 0.01 2.46 1.32 0.84 -0.44 Durpme 1.72 2.25 0.67 0.52 0.30 2.07 2.35 0.84 -0.44 0.01 Uci1989 1.76 0.76 0.84 -0.01 0.00 1.66 1.82 0.84 -0.44 Uci1989 1.76 0.75 0.84 -0.02 0.075 0.17 0.51 0.51 0.51 0.51 0.5	Goodwincreek	4.69	4.64	0.85	-0.04	-0.01	3.99	4.48	0.71	0.49	0.11
Willewerreck 2.60 2.79 0.81 0.19 0.07 4.88 4.12 0.76 -0.76 -0.78 Blackpruce 1.80 2.10 0.87 0.31 0.17 2.37 2.07 0.82 -0.38 -0.14 Blackpruce 4.82 4.57 0.73 -0.05 5.24 4.79 0.75 -0.45 -0.03 Bowland 2.77 3.04 0.86 0.02 0.10 4.29 4.57 0.38 0.28 0.016 Jardpine 1.72 2.00 0.83 0.21 0.10 2.57 0.50 0.75 0.64 -0.16 Unlisbe 1.79 2.00 0.83 -0.21 -0.16 3.50 0.57 -0.17 -0.05 Dukegrass 4.13 4.09 0.74 -0.04 -0.01 3.07 2.18 0.74 -0.42 Vindriver 3.77 3.56 0.66 -0.21 -0.05 2.78 2.64 0.99 -0.14<	Toledo	4.86	4.87	0.83	0.01	0.00	5.63	5.69	0.78	0.06	0.01
Patchaban 3.15 2.57 0.74 -0.17 -0.05 3.76 2.28 0.40 -0.38 -0.30 -0.14 Backspruce 1.80 2.10 0.87 0.31 0.17 2.37 2.07 0.82 -0.30 -0.14 Boess, na 1.84 1.92 0.87 -0.45 -0.09 Howland 2.77 3.04 0.86 0.28 0.10 4.29 4.57 0.88 0.28 0.01 Jackpine 1.72 2.25 0.67 0.52 0.30 2.07 2.35 0.84 0.08 0.12 Uniskes 1.79 2.00 0.83 0.21 0.12 1.25 2.50 0.72 1.25 0.50 Windriver 3.42 3.20 0.43 0.21 0.06 3.78 2.64 0.69 -0.17 -0.06 Windriver 3.42 2.66 0.87 -0.48 6.62 3.31 0.72 -0.42 -0.17 4.81	Willowcreek	2.60	2.79	0.81	0.19	0.07	4.88	4.12	0.76	-0.76	-0.18
Blackspruce 1.80 2.10 0.87 0.31 0.17 2.37 2.07 0.82 -0.30 -0.14 Dokepine 4.82 4.57 0.79 -0.25 -0.05 5.24 4.79 0.75 -0.45 -0.28 Dokepine 4.82 4.57 0.79 -0.25 -0.05 5.24 4.79 0.75 -0.45 -0.28 Dokepine 1.72 2.25 0.67 0.52 0.30 2.07 2.35 0.84 0.28 0.006 Jackpine 1.72 2.25 0.67 0.52 0.30 2.07 2.35 0.84 0.28 0.028	Puechabon	3.15	2.97	0.74	-0.17	-0.05	3.76	2.88	0.40	-0.88	-0.31
Beces.nsh 1.84 1.82 0.83 0.04 2.46 1.92 0.86 -0.54 -1.03 Bowland 2.77 3.04 0.66 0.22 0.10 4.29 4.75 0.88 0.028 0.00 Iaxinand 3.09 2.70 0.80 -0.23 0.51 2.35 0.84 0.28 0.01 Ucit964 1.76 1.75 0.84 -0.01 0.00 1.66 1.82 0.84 -0.41 0.01 0.66 1.82 0.84 -0.17 -0.05 0.57 -0.17 -0.05 0.57 -0.17 -0.05 0.57 -0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14 -0.05 0.57 0.14	Blackspruce	1.80	2.10	0.87	0.31	0.17	2.37	2.07	0.82	-0.30	-0.14
Dukepine 4.82 4.57 0.79 -0.25 -0.05 5.24 4.79 0.75 -0.45 -0.09 Jackpine 1.72 2.25 0.67 0.52 0.30 2.07 2.35 0.84 0.28 0.016 Lirisb9 1.76 1.75 0.84 -0.01 0.00 1.66 1.82 0.84 0.16 0.09 Windriver 3.42 3.20 0.74 -0.23 -0.07 3.67 3.50 0.57 -0.17 -0.05 Dukegrass 4.13 4.09 0.74 -0.23 -0.07 3.67 3.50 0.57 -0.14 -0.05 Validation 3.77 3.56 0.86 -0.21 -0.06 2.78 2.64 0.90 0.62 0.16 Validation sites	Boeas_nsa	1.84	1.92	0.83	0.08	0.04	2.46	1.92	0.86	-0.54	-0.28
Howland 2.77 3.04 0.86 0.28 0.10 4.29 4.57 0.88 0.28 0.01 Tharandt 3.09 2.70 0.80 -0.33 -0.13 5.12 3.64 0.83 -1.48 -0.01 Uci1956 1.76 1.75 0.84 -0.01 0.00 1.66 1.82 0.84 0.61 0.09 1.64 1.82 0.84 0.61 0.09 1.64 1.82 0.84 0.61 0.09 1.64 0.83 0.72 1.25 0.50 0.72 1.25 0.50 0.72 1.25 0.50 Ukintriver 3.71 2.66 0.87 -0.06 0.78 2.64 0.90 -0.14 -0.05 Lavarone 3.41 2.47 0.74 -0.49 -0.17 3.43 3.66 0.90 0.62 0.16 Waindringted 3.62 0.68 -0.17 4.65 3.52 0.84 -1.19 -0.31 2.81 1.73	Dukepine	4.82	4.57	0.79	-0.25	-0.05	5.24	4.79	0.75	-0.45	-0.09
jackpine 1.72 2.25 0.67 0.52 0.30 2.07 2.25 0.84 0.028 0.113 Uci 1959 1.76 1.75 0.84 -0.01 0.00 1.66 1.82 0.84 0.16 0.09 Uci 1959 1.79 2.00 0.83 0.21 0.12 1.25 2.50 0.72 1.25 0.50 Windriver 3.42 3.20 0.74 -0.23 -0.07 3.67 3.50 0.57 -0.11 -0.05 Dukegrass 4.13 4.09 0.74 -0.24 -0.06 2.78 2.64 0.90 -0.14 -0.05 Valuationi stes Lavarone 3.41 2.47 0.76 0.87 0.40 0.17 3.34 3.96 0.90 0.62 0.16 Valuation istes Lavarone 4.03 0.81 0.87 -0.40 -0.16 5.26 3.21 0.82 -0.63 0.20 0.84 -1.24 -0.33 Meatirrotate 4.	Howland	2.77	3.04	0.86	0.28	0.10	4.29	4.57	0.88	0.28	0.06
Tharandt 3.09 2.70 0.80 -0.39 -0.13 5.12 3.64 0.83 -1.48 -0.41 Uci1989 1.79 2.00 0.83 0.21 0.12 1.25 2.50 0.72 1.25 0.50 Dukegrass 4.13 4.09 0.74 -0.04 -0.01 3.07 2.18 0.74 -0.89 -0.41 Wahurtiver 3.77 3.56 0.86 -0.21 -0.06 2.78 2.64 0.90 -0.62 0.14 -0.05 Lavarone 3.41 2.47 0.74 -0.04 -0.28 5.05 3.31 0.72 -1.74 -0.52 Sylvania 2.72 2.66 0.87 -0.41 -0.35 5.91 4.81 0.88 -1.10 -0.23 Vibidation sites - - 0.43 0.87 -0.64 -0.16 5.26 0.52 -0.26 -0.55 -0.26 -0.06 3.21 0.82 -0.65 -0.26 0	Jackpine	1.72	2.25	0.67	0.52	0.30	2.07	2.35	0.84	0.28	0.12
Uci 1964 1.76 1.75 0.84 -0.01 0.00 1.66 1.82 0.84 0.16 0.09 Windriver 3.42 3.20 0.74 -0.23 -0.07 3.67 3.50 0.57 -0.17 -0.05 Dukegrass 4.13 4.09 0.74 -0.04 -0.06 2.78 2.64 0.90 -0.14 -0.05 Lavarone 3.41 2.47 0.74 -0.24 5.05 3.31 0.72 -1.74 -0.52 Sylvania 2.27 2.66 0.87 0.40 -0.17 3.43 3.96 0.90 0.62 0.16 Wimmahard 4.65 4.43 0.81 -0.22 -0.55 5.91 4.81 0.88 -1.10 -0.21 Windriver 3.82 2.63 0.68 -0.17 4.66 3.21 0.82 -0.85 Meadiringrated 3.95 3.47 0.79 -0.48 -0.17 4.66 3.21 0.82 -	Tharandt	3.09	2.70	0.80	-0.39	-0.13	5.12	3.64	0.83	-1.48	-0.41
Uci 1989 1.79 2.00 0.83 0.21 0.12 1.25 2.50 0.72 1.25 0.50 Dukegrass 4.13 4.09 0.74 -0.04 -0.01 3.67 3.50 0.57 -0.14 -0.05 Lavarone 3.41 2.47 0.74 -0.04 -0.28 5.05 3.31 0.72 -1.74 -0.52 Sylvania 2.72 2.66 0.87 0.40 0.17 3.34 3.96 0.90 0.62 0.16 Wildardm stres U U -0.23 -0.05 5.91 4.81 0.88 -1.10 -0.23 Validarius stres U U -0.016 5.26 0.51 4.81 0.88 -1.10 -0.23 Validarius stres U U 0.37 -0.64 -0.16 5.26 0.52 0.62 0.62 0.62 0.62 0.62 0.62 0.61 0.43 0.10 Hain 0.55 0.74 -0.26	Uci1964	1.76	1.75	0.84	-0.01	0.00	1.66	1.82	0.84	0.16	0.09
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Uci1989	1.79	2.00	0.83	0.21	0.12	1.25	2.50	0.72	1.25	0.50
Dukegrass 4.13 4.09 0.74 -0.04 -0.01 3.07 2.18 0.74 -0.68 -0.61 Lavarone 3.41 2.47 0.74 -0.04 -0.28 5.05 3.31 0.72 -1.74 -0.05 Sylvania 2.27 2.66 0.87 0.40 0.17 3.34 3.96 0.90 0.62 0.16 Winmahard 4.65 4.43 0.81 -0.22 -0.05 5.91 4.81 0.88 -1.10 -0.23 Validation sites 0.62 0.13 0.67 -0.92 -0.35 Meadiringted 3.95 3.30 0.87 -0.64 -0.17 4.06 3.21 0.82 -0.25 -0.031 Meadiringted 3.95 -0.11 -0.031 Meadiringted 3.93 0.87 -0.018 Nationa 0.02 4.13 3.55 0.74 -0.76 -0.18 Meadiringted 4.03 3.77 0.76 <td>Windriver</td> <td>3.42</td> <td>3.20</td> <td>0.74</td> <td>-0.23</td> <td>-0.07</td> <td>3.67</td> <td>3.50</td> <td>0.57</td> <td>-0.17</td> <td>-0.05</td>	Windriver	3.42	3.20	0.74	-0.23	-0.07	3.67	3.50	0.57	-0.17	-0.05
Walnutriver 3.77 3.56 0.86 -0.21 -0.06 2.78 2.64 0.09 -0.14 -0.05 Sylvania 2.27 2.66 0.87 0.40 0.17 3.34 3.96 0.90 0.62 0.16 Winnahard 4.65 4.43 0.81 -0.22 -0.05 5.91 4.81 0.88 -1.10 -0.23 Winduition site: - - 0.05 5.91 4.81 0.88 -1.02 -0.33 Meadirrigated 3.95 3.30 0.67 -0.64 -0.16 5.26 3.52 0.84 -0.21 Meadirrigated 3.95 3.47 0.79 -0.48 -0.12 4.11 3.55 0.74 -0.76 -0.18 Meadirinifed 2.32 2.55 0.82 0.32 0.14 4.94 3.93 0.85 -1.01 -0.20 Dubehardwood 4.33 4.42 0.85 0.08 0.27 2.73 0.71 -0.44	Dukegrass	4.13	4.09	0.74	-0.04	-0.01	3.07	2.18	0.74	-0.89	-0.41
Lavarone 3.41 2.47 0.74 -0.94 -0.28 5.05 3.31 0.72 -1.74 -0.52 Sylvania 2.72 2.66 0.87 0.40 0.17 3.34 3.96 0.90 0.62 0.16 Winmahard 4.65 4.43 0.81 -0.22 -0.05 5.91 4.81 0.88 -1.10 -0.23 Validation sites	Walnutriver	3.77	3.56	0.86	-0.21	-0.06	2.78	2.64	0.90	-0.14	-0.05
Sylvania 2.27 2.66 0.87 0.40 0.17 3.34 3.96 0.90 0.62 0.10 Vininahard 4.65 4.43 0.81 -0.22 -0.05 5.91 4.81 0.88 -1.10 -0.23 Vining 3.82 2.63 0.68 -1.19 -0.31 2.81 1.73 0.67 -0.92 -0.33 Meadirrigated 3.30 0.87 -0.64 -0.16 5.26 3.52 0.84 -1.74 -0.33 Meadirrigated 3.95 3.47 0.79 -0.48 -0.12 4.31 3.55 0.74 -0.76 -0.18 Mieadirrich 2.33 0.87 -0.22 -0.09 5.37 2.73 0.71 -0.64 -0.08 Mieadirrich 3.33 0.82 0.82 -0.06 5.49 5.05 0.59 -0.44 -0.08 Mieadirrich 3.33 0.77 0.76 -0.26 -0.06 5.49 5.05 0.59	Lavarone	3.41	2.47	0.74	-0.94	-0.28	5.05	3.31	0.72	-1.74	-0.52
Winmahard 4.65 4.43 0.81 -0.22 -0.05 5.91 4.81 0.88 -1.10 -0.23 Validation sites Bondville 3.82 2.63 0.68 -1.19 -0.31 2.81 1.73 0.67 -0.023 -0.031 Meadimingated 3.95 3.30 0.87 -0.64 -0.16 5.26 3.52 0.84 -1.74 -0.33 Meadiminated 3.95 3.47 0.79 -0.48 -0.12 4.31 3.55 0.74 -0.76 -0.18 Dukehardwood 4.33 4.42 0.85 0.08 0.02 4.15 4.58 0.77 0.43 0.10 Hainich 2.32 2.55 0.82 0.32 0.14 4.94 3.93 0.85 -1.01 -0.26 Heise 2.78 2.53 0.87 -0.39 -0.10 4.50 2.51 0.91 -1.99 -0.44 Musicary 3.54 4.27 0.69 0.74 <td>Sylvania</td> <td>2.27</td> <td>2.66</td> <td>0.87</td> <td>0.40</td> <td>0.17</td> <td>3.34</td> <td>3.96</td> <td>0.90</td> <td>0.62</td> <td>0.16</td>	Sylvania	2.27	2.66	0.87	0.40	0.17	3.34	3.96	0.90	0.62	0.16
Validation sites 9 0.68 -1.19 -0.31 2.81 1.73 0.67 -0.92 -0.33 Meadirirgated 3.95 3.30 0.87 -0.64 -0.16 5.26 3.52 0.84 -1.74 -0.33 Meadrinifed 3.95 3.30 0.82 -0.69 -0.17 4.06 3.21 0.82 -0.85 -0.21 Meadrinifed 3.95 0.74 -0.76 -0.18 0.12 4.31 3.55 0.74 -0.76 -0.18 Dukehardwood 4.33 4.42 0.85 0.08 0.02 4.15 4.58 0.77 0.43 0.10 Hainch 2.23 2.55 0.82 0.32 0.14 4.94 3.93 0.85 -1.01 -0.49 Indianamms 4.03 3.77 0.76 -0.26 -0.09 4.50 5.55 0.41 0.66 0.19 ParcoTicino 3.90 3.51 0.88 -0.37 0.48 0.09	Winmahard	4.65	4.43	0.81	-0.22	-0.05	5.91	4.81	0.88	-1.10	-0.23
bondville 3.82 2.63 0.68 -1.19 -0.31 2.81 1.73 0.67 -0.92 -0.33 Meadirrigated 3.95 3.30 0.87 -0.64 -0.16 5.26 3.52 0.84 -1.74 -0.33 Meadirrotate 4.00 3.31 0.82 -0.69 -0.17 4.06 3.21 0.82 -0.85 -0.21 Meadirrotate 3.95 3.47 0.79 -0.48 -0.12 4.31 3.55 0.74 -0.76 -0.18 Michinch 2.23 2.55 0.82 0.32 0.14 4.94 3.93 0.85 -1.01 -0.20 Hesse 2.78 2.53 0.87 -0.26 -0.06 5.49 5.05 0.59 -0.44 -0.08 Walkerbrach 5.11 4.63 0.73 -0.48 -0.09 2.55 0.41 0.06 0.21 0.22 1.59 0.64 -0.63 -0.28 0.61 0.24 0.08	Validation sites										
Meadirrigated 3.95 3.30 0.87 -0.64 -0.16 5.26 3.52 0.84 -1.74 -0.33 Meadirrighted 3.95 3.47 0.79 -0.48 -0.12 4.31 3.55 0.74 -0.76 -0.18 Dukehardwood 4.33 4.42 0.85 0.02 4.15 4.58 0.77 0.43 0.10 Heisne 2.78 2.53 0.87 -0.26 -0.06 5.37 2.73 0.71 -2.64 -0.49 Malkerbrach 5.11 4.63 0.73 -0.426 -0.09 5.95 0.41 0.96 0.19 ParcoTicino 3.90 3.51 0.88 -0.39 -0.10 4.50 2.51 0.91 -1.99 -0.44 Austincary 3.54 4.27 0.69 0.74 0.21 4.21 5.14 0.66 0.92 0.222 Blackhill 3.35 2.44 0.67 -0.90 -0.27 2.22 1.59 0.64 -0.63 -0.28 Blodgett 3.17 3.56 0.	Bondville	3.82	2.63	0.68	-1.19	-0.31	2.81	1.73	0.67	-0.92	-0.35
Meadrainrotate 4.00 3.11 0.82 -0.69 -0.17 4.06 3.21 0.82 -0.85 -0.21 Meadrainfed 3.95 3.47 0.79 -0.48 -0.12 4.31 3.55 0.74 -0.76 -0.18 Dukehardwood 4.33 4.42 0.85 0.08 0.02 4.15 4.58 0.77 0.43 0.10 Hainch 2.23 2.55 0.82 0.32 0.014 4.94 3.93 0.85 -1.01 -0.26 Hesse 2.78 2.53 0.87 -0.25 -0.09 5.49 5.05 0.59 -0.44 -0.08 Walkerbrach 5.11 4.63 0.73 -0.48 -0.09 4.50 2.51 0.91 -1.99 -0.44 Austincary 3.54 4.27 0.69 0.74 0.21 4.21 5.14 0.56 0.92 0.22 Blachill 3.35 2.44 0.67 0.93 5.88	Meadirrigated	3.95	3.30	0.87	-0.64	-0.16	5.26	3.52	0.84	-1.74	-0.33
Meadrainfed 3.95 3.47 0.79 -0.48 -0.12 4.31 3.55 0.74 -0.76 -0.18 Dukehardwood 4.33 4.42 0.85 0.08 0.02 4.15 4.58 0.77 0.43 0.10 Hainch 2.23 2.55 0.82 0.32 0.14 4.94 3.93 0.85 -1.01 -0.26 Hesse 2.78 2.53 0.87 -0.26 -0.06 5.49 5.05 0.59 -0.44 -0.08 Walkerbrach 5.11 4.63 0.73 -0.48 -0.09 4.90 5.95 0.41 0.96 0.19 ParcoTicino 3.90 3.51 0.88 -0.39 -0.10 4.50 2.51 0.91 -1.99 -0.44 Austincary 3.54 4.27 0.69 0.73 0.21 4.21 5.14 0.56 0.92 0.22 1.59 0.64 -0.63 -0.28 0.61 0.24 0.08 0.51<	Meadirrrotate	4.00	3.31	0.82	-0.69	-0.17	4.06	3.21	0.82	-0.85	-0.21
Dukehardwood4.334.420.850.080.024.154.580.770.430.10Hainich2.232.550.820.320.144.943.930.85-1.01-0.20Hesse2.782.530.87-0.25-0.095.372.730.71-2.64-0.49Indianammsf4.033.770.76-0.26-0.065.495.050.59-0.44-0.09Walkerbrach5.114.630.73-0.48-0.094.905.950.410.060.19ParcoTcino3.903.510.88-0.39-0.104.502.510.91-1.99-0.44Austincary3.544.270.690.740.214.215.140.560.920.22Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.33-0.16Donaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15Lefray4.673.320.68-0.570.203.893.360.69-0.33-0.16Niwotridge3.392.960.81-0.030.152.260.700.160.08Uci19302.032.210.820.160.091.542.400.670.930.	Meadrainfed	3.95	3.47	0.79	-0.48	-0.12	4.31	3.55	0.74	-0.76	-0.18
Halinch2.232.550.820.320.144.943.930.85-1.01-0.20Hesse2.782.530.87-0.25-0.095.372.730.71-2.64-0.49Malkerbach5.114.630.73-0.48-0.094.905.950.410.960.19ParcoTicino3.903.510.88-0.39-0.104.502.510.91-1.99-0.44Austincary3.544.270.690.740.214.215.140.560.920.22Blackhill3.352.440.67-0.90-0.272.221.590.64-0.63-0.28Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.30-0.16Danaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15Lebray4.673.220.680.570.232.232.560.690.340.160.08Metoliusoldyong2.523.990.680.570.232.232.560.690.340.15Uci19302.032.210.81-0.43-0.132.102.260.700.160.08Uci19302.392.540.51-0.132.102.260.700.16<	Dukehardwood	4.33	4.42	0.85	0.08	0.02	4.15	4.58	0.77	0.43	0.10
Hesse2.782.530.87-0.25-0.095.372.730.71-2.64-0.49Indianammsf4.033.770.76-0.26-0.065.495.050.59-0.44-0.08Walkerbrach5.114.630.73-0.48-0.094.905.950.410.960.19ParcoTicino3.903.510.88-0.39-0.104.502.510.91-1.99-0.44Austincary3.544.270.690.740.214.215.140.560.920.22Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.30-0.16Donaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusoidyoung2.523.090.680.570.232.232.260.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19302.032.210.81-0.42-0.231.121.480.630.460.45Uci19981.801.380.91-0.42-0.231.121.480.63 </td <td>Hainich</td> <td>2.23</td> <td>2.55</td> <td>0.82</td> <td>0.32</td> <td>0.14</td> <td>4.94</td> <td>3.93</td> <td>0.85</td> <td>-1.01</td> <td>-0.20</td>	Hainich	2.23	2.55	0.82	0.32	0.14	4.94	3.93	0.85	-1.01	-0.20
Indianammsf4.033.770.76-0.26-0.065.495.050.59-0.44-0.08Walkerbrach5.114.630.73-0.48-0.094.905.950.410.900.19ParcoTicino3.903.510.88-0.39-0.104.502.510.91-1.99-0.44Austincary3.544.270.690.740.214.215.140.560.920.22Blackhill3.352.440.67-0.90-0.272.221.590.64-0.63-0.28Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.30-0.16Danaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15Lebray4.673.320.600.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19981.801.800.91-0.42-0.231.121.480.83	Hesse	2.78	2.53	0.87	-0.25	-0.09	5.37	2.73	0.71	-2.64	-0.49
Walkerbrach5.114.630.73-0.48-0.094.905.950.410.960.19ParcoTicino3.903.510.88-0.39-0.104.502.510.91-1.99-0.42Blackhill3.352.440.67-0.90-0.272.221.590.64-0.63-0.28Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.30-0.15Lebray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusnidpine2.823.390.500.570.203.893.360.69-0.43-0.15Nivotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19302.032.210.82-0.180.091.542.400.670.930.63Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19841.801.380.91-0.42-0.231.121.480.830.460.43Uci19981.801.380.91-0.42-0.231.121.480.83-0.62-0.33Uci19981.801.840.99-0.66-0.030.920.530.63 <t< td=""><td>Indianammsf</td><td>4.03</td><td>3.77</td><td>0.76</td><td>-0.26</td><td>-0.06</td><td>5.49</td><td>5.05</td><td>0.59</td><td>-0.44</td><td>-0.08</td></t<>	Indianammsf	4.03	3.77	0.76	-0.26	-0.06	5.49	5.05	0.59	-0.44	-0.08
ParcoTicino3.903.510.88-0.39-0.104.502.510.91-1.99-0.44Austincary3.544.270.690.740.214.215.140.560.920.22Blackhill3.352.440.67-0.09-0.272.221.590.64-0.63-0.28Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.01-0.15LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusmidpine2.823.390.500.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Uci 19302.032.210.820.180.091.542.400.670.930.63Uci 19812.852.570.84-0.28-0.101.201.280.610.090.08Uci 19812.792.280.75-0.51-0.184.452.890.82-1.56-0.35Wimmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.660.67<	Walkerbrach	5.11	4.63	0.73	-0.48	-0.09	4.90	5.95	0.41	0.96	0.19
Austincary3544.270.690.740.214.215.140.560.920.020.22Blackhill3.352.440.67-0.90-0.272.221.590.64-0.63-0.28Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.30-0.16Donaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusoldyoung2.523.090.680.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.532.570.84-0.132.102.260.700.160.08Uci19302.032.210.820.180.091.542.400.670.930.63Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19841.800.91-0.42-0.231.121.480.830.460.43Uci19981.800.91-0.42-0.231.121.480.830.460.43Uci19981.995.540.430.160.036.195.520.68-0.75-0.12	ParcoTicino	3.90	3.51	0.88	-0.39	-0.10	4.50	2.51	0.91	-1.99	-0.44
Blackhill 3.35 2.44 0.67 -0.90 -0.27 2.22 1.59 0.64 -0.63 -0.28 Blodgett 3.17 3.65 0.73 0.48 0.15 3.25 3.50 0.61 0.24 0.08 Control 2.35 2.49 0.75 0.14 0.06 1.94 1.64 0.68 -0.30 -0.16 Donaldson 5.85 4.91 0.42 -0.93 -0.16 6.93 5.88 0.42 -1.05 -0.15 LeBray 4.67 3.32 0.68 -1.35 -0.29 6.20 3.87 0.65 -2.37 -0.38 Metoliusoidyoung 2.52 3.09 0.68 0.57 0.20 3.89 3.36 0.69 -0.53 -0.14 Metoliusoidyoung 2.52 3.09 0.68 0.57 0.23 2.23 2.56 0.69 0.34 0.15 Metoliusoidyoung 2.52 3.09 0.68 0.57 0.23 2.12 1.48 0.61 0.09 0.08 Uci1981 2.85	Austincary	3.54	4.27	0.69	0.74	0.21	4.21	5.14	0.56	0.92	0.22
Blodgett3.173.650.730.480.153.253.500.610.240.08Control2.352.490.750.140.061.941.640.68-0.30-0.16Donaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19302.032.210.820.180.091.542.400.670.930.63Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19821.801.380.91-0.42-0.231.121.480.830.460.45Wimared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Caaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethridge1.901.840.59-0.06-0.030.920.530.28-0.39 <td>Blackhill</td> <td>3.35</td> <td>2.44</td> <td>0.67</td> <td>-0.90</td> <td>-0.27</td> <td>2.22</td> <td>1.59</td> <td>0.64</td> <td>-0.63</td> <td>-0.28</td>	Blackhill	3.35	2.44	0.67	-0.90	-0.27	2.22	1.59	0.64	-0.63	-0.28
Control2.352.490.750.140.061.941.640.68-0.30-0.16Donaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusmidpine2.823.390.500.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19302.032.210.820.180.091.542.400.670.930.63Uci19842.852.570.84-0.28-0.101.201.280.610.090.08Uci19951.801.380.91-0.42-0.231.121.480.830.460.45Wimared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Cananvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethridge1.901.840.59-0.06-0.030.920.530.28	Blodgett	3.17	3.65	0.73	0.48	0.15	3.25	3.50	0.61	0.24	0.08
Donaldson5.854.910.42-0.93-0.166.935.880.42-1.05-0.15LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusnidpine2.823.390.500.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.523.090.680.570.232.232.260.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19302.032.210.820.180.091.542.400.670.930.63Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19981.801.380.91-0.42-0.231.121.480.830.460.45Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Caaaavalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.550.68 <td>Control</td> <td>2.35</td> <td>2.49</td> <td>0.75</td> <td>0.14</td> <td>0.06</td> <td>1.94</td> <td>1.64</td> <td>0.68</td> <td>-0.30</td> <td>-0.16</td>	Control	2.35	2.49	0.75	0.14	0.06	1.94	1.64	0.68	-0.30	-0.16
LeBray4.673.320.68-1.35-0.296.203.870.65-2.37-0.38Metoliusmidpine2.823.390.500.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci19302.032.210.820.180.091.542.400.670.930.63Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19981.801.380.91-0.42-0.231.121.480.830.460.45Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Ganavalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.42Vairarach2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.8	Donaldson	5.85	4.91	0.42	-0.93	-0.16	6.93	5.88	0.42	-1.05	-0.15
Metoliusmidpine2.823.390.500.570.203.893.360.69-0.53-0.14Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci 19302.032.210.820.180.091.542.400.670.930.63Uci 19812.852.570.84-0.28-0.101.201.280.610.090.08Uci 19981.801.380.91-0.42-0.231.121.480.830.460.45Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Canaavalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.22Fortdix3.142.600.78-0.47-0.181.762.730.	LeBray	4.67	3.32	0.68	-1.35	-0.29	6.20	3.87	0.65	-2.37	-0.38
Metoliusoldyoung2.523.090.680.570.232.232.560.690.340.15Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci 19302.032.210.820.180.091.542.400.670.930.63Uci 19812.852.570.84-0.28-0.101.201.280.610.090.08Uci 19981.801.380.91-0.42-0.231.121.480.830.460.45Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.07Vairarach2.252.054-0.47-0.164.612.520.47-2.09-0.45Nonantola2.992.520.54-0.47-0.164.612.520.47	Metoliusmidpine	2.82	3.39	0.50	0.57	0.20	3.89	3.36	0.69	-0.53	-0.14
Niwotridge3.392.960.81-0.43-0.132.102.260.700.160.08Uci 19302.032.210.820.180.091.542.400.670.930.63Uci 19812.852.570.84-0.28-0.101.201.280.610.090.08Uci 19981.801.380.91-0.42-0.231.121.480.830.460.45Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Vairaranch2.252.054-0.47-0.164.612.520.47-2.09-0.45Nonantola2.992.520.54-0.47-0.164.612.520.47	Metoliusoldyoung	2.52	3.09	0.68	0.57	0.23	2.23	2.56	0.69	0.34	0.15
Uci19302.032.210.820.180.091.542.400.670.930.63Uci19812.852.570.84-0.28-0.101.201.280.610.090.08Uci19981.801.380.91-0.42-0.231.121.480.830.460.45Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.80<	Niwotridge	3.39	2.96	0.81	-0.43	-0.13	2.10	2.26	0.70	0.16	0.08
Uci1981 2.85 2.57 0.84 -0.28 -0.10 1.20 1.28 0.61 0.09 0.08 Uci1998 1.80 1.38 0.91 -0.42 -0.23 1.12 1.48 0.83 0.46 0.45 Wetzstein 2.79 2.28 0.75 -0.51 -0.18 4.45 2.89 0.82 -1.56 -0.35 Winmared 5.39 5.54 0.43 0.16 0.03 6.19 5.52 0.68 -0.75 -0.12 Burn99 2.19 2.30 0.73 0.11 0.05 1.02 1.65 0.67 0.63 0.62 Canaanvalley 5.23 3.28 0.20 -1.95 -0.37 3.53 4.01 0.52 0.49 0.14 Lethbridge 1.90 1.84 0.59 -0.06 -0.03 0.92 0.53 0.28 -0.39 -0.43 Monte Bondone 3.37 2.04 0.91 -1.33 -0.39 3.67 2.11 0.80 -1.55 -0.42 Vairaranch 2.25 2.09 0.51 -0.16 -0.07 2.97 2.94 0.55 -0.07 -0.25 Fortdix 3.14 2.60 0.78 -0.59 -0.18 1.76 2.73 0.86 0.97 0.55 Umichigan 3.60 3.19 0.86 -0.41 -0.11 4.73 5.96 0.78 1.12 0.23 Tonzi Ranch 1.15 2.21 0.57	Uci1930	2.03	2.21	0.82	0.18	0.09	1.54	2.40	0.67	0.93	0.63
Uci1998 1.80 1.38 0.91 -0.42 -0.23 1.12 1.48 0.83 0.46 0.45 Wetzstein 2.79 2.28 0.75 -0.51 -0.18 4.45 2.89 0.82 -1.56 -0.35 Winmared 5.39 5.54 0.43 0.16 0.03 6.19 5.52 0.68 -0.75 -0.12 Burn99 2.19 2.30 0.73 0.11 0.05 1.02 1.65 0.67 0.63 0.62 Canaanvalley 5.23 3.28 0.20 -1.95 -0.37 3.53 4.01 0.52 0.49 0.14 Lethbridge 1.90 1.84 0.59 -0.06 -0.03 0.92 0.53 0.28 -0.39 -0.43 Monte Bondone 3.37 2.04 0.91 -1.33 -0.39 3.67 2.11 0.80 -1.55 -0.42 Vairaranch 2.25 2.09 0.51 -0.16 -0.07 2.97 2.94 0.55 -0.07 -0.02 Fortdix 3.14	Uci1981	2.85	2.57	0.84	-0.28	-0.10	1.20	1.28	0.61	0.09	0.08
Wetzstein2.792.280.75-0.51-0.184.452.890.82-1.56-0.35Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.42Vairarach2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Uci1998	1.80	1.38	0.91	-0.42	-0.23	1.12	1.48	0.83	0.46	0.45
Winmared5.395.540.430.160.036.195.520.68-0.75-0.12Burn992.192.300.730.110.051.021.650.670.630.62Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.02Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.161.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Wetzstein	2.79	2.28	0.75	-0.51	-0.18	4.45	2.89	0.82	-1.56	-0.35
Burn992.192.300.730.110.051.021.650.670.630.62Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.161.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Winmared	5.39	5.54	0.43	0.16	0.03	6.19	5.52	0.68	-0.75	-0.12
Canaanvalley5.233.280.20-1.95-0.373.534.010.520.490.14Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.993.672.110.80-1.55-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Burn99	2.19	2.30	0.73	0.11	0.05	1.02	1.65	0.67	0.63	0.62
Lethbridge1.901.840.59-0.06-0.030.920.530.28-0.39-0.43Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Canaanvalley	5.23	3.28	0.20	-1.95	-0.37	3.53	4.01	0.52	0.49	0.14
Monte Bondone3.372.040.91-1.33-0.393.672.110.80-1.55-0.42Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Lethbridge	1.90	1.84	0.59	-0.06	-0.03	0.92	0.53	0.28	-0.39	-0.43
Vairaranch2.252.090.51-0.16-0.072.972.940.55-0.07-0.02Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Monte Bondone	3.37	2.04	0.91	- 1.33	-0.39	3.67	2.11	0.80	- 1.55	-0.42
Fortdix3.142.600.78-0.59-0.181.762.730.860.970.55Nonantola2.992.520.54-0.47-0.164.612.520.47-2.09-0.45Umichigan3.603.190.86-0.41-0.114.735.960.781.120.23Tonzi Ranch1.152.210.571.060.931.112.090.800.980.89	Vairaranch	2.25	2.09	0.51	-0.16	-0.07	2.97	2.94	0.55	-0.07	-0.02
Nonantola 2.99 2.52 0.54 -0.47 -0.16 4.61 2.52 0.47 -2.09 -0.45 Umichigan 3.60 3.19 0.86 -0.41 -0.11 4.73 5.96 0.78 1.12 0.23 Tonzi Ranch 1.15 2.21 0.57 1.06 0.93 1.11 2.09 0.80 0.98 0.89	Fortdix	3.14	2.60	0.78	-0.59	-0.18	1.76	2.73	0.86	0.97	0.55
Umichigan 3.60 3.19 0.86 -0.41 -0.11 4.73 5.96 0.78 1.12 0.23 Tonzi Ranch 1.15 2.21 0.57 1.06 0.93 1.11 2.09 0.80 0.98 0.89	Nonantola	2.99	2.52	0.54	-0.47	-0.16	4.61	2.52	0.47	-2.09	-0.45
Tonzi Ranch 1.15 2.21 0.57 1.06 0.93 1.11 2.09 0.80 0.98 0.89	Umichigan	3.60	3.19	0.86	-0.41	-0.11	4.73	5.96	0.78	1.12	0.23
	Tonzi Ranch	1.15	2.21	0.57	1.06	0.93	1.11	2.09	0.80	0.98	0.89

^a Observed ET from eddy covariance measurements.

^b Predicted ET by the revised RS-PM model.

^c Observed GPP from eddy covariance measurements.

^d Predicted GPP by the revised EC-LUE model.

of GPP simulations in the some study sites. For example, overestimates of ET at Tonzi Ranch induced overestimates of GPP.

Four cropland sites were included in this study for testing the performance of EC-LUE at cropland ecosystems. These four sites were characterized by different ecosystem features: (a) irrigated continuous maize (Meadirrigated), (b) irrigated maize–soybean rotation (Bondville and Meadirrotate), and (c) rainfed maize–soybean rotation (Meadrainfed). The EC-LUE model performed very well for predicting the soybean ecosystem, but significantly underestimated the GPP for

maize. There was similar model performance in irrigated and rain fed ecosystems.

We compared the annual mean GPP observations measured at the flux towers and two sets of estimated GPP with the revised EC-LUE driven by tower-specific meteorology (Fig. 8a) and the global MERRA meteorology (Fig. 8b), respectively. The coefficient of determination between the GPP observations and the tower-driven algorithm estimates was 0.81 with a slight underestimate of GPP (Fig. 8a). The model explained 67% of the variations of GPP using MERRA dataset,



Fig. 4. Comparison of annual mean evapotranspiration (ET) observations from the flux tower sites and estimated by the revised RS-PM model. These data were created using (a) tower-specific meteorology (y = 0.91x + 0.24, $R^2 = 0.83$) and (b) the global MERRA meteorology (y = 0.57x + 0.57, $R^2 = 0.67$).

and significantly underestimated GPP across the spatial scales (Fig. 8b).

3.3. Global spatial patterns of ET and GPP

We assessed the global spatial patterns of ET and GPP averaged from 2000 to 2003 using $0.5^{\circ} \times 0.6^{\circ}$ monthly gridded MERRA input data. ET was high over the tropical rain forests and subtropical forest regions like the southeastern United States and the Pantanal region of South American. ET was low over deserts, high mountain regions, and the polar zones (Fig. 9). The southern hemispheric tropics remained consistently high, while the major deserts of northern Africa and Australia remain consistently low. Global mean ET estimated by our revised RS-PM model was 417 ± 38 mm year⁻¹ across the vegetated area.

Global annual GPP was 110.5 ± 21.3 Pg C. The highest annual production (>2000 g C m⁻²) is found in the humid tropics (Amazonia, Central Africa, South-east Asia), where both temperature and moisture requirements are fully satisfied for photosynthesis. Temperate regions have an intermediate GPP (1000–1400 g C m⁻²), and the lowest GPP (<400 g C m⁻²) is found in both cold and arid regions, where either temperature or precipitation are limiting factors (Fig. 10).

4. Discussion

4.1. Model performance analysis

Model calibration and validation at 54 EC sites in North America and Europe suggested that the revised RS-PM and EC-LUE models were robust and reliable across the most of biomes and geographic regions. Fig. 3 showed that the revised RS-PM model did not produce significant predictive errors of ET across the calibration and validation sites (Fig. 3). The EC-LUE model underestimated GPP at the validation sites (Fig. 7b), however, several croplands were included in validation sites, and the EC-LUE model significantly underestimated the GPP for maize. When excluding the data from the four croplands, the performance of EC-LUE model get much better.

Under the same climate conditions, C_4 crops have greater photosynthetic capacity and more rapid accumulation of green leaf area than C_3 crops (Suyker et al., 2005). Parameters of EC-LUE model,

however, were calibrated at C_3 plant dominant ecosystems, which was the major cause for underestimation of GPP at the maize crops. It is worth noting, however, that overestimating magnitude of GPP for maize were close at the four croplands, and peak simulated GPP were 50% smaller than observed GPP. Consistent potential light use efficiency can be derived for C_4 crop to improve the performance of EC-LUE model at the maize croplands. Meadirrigated site was selected to calibrate the EC-LUE model for maize croplands, and the calibrated values for optimal temperature and potential LUE were 19 °C and 4.06 g C MJ⁻¹. The EC-LUE model successfully predicted the magnitudes and seasonal variations of observed GPP at the Meadirrigated site and other three croplands using different parameters value for C_3 and C_4 crops (Fig. 11). This result implied that it is necessary to use a spatial distribution map of C_3 and C_4 crops for improving the accuracy for quantifying GPP across the global scale.

The revised RS-PM and EC-LUE models used satellite data to provide temporally and spatially continuous information over vegetated surfaces, which significantly strengthened model performances across the regional scales. This study used MODIS/Terra NDVI and LAI products, directly downloaded from the MODIS Web site. No attempt was made to improve the quality of the NDVI or LAI data. Therefore, any noise or errors in the satellite data was transferred to ET and GPP predictions. In addition, we used 1-km² MODIS NDVI and LAI pixels for amorphous polygon eddy flux footprints that change throughout the day and year. If the vegetation and environmental characteristics within the footprint are representative of the surrounding area in which the MODIS pixels contain, then the pixel-to-footprint match should be adequate. A forested eddy flux site adjacent to a clear cut, for example, would induce problems if both the forest and clear cut were included in the MODIS overlap. Thus, some error in our model estimates for the eddy flux sites can be attributed to inaccurate NDVI and LAI estimates for the footprints.

In order to strengthen the applicability of EC-LUE at the regional scale, net radiation was used to substitute the summation of H and LE for representing the downward-regulation scalars for the effect of moisture on LUE of vegetation. However, we reasoned that soil heat flux (G_s) has high spatial variability mismatching with the R_n and (H + LE) measurement, which resulted in prediction errors of modeling GPP. Clearly, the uncertainty in the G_s is large because of the spatial variability of vegetation and soil (Mayocchi & Bristow, 1995; Twine et al., 2000). In grasslands and other ecosystems with sparse canopies, G_s plays a more critical role in the energy fluxes. For example, Meyers (2001) found in grasslands that G_s accounted for 25% of R_n . In forests, however, G_s usually accounts for <5% of R_n (Beringer et al., 2005; Chen et al., 2002), and can be neglected. Estimation of G_s across the regional scales will improve the accuracy for quantifying GPP at large regions.

Significant underestimation of GPP was found at several European sites (e.g., Hesse, MonteBondone, Nonantola) (Fig. 3). Recent studies found increased fraction of diffuse radiation results in higher light use efficiencies of plant canopies (Alton et al., 2007; Gu et al., 2003) because increases in the blue/red light ratio may lead to higher photosynthesis rates per unit leaf area with diffuse radiation (Urban et al., 2007). Our results showed significantly higher proportion of cloudy days (the ratio of gross radiation at the top of the canopy with its top-of-atmosphere is less than 0.5) in Europe $(32 \pm 7\%)$ compared with American and Asian sites $(14 \pm 9\%)$, which was likely a major cause for underestimation of GPP at several European sites.

The EC-LUE model obviously overestimated GPP at several high latitude sites: Burn99, Uci1930, Uci1981, Uci1989 and Uci1998. For example, predicted GPP was higher than estimated GPP at Burn99 with PE values being 0.7 g C m⁻² day⁻¹ and RPE values were 69%, respectively (Table 2). Mosses probably play an important role for quantifying GPP at the northern regions. Mosses are an important component of ecosystem at the high latitude regions, where they



Fig. 5. Variation in 8-day mean value of predicted GPP and observed GPP at model calibration sites. The black solid lines represent the predicted GPP, and the open circle dots represent observed GPP.

often dominate the ground cover. For example, at Burn99 site, in 2002, 30% of the surface was covered by grasses and deciduous shrubs, and the remaining 70% of the surface was covered by moss (Liu & Randerson, 2008). The northern ecosystems are relatively open, due to the narrow canopy and low density of trees, which makes mosses an important contributor to the NDVI signal. On the other hand, mosses are fundamentally different from vascular plants with respect to vegetation production. Field experiments showed significantly low light use efficiency in mosses, ranging from 10 to 50% of that found in vascular plants (Whitehead & Gower, 2001). Therefore, high distribution and low photosynthetically capacity of mosses resulted in a significant overestimation of GPP at the high latitude ecosystems. Further improvement of the light use efficiency model needs to consider the function of mosses across the entire northern ecosystems.

4.2. Global estimates of ET and GPP

Although global validation of ET or GPP is problematic, we are able to investigate its reliability by comparison with other global models from the literature. Our estimate of annual global mean ET was 417 mm year⁻¹, which was comparable to other estimations. The comparison of 15-model simulation from the Global Soil Wetness Project-2 (GSWP-2; Dirmeyer et al., 2006) suggested that the annual ET ranges from 272 to 441 mm year⁻¹. A global evapotranspiration estimation of ET by Fisher et al. (2008) showed 444 mm year⁻¹ using globally consistent datasets from the International Satellite Land-Surface Climatology Project, Initiative II (ISLSCP-II) and the Advanced Very High Resolution Spectroradiometer (AVHRR).

The global magnitude of GPP agreed, in general, with results obtained by an increasing number of models (Cramer et al., 1999;



Fig. 6. Variation in 8-day mean value of predicted GPP and observed GPP at model validation sites. The black solid lines represent the predicted GPP, and the open circle dots represent observed GPP.

Goetz et al., 2000). Comparison of 16 global NPP models showed a range of global NPP from 39.9 to $80 \text{ Pg C m}^{-2} \text{ year}^{-1}$ with a mean of 54.9 Pg C m⁻² year⁻¹ (Cramer et al., 1999). The EC-LUE model

estimated global GPP at 110.5 Pg C year⁻¹, which falls in the range of Cramer's representation (0.5 as ratio of NPP and GPP). The MODIS-GPP product (MOD17A) estimates global GPP at 113 Pg C. Fig. 12 showed



Fig. 7. Observed vs. the predicted GPP at the model calibration (a) and validation (b) sites in Table 1. The short dash lines are 1:1 line and the solid lines are linear regression line. Triangles in b indicate the data of four cropland sites, and short-dot-dot line is linear regression line after excluding the data of four cropland sites (y = 0.84x, $R^2 = 0.62$).

these estimates aggregated for vegetation types. On a biome basis, the EC-LUE model had good agreement in its representation of MODIS-GPP.

The accuracy of global estimates in ET and GPP are highly dependent on the global meteorology dataset. The accuracy of the existing meteorological reanalysis data sets showed marked differences both spatially and temporally. Zhao et al. (2006) compared surface meteorological datasets from three well-documented global reanalyses: DAO (NASA Data Assimilation Office). ECMWF (European Centre for Medium-Range Weather Forecasts), and NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis) with observed weather station data. The results showed NCEP tends to overestimate surface solar radiation, and underestimate both temperature and vapor pressure deficit (VPD). ECMWF has the highest accuracy, but its radiation is lower in tropical regions, and the accuracy of DAO lies between NCEP and ECMWF. Global MODIS-GPP driven by DAO, ECMWF, and NCEP displayed notable differences (>20 Pg C m⁻² year⁻¹). In this study, MERRA tended to underestimate surface net radiation (Fig. 13), which resulted in lower predicted ET and GPP. Our results revealed that the



Fig. 8. Comparison of annual mean GPP observations from the flux tower sites and the ET estimates by the revised EC-LUE model. These data were created using (a) tower-specific meteorology (y = 0.77x + 0.64, $R^2 = 0.81$) and (b) the global MERRA meteorology (y = 0.59x + 0.73, $R^2 = 0.67$).

biases in meteorological reanalysis can introduce substantial errors into GPP and ET estimations, and emphasize the need to minimize these biases to improve the quality of GPP and ET products. In addition, due to the complex terrain and resulting heterogeneity of the landscape surrounding flux towers, model biases resulted in part by upscaling from flux tower to the larger $0.5^{\circ} \times 0.6^{\circ}$ area. The comparison of observed ET or GPP with the estimated using MERRA dataset across all 54 sites may introduce uncertainties due to the differences in tower footprints and under varying environmental conditions for a given tower.

4.3. Model advantages and limitations

A broad range of models exist now, and they are being used to investigate the magnitude and geographical distributions of carbon and water fluxes at a global scale (Brisson et al., 1998; Foley et al., 1996; Potter et al., 1993; Running et al., 2000). Many models are now being compared to detailed biophysical measurements obtained at individual field sites. However, for global- and regional-scale ecosystem models, it is necessary to make these comparisons at various geographical regions for accurate quantification of temporal and spatial variations in vegetation production (Delire & Foley, 1999). In this study, 54 eddy covariance towers were included to calibrate and validate the models, which confirmed the accuracy and applicability of the EC-LUE and revised RS-PM models across wide range of climate and ecosystem types.

Parameterization is critical for global simulation of carbon and water fluxes, and directly determines the model performance. For example, although PLAI (Potsdam Land Atmosphere Interaction Model, Plőchl & Cramer, 1995) uses the same functional formulations for simulating vegetation production as FBM (Frankfurt Biosphere Model, Kindermann et al., 1993), the seasonal and spatial distribution of vegetation production estimated by PLAI is different from FBM due to differences in parameterization and vegetation classification schemes (Kicklighter et al., 1999). However, regional parameterization of ecosystem models probably presents the most difficult task for estimating water and carbon fluxes. The light use efficiency (LUE) model may have the most potential to successfully solve the problems because of its theoretical basis (Running et al., 2000). Potential light use efficiencies in light use efficiency models are theoretically consistent in various vegetation types (Monteith, 1972, 1977), except the difference between C_4 and C_3 vegetation types. Most light use efficiency models, however, did not achieve this assumption because they failed to develop the uniform environmental constraint equations to LUE among the various ecosystems. The EC-LUE model



Fig. 9. Global evapotranspiration (ET) driven by interpolated 0.5°×0.6° MERRA meteorological data and MODIS data averaged from 2000 to 2003.



Fig. 10. Global GPP driven by interpolated 0.5°×0.6° MERRA meteorological data and MODIS data averaged from 2000 to 2003.

successfully generated invariant potential light use efficiency with vegetation types by using the general water and temperature constrains equations to downscale potential light use efficiency. Uniform model parameters of the EC-LUE model across the various ecosystem types and geographical regions produced many benefits to map GPP over large areas with high accuracy and applicability avoiding regional model parameterization.

The EC-LUE and revised RS-PM models based on remote sensing data have a relatively strong potential to analyze temporal changes. Without additional algorithms for simulating changes in NDVI under altered conditions, however, these two models have limited use for climate- or vegetation-change scenarios. Extensions and improvements in the satellite record will serve to enhance remote sensing's usefulness for detecting and quantifying global change.

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Fig. 11. Simulations of EC-LUE model at the four croplands using different parameter values for C₃ and C₄ crops. Meadirrigated site was planted with continuous maize. Other three sites were planted with maize-soybean rotation, and "C₃" and "C₄" were used to indicate maize and soybean crops respectively.



Fig. 12. Comparison of EC-LUE and MODIS-GPP product at the various ecosystem types. ENF: evergreen needleleaf forest; EBF: evergreen broadleaf forest; DNF: deciduous needleleaf forest; DBF: deciduous broadleaf forest; MIX: mixed forest of DBF and ENF; CSH: closed shrubland; OSH: open shrubland; WSA: woody savanna; SAV: savanna; GRS: grassland; CRP: cropland.



Fig. 13. Correlation of net radiaton (R_n) between EC tower and MERRA dataset.

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