



Potential of MODIS data to track the variability in ecosystem water-use efficiency of temperate deciduous forests



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ABSTRACT

One of the most important linkage that coupled terrestrial carbon and water cycles is ecosystem water use efficiency (WUE), which is also relevant to the appropriate ecosystem management actions. The eddy covariance technique provides continuous observations of carbon and water fluxes at the landscape level, presenting an opportunity to infer ecosystem WUE at daily or annual time scales. Scaling up such measurements to regional or national scale, however, remains challenging. Few studies have been reported on direct estimation of WUE from remotely-sensed data, particularly the seasonal dynamics of forests. Therefore, this study aims to assess the potential of tracking the variability in WUE by exclusively using time-series MODIS data at 8 flux tower sites of temperate deciduous forests. Our analyses showed that the 8-day variations in WUE were mainly subject to control by temperature, solar radiation and vapor pressure deficit. As a proxy of plant response to the environmental controls, MODIS-derived vegetation index was found to strongly correlate with ecosystem WUE and could be used for remote quantification. Then, both performance of the indirect WUE estimated from MODIS GPP and ET products (WUE_{MOD}) and the direct estimates from MODIS data using the calibrated temperature and greenness (TG) model were evaluated using tower-based measurements (WUE_{EC}). In general, WUE_{EC} was overly predicted at the start and end of the vegetation period and badly underestimated during the summertime by WUE_{MOD} because of the discrepancy in GPP_{MOD} . However, the proposed TG model provided substantially good estimates of ecosystem WUE in spite of lacking skills in monitoring summer troughs. Independent validation at four additional sites further certified the improvement, which provided a new framework for quantifying the seasonal variations in ecosystem WUE.

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1. Introduction

Water-use efficiency (WUE) defined as the ratio of carbon uptake during plant photosynthesis to water loss through

evapotranspiration, has been widely recognized as an important linkage coupling the global carbon and water cycles in terrestrial ecosystems (Beer et al., 2009; Niu et al., 2011). Water availability is the primary limiting factor for plant growth in more than 40% of vegetated areas, while another 33% of the area is limited by cold temperature and frozen soil (Nemani et al., 2003). The exchanges of both CO₂ and water vapor between the biosphere and atmosphere are controlled by stomatal aperture for leaf-level WUE (Cowan, 1977; Farquhar and Sharkey, 1982), while ecosystem-level WUE varies among plant properties and environmental conditions (Keenan et al., 2013; Zhou et al., 2014). Because of its importance as a functional parameter in ecosystem models, several studies have used a known WUE to predict terrestrial gross primary production (GPP) from the measured evapotranspiration (ET) for specific ecosystem (Zhang et al., 2012; Yang et al., 2014). Therefore, the successful applications of these models to a certain degree rely on the performance of ecosystem WUE estimation.

Abbreviations: MODIS, moderate resolution imaging spectrometer; GPP, gross primary production by vegetation photosynthesis; ET, evapotranspiration; WUE, ecosystem water-use efficiency; TG, temperature and greenness model developed in this study; WUE_{EC} , *in situ* measurements of WUE using eddy covariance technique; WUE_{MOD} , indirect WUE estimates from MODIS GPP and ET products; WUE_{TG} , WUE estimates using the developed TG model; GPP_{EC} , GPP derived from the eddy covariance measurements; GPP_{MOD} , GPP product from MOD17A2 by Zhao et al.; ET_{EC} , ET derived from the eddy covariance measurements; ET_{MOD} , ET product from MOD16A2 by Mu et al.; NEE, net ecosystem carbon exchange from eddy covariance measurements; EVI, enhanced vegetation index; LST, land surface temperature; LAI, leaf area index; R_g , solar radiation; T_a , air temperature; VPD, vapor pressure deficit; P, natural precipitation.

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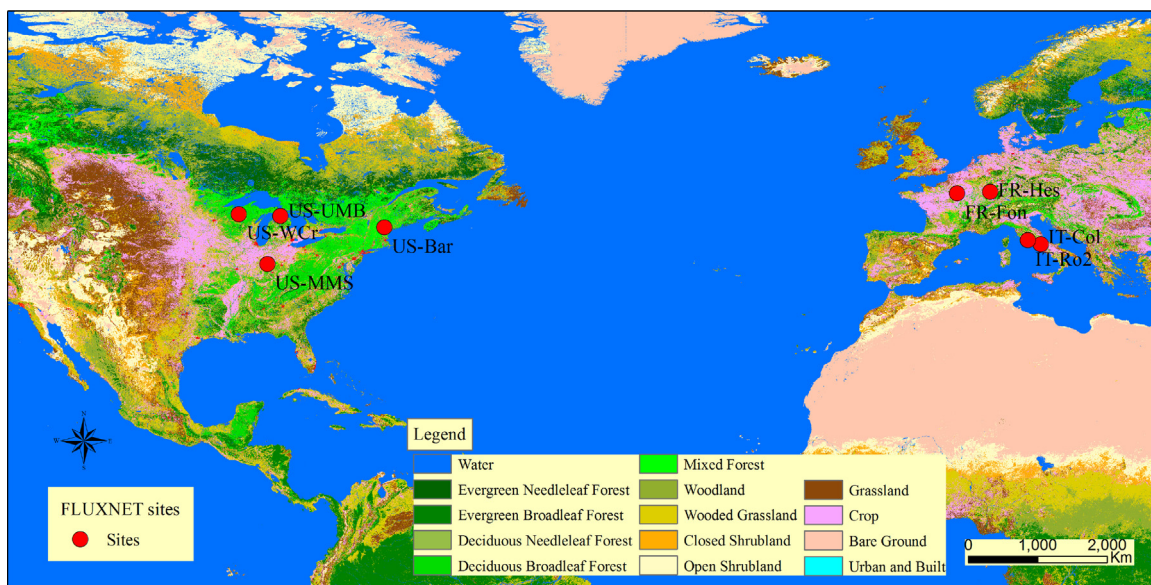


Fig. 1. Geographic locations of the FLUXNET sites.

With the development of eddy covariance technique, long-term and continuous measurements of WUE have become available in recent decades (Law et al., 2002; Yu et al., 2008). It directly measures the carbon and water fluxes at the landscape scale across varied times scales from hours to years (Baldocchi et al., 2001). Nevertheless, tower-based observations are spatially limited for adequate sampling of natural ecosystems. The spatiotemporal variability of WUE in large areas has been rarely quantified mainly owing to the complicated interactions between water and carbon as well as the uncertainty in the interactive influences of multiple environmental controls (Tian et al., 2010; Tang et al., 2015a). Although it can be estimated using empirical models driven by highly-related meteorological inputs (Wang et al., 2007; Beer et al., 2009; Yang et al., 2013a), it is worthwhile exploring methods to quantify WUE entirely from remotely sensed information as this could greatly reduce the difficulty in acquiring infrequently meteorological data. Hence, how to extrapolate site-level WUE to large areas remains a challenge.

Remote sensing techniques have been used to estimate GPP and ET with high spatial and temporal coverage (Sobrino et al., 2007; Wu et al., 2010; Donohue et al., 2014; Yang et al., 2013a, 2014), as both photosynthesis and evapotranspiration are closely related to biophysical properties and environmental factors (Zhang et al., 2009; Reichstein et al., 2014). By means of MODIS GPP and ET products, large-scale ecosystem WUE can be calculated by dividing GPP with ET as defined (Sur and Choi, 2013). Although Tang et al. (2014) used these products to evaluate the distribution and changes in the global WUE of terrestrial ecosystems at the annual time scale, the

consistency with tower-based WUE on short time scales remains unclear. Accurate monitoring of seasonal variations in WUE will greatly improve our understanding of the climate change–carbon cycle feedback. Additionally, alternative methods involving direct estimation of WUE from satellite data are needed.

Temperate deciduous forests occupy a substantial proportion of world forests and have been identified as an important sink for storing atmospheric CO₂ as well as mitigating climate change. In this study, our objectives are: (i) to explore the underlying mechanisms of environmental/biological factors that affect the seasonal variations in WUE; (ii) to examine the performance of MODIS WUE estimates from GPP and ET products in capturing seasonal dynamics of tower-based WUE and the possible error source; and (iii) to propose a new method directly based on the remotely sensed data.

2. Materials and methods

2.1. Study sites description

Our analysis is based on climate and flux data from a total of 8 AmeriFlux and EuroFlux sites where temperate deciduous forests mainly occupy in the Northern Hemisphere (Fig. 1). These sites also represent considerable variations in geographical location, microclimate condition, stand age, and species composition. The information including site name, latitude/longitude, tree age, maximum leaf area index (LAI), years of data used, and references are summarized in Table 1. The calibration data set comprises four sites in the eastern United States and mid-western Europe. FR-Hes is

Table 1
Characteristics of the flux tower sites used in this study.

Sites	Latitude	Longitude	Stand age	LAI	Year used	Reference
<i>Calibration sites</i>						
FR-Hes	48.674° N	7.066° E	~35 yr	7.6	2004–2006	Granier et al. (2000)
US-MMS	39.323° N	86.413° W	~70 yr	4.6	2004–2006	Schmid et al. (2000)
US-UMB	45.560° N	84.714° W	79–90 yr	3.7	2004–2006	Gough et al. (2008)
IT-Col	41.849° N	13.588° E	114 yr	5.5	2005, 2007–2008	Valentini et al. (1996)
<i>Validation sites</i>						
IT-Ro2	42.390° N	11.920° E	15 yr	3.9	2006	Tedeschi et al. (2006)
US-WCr	45.806° N	90.080° W	55–90 yr	5.3	2006	Desai et al. (2005)
US-Bar	44.065° N	71.288° W	~99 yr	4.5	2006	Jenkins et al. (2007)
FR-Fon	48.476° N	2.780° E	100–150 yr	5.1	2007	Kuppel et al. (2012)

a young beech forest. The stand is mainly composed of naturally established beech (*Fagus sylvatica* L.), but also contains scattered *Carpinus betulus* L., *Betula pendula* Roth, *Quercus petraea* (Matt.) Liebl., *Larix decidua* Mill., *Prunus avium* L. and *Fraxinus excelsior* L. The experimental plot of US-MMS is primarily covered by a secondary successional broadleaf forest within the maple-beech to oak-hickory transition zone of the eastern deciduous forest, nearly 3/4 of which are sugar maple (*Acer saccharum*), tulip poplar (*Liriodendron tulipifera*), sassafras (*Sassafras albidum*), white oak (*Quercus alba*), and black oak (*Quercus nigra*). The University of Michigan Biological Station (US-UMB) site is located within a protected forest owned by the University of Michigan. The arboreal composition of the forest consists of mid-aged northern hardwoods, aspen, and old-growth hemlock. The montane deciduous forest site (IT-Col) is a mature natural-origin stands, with *Fagus sylvatica* L. as the dominant tree specie.

The validation data set comprises four additional flux sites that are widely distributed in the major areas of temperate deciduous forests and subject to various management regimes. The climate of IT-Ro2 is Mediterranean with a drought period in summer of approximately 2 months. *Quercus cerris* L. is the dominant overstorey species, but *Q. pubescens* L., *Q. suber* L. and *Q. ilex* L. also sporadically occurs. US-WCr is located in the upland mature deciduous forests of the Chequamegon–Nicollet National Forest and supervised by the USDA-Forest Service. This site primarily consists of sugar maple (*Acer saccharum* Marsh.; 68%), American basswood (*Tilia americana* L.; 24%) and green ash (*Fraxinus pennsylvanica* Marsh.; 8%). The Bartlett Experimental Forest site (US-Bar) lies in the White Mountains National Forest in New Hampshire of USA. Plants are dominated by northern hardwoods such as American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), with some red maple (*Acer rubrum*) and paper birch (*Betula papyrifera*). The experiment plot of FR-Fon is a managed mature oak forest (*Quercus petraea* L., 100–150 years old) with a dense understorey of coppiced hornbeam (*Carpinus betulus* L.). These sites are used to verify the performance of the developed model.

2.2. Site-specific climate and flux data

Tower-based measurements of CO₂, H₂O, energy and routine meteorological variables at these forest sites were obtained from the FLUXNET community, a network coordinating global analyses of observations from micrometeorological technique (Baldocchi et al., 2001). It provides continuous site-specific climate and flux data at the ecosystem scale with various levels of data. The level-4 weekly product in this study consists of the meteorological variables including global solar radiation (R_g), air temperature (T_a), vapor pressure deficit (VPD) and precipitation (P), as well as measurements of canopy-scale water vapor flux (LE) and GPP estimates derived from CO₂ fluxes. The original CO₂ flux data (NEE) are gap-filled using the marginal distribution sampling (MDS) and artificial neural network (ANN) methods, respectively. The ANN method is generally superior to the MDS method (Papale and Valentini, 2003; Reichstein et al., 2005; Tang et al., 2012a). Therefore, the gap-filled NEE and GPP data based on the ANN method are used in this study. Data were quality checked and gaps resulting from system failure or data rejection were filled using standardized methods to provide complete and standardized data sets (Reichstein et al., 2005; Moffat et al., 2007). Three years of data for each calibration site and one-year data for each validation site were used for analyses (Table 1).

WUE can be calculated in various ways based on scientific disciplines and the temporal and spatial scales of interest (Kuglitsch et al., 2008; Zhou et al., 2014). Here we used the ecosystem-level definition (WUE; g C kg⁻¹ H₂O) as the ratio of 8-day GPP to ET (Law et al., 2002; Hu et al., 2008). The measured latent heat (LE;

w/m²) fluxes were used to determine water loss (ET; mm/day) by multiplying a factor of 0.035 with the formula $ET = LE/\lambda$ (λ represented the amount of energy to evaporate a unit weight of water, 2,454,000 J kg⁻¹).

2.3. MODIS products and processing

MODIS-based estimates of terrestrial GPP and ET have been developed and continuously improved over the past decade (Yang et al., 2013a; Tang et al., 2014). The previous Collection 4 GPP product presents several errors because of problems in the upstream inputs. Zhao et al. (2005) improved the data processing methods and modified the parameters in the algorithm used to generate the improved Collection 5 MOD17 product. The 8-day composite 1 km fraction of photosynthetically active radiation (FPAR) and LAI data from the MODIS sensor were used as remotely sensed vegetation property for dynamic inputs to the algorithm. Data gaps in the 8-day temporal MODIS FPAR/LAI caused by cloudiness were filled with information from accompanying quality assessment flags. For the daily meteorological data required, 6-hourly reanalysis II data of the National Center for Environmental Prediction/Department of Energy (NCEP/DOE) were implemented. Monthly and annual GPP averages were derived by summing up each 8-day period. Mu et al. (2011) also improved a satellite remote sensing-based ET algorithm to assess global terrestrial ET by using MODIS and global meteorology data. The process employed were as follows: (1) simplifying the calculation of vegetation cover fraction; (2) calculating ET as the sum of daytime and nighttime components; (3) adding soil heat flux calculation; (4) improving estimates of stomatal conductance, aerodynamic resistance and boundary layer resistance; (5) separating dry canopy surface from the wet; and (6) dividing soil surface into saturated wet and moist surfaces. Both MODIS GPP and ET products at 8-day time scale can be freely downloaded from <http://www.nts.gov/umt.edu/project>. Ecosystem WUE can be indirectly acquired by dividing MODIS GPP with ET.

Moreover, the 8-day Land Surface Reflectance (MOD09A1, with a resolution of 500 m) and Land Surface Temperature/Emissivity (LST-MOD11A2 & MYD11A2, with a resolution of 1 km) data from one MODIS pixel where these flux tower sites lay, were downloaded from the Oak Ridge National Laboratory's Distributed Active Archive Center website (<http://daac.ornl.gov/MODIS/>). Reflectance values of three spectral bands (blue, red, and near infrared (841–875 nm)) were used to calculate the enhanced vegetation index (EVI) developed by Huete et al. (2002). It is defined as:

$$EVI = 2.5 \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + (6\rho_{red} - 7.5\rho_{blue}) + 1} \quad (1)$$

where ρ_{nir} , ρ_{red} , and ρ_{blue} are the spectral reflectance in MODIS bands 2, 1 and 3, respectively. Cloudy observations in vegetation index were gap-filled using a simple gap-filling method and the cloud quality flag in the surface reflectance files (Xiao et al., 2003). Chen et al. (2015) suggested that a reasonable representation of vegetation phenology and biophysical processes in ecosystem models was helpful to accurately simulate land surface exchanges. Thus, the phenological information of each site-year was also extracted from the time-series MODIS EVI data to distinguish the growing and dormant seasons. The processing procedure has been described in detail by Tang et al. (2013). The MODIS LST products provide spatial estimates of the near-surface temperature with two sets of data named LST-Day and LST-Night. The frequency of acquisition can be up to 4 times per day if Terra and Aqua data were combined (Hachem et al., 2012). Notably, LST here represents the mean daily value of LST-Day and LST-Night to match the ground-based air temperature (T_a). MYD11A2 was used to fill the missing LST values of MOD11A2.

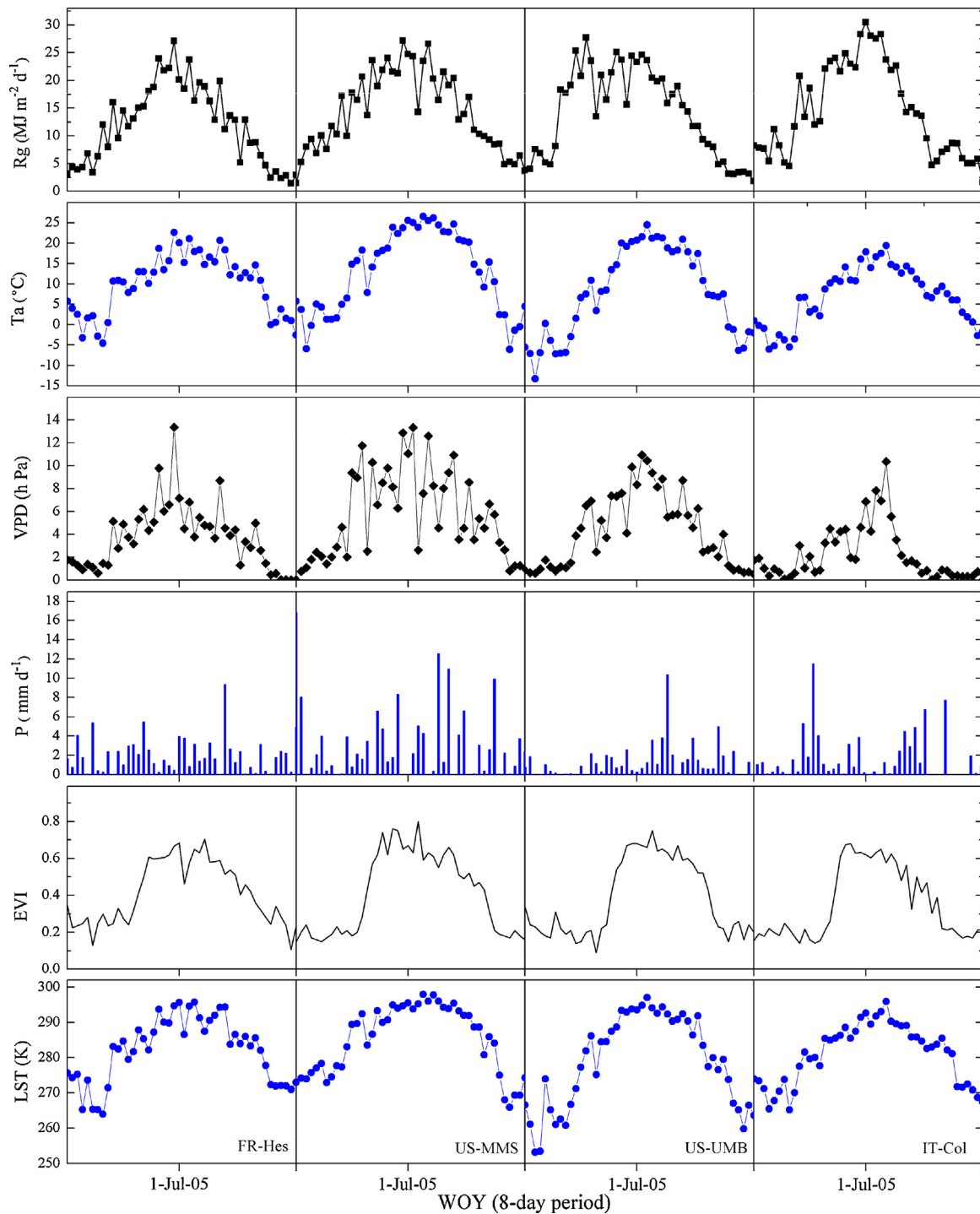


Fig. 2. Seasonal variations of solar radiation (R_g), air temperature (T_a), vapor pressure deficit (VPD), precipitation (P), MODIS-derived vegetation index (EVI) and land surface temperature (LST) observed at the four flux tower calibration sites of temperate deciduous forests during the period of 2005.

2.4. Statistical analysis

The MODIS observation periods are consistent with tower-based measurements for comparison. Firstly, the performance of MODIS-derived WUE estimates from time-series GPP and ET products was examined to determine the variability in ecosystem WUE. Pearson's correlation analysis was then conducted to explore the regulatory mechanisms between ecosystem WUE and controlling environmental/biophysical factors for temperate deciduous forests. Based

on analysis results, this study aims to propose an alternative method to track the temporal changes in ecosystem WUE by exclusive use of remotely sensed data. In order to explore the potential of upscaling tower-based measurements to large scales, the robustness of the calibrated model was tested at four additional forest sites. Model performance was comprehensively evaluated using coefficient of determination (R^2), root mean squared error (RMSE), scatter plot comparison, and seasonal variations in predicted WUE against *in situ* WUE.

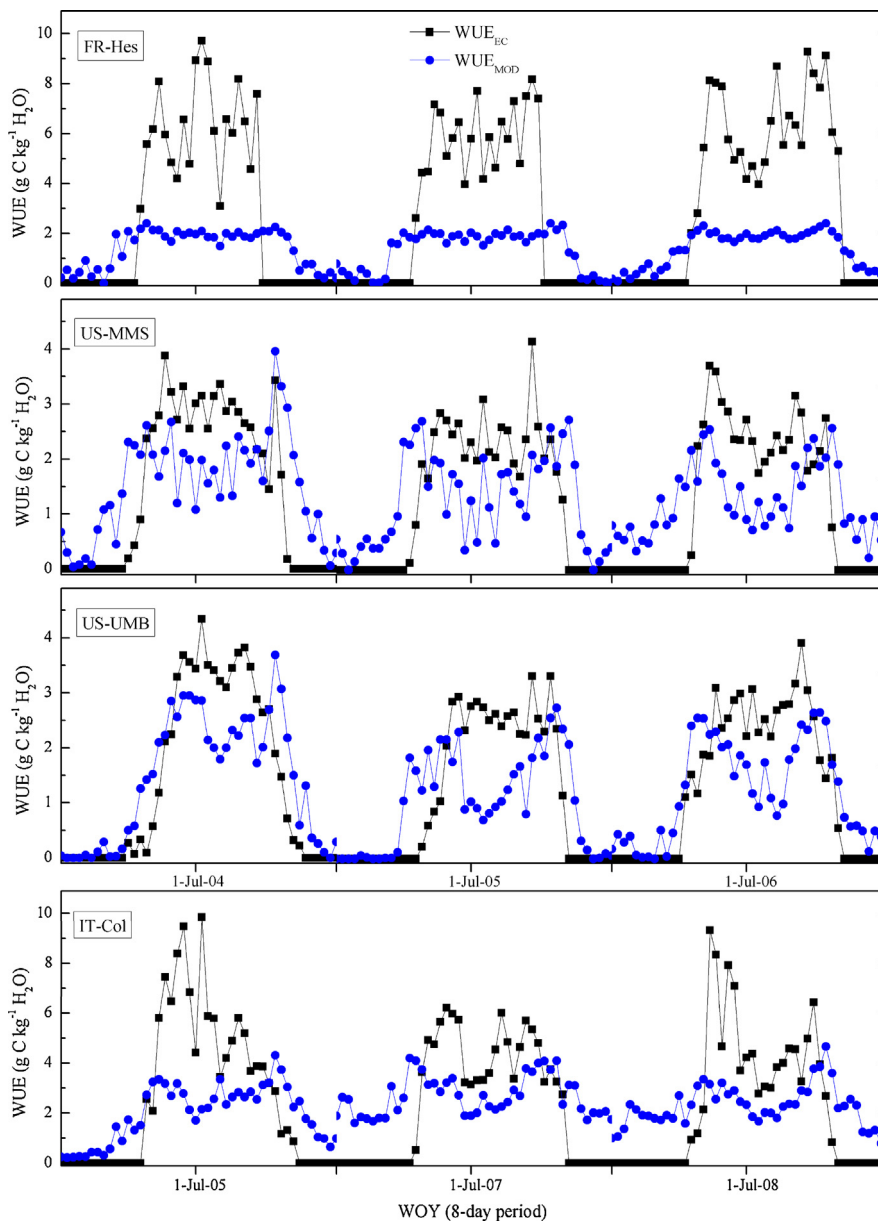


Fig. 3. Seasonal dynamics of 8-day ecosystem water use efficiency from tower-based measurements (WUE_{EC}) and the indirect satellite-based estimates from MODIS GPP and ET products (WUE_{MOD}) at the four flux tower calibration sites of temperate deciduous forests in Table 1.

3. Results

3.1. Seasonal variations in ecosystem WUE with environmental/biological controls

The latitudinal span of these flux tower sites is about 10° from the south to the north. Characteristics of local climate directly affect plant growth and ecosystem functions related to gas and energy exchanges (Desai et al., 2008; Hu et al., 2008; Reichstein et al., 2014). Thus, it is necessary to explore how ecosystem WUE of temperate deciduous forests correlated with these environmental and biological controls. Seasonal variations in 8-day WUE derived from flux measurements (WUE_{EC}) with the meteorological conditions including R_g , T_a , VPD, P and the MODIS-derived parameters—EVI and LST at the four calibration sites were illustrated in Figs. 2 and 3. The physical performance of these biotic and abiotic factors explaining the variability in WUE was also examined using Pearson's correlation analysis (Table 2).

Time-series WUE dynamics demonstrated the distinct seasonal patterns that strongly covaried with T_a , R_g and VPD. At the 8-day time scale, the strongest correlation was found in T_a , followed by R_g and VPD, and the weakest in P . During the dormant periods, the canopy was nearly bare. Low temperature and frozen soils hindered the plant growth and photosynthetic activities, and WUE values were nearly zero. As temperature rose and leaves flushed, vegetation began to grow and ecosystem photosynthesis capability gradually increased accompanying by plant transpiration with an abrupt increase in WUE. Consequently, ecosystem WUE retained high values nearly throughout the vegetation season. However, a trough was found during the peak period of deciduous forests at certain site-years such as IT-Col, which was partly explained by the driest summer months. Reichstein et al. (2002) also found a similar pattern in WUE at three Mediterranean evergreen forest sites with the maximum in winter and the minimum in the peak vegetative season, and they attributed it to the effects of drought. Although natural rainfall is vital to plant growth as the only water supply, the

Table 2
Correlation analysis between ecosystem water-use efficiency and the controlling environmental/biophysical factors at the four flux tower sites of temperate deciduous forests.

	Site	GPP ($\text{g C m}^{-2} \text{ d}^{-1}$)	ET (mm d^{-1})	R_g ($\text{MJ m}^{-2} \text{ d}^{-1}$)	T_a ($^{\circ}\text{C}$)	VPD (hPa)	P (mm d^{-1})	LST (K)	EVI
WUE	FR-Hes	0.814**	0.646**	0.653**	0.722**	0.558**	0.182	0.719**	0.809**
	US-MMS	0.886**	0.806**	0.714**	0.797**	0.510**	0.078	0.787**	0.918**
	US-UMB	0.899**	0.863**	0.605**	0.867**	0.755**	0.226	0.837**	0.908**
	IT-Col	0.845**	0.610**	0.663**	0.696**	0.378**	–	0.685**	0.827**
	All	0.779**	0.503**	0.581**	0.636**	0.443**	0.066	0.618**	0.752**

** Correlation is significant at the 0.01 level.

seasonal patterns of P poorly agreed with ecosystem WUE. In comparison with T_a , MODIS-derived LST was in good agreement with WUE despite a slightly weaker correlation. As a proxy of vegetation response to the environmental factors, time-series MODIS EVI data exhibited consistent variability in WUE and reflected the seasonal cycles. The correlation coefficients at four forest sites ranged from 0.809 to 0.918, which indicated the great potential of remotely quantifying seasonal variations in WUE by using MODIS EVI data. If combined together, it reached up to 0.752. These coincident variations favored high efficiency of water consumption. Previous findings also proved that MODIS data can be effectively applied to monitor GPP and ET dynamics in forests (Desai et al., 2008; Yang et al., 2013a), crops (Glenn et al., 2011; Wagie et al., 2015), and grasslands (Niu et al., 2011; Zhu et al., 2014).

3.2. Quantification of the variability in WUE from satellite remote sensing data

3.2.1. Indirect MODIS WUE estimates from GPP and ET products

Ecosystem WUE can be indirectly estimated by dividing MODIS GPP with ET product. Nevertheless, few studies have certified its performance at the 8-day time scale. Fig. 3 exhibited the consistency between WUE_{MOD} and WUE_{EC} at the four calibration sites. As WUE_{EC} changes, WUE_{MOD} only captured the broad trend with two pronounced biases at all sites. These estimates significantly

overpredicted WUE_{EC} at the beginning and end of the vegetation seasons. Conversely, ecosystem WUE throughout the summertime was poorly underestimated, which was particularly remarkable for FR-Hes with a nearly constant value about $2 \text{ g C kg}^{-1} \text{ H}_2\text{O}$. Compared with WUE_{EC} , WUE_{MOD} fluctuated more severely during the peak periods at US-MMS and US-UMB. However, WUE_{EC} showed the maximum at the onset of summertime which was not well captured by WUE_{MOD} at IT-Col. Therefore, an alternative method was needed to accurately monitor ecosystem dynamics of WUE.

3.2.2. A novel method to estimate WUE by exclusive use of time-series MODIS data

Correlations between ecosystem WUE with MODIS-derived EVI and LST data indicated the potential of predicting WUE_{EC} of temperate deciduous forest by using these remotely sensed variables. This study aimed to propose a general model to extrapolate site-level observations to different time and space scales. Therefore, a simple linear temperature and greenness (TG) model was developed using a combination of 8-day MODIS EVI and LST products. Then, ecosystem WUE of temperate deciduous forests can be calculated using Eq. (2) as follows:

$$\text{WUE}_{\text{TG}} = -10.16 \pm 3.18 + 8.14 \pm 0.57 \times \text{EVI} + 0.032 \pm 0.012 \times \text{LST} \quad (2)$$

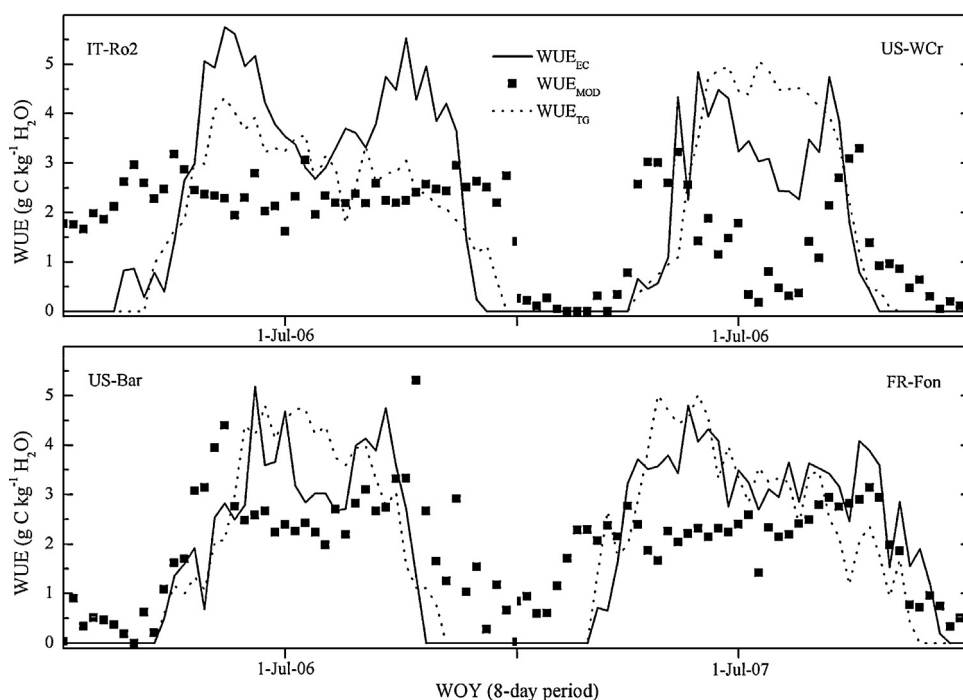


Fig. 4. Multiple comparisons of temporal changes in 8-day ecosystem water use efficiency from tower-based measurements (WUE_{EC}), the indirect predictions from MODIS GPP and ET products (WUE_{MOD}), and the direct estimates on the use of MODIS EVI and LST data (WUE_{TG}) at the four flux tower validation sites.

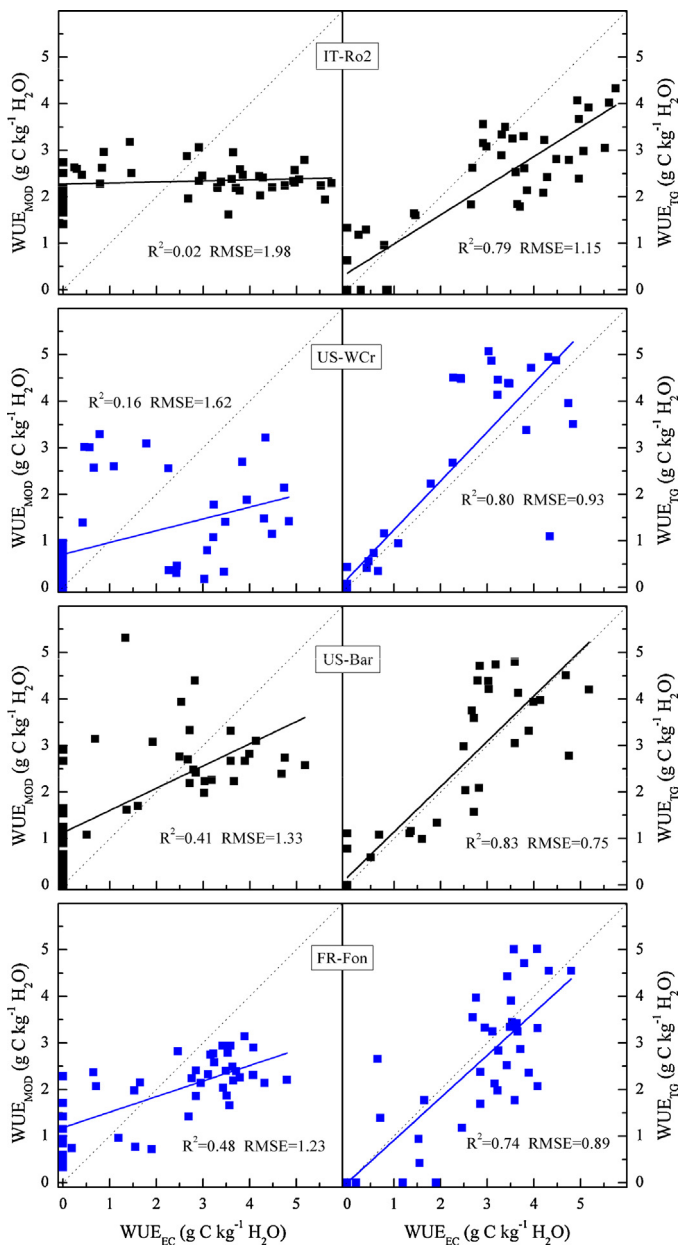


Fig. 5. Scatter plot of relationships between 8-day tower-based ecosystem water use efficiency with the indirect predictions from MODIS GPP and ET products (WUE_{MOD}), and the direct estimates on the use of MODIS EVI and LST data (WUE_{TG}) at the four flux tower validation sites.

As the performance of the calibrated model to other deciduous forests directly affected spatial upscaling, tower-based measurements of carbon and water fluxes at four additional flux sites were used for independent validation.

As shown in Figs. 4 and 5, overall, the proposed model estimated 8-day ecosystem WUE reasonably well with reference to tower-based measurements. The scatter plots between WUE_{TG} and WUE_{EC} also exhibited a nearly linear relationship. At the four validation sites, R^2 ranged from 0.74 to 0.83 and RMSE values were found between 0.75 and $1.15 \text{ g C kg}^{-1} \text{ H}_2\text{O}$. The TG model performed a significant potential to monitor seasonal variations in ecosystem WUE of temperate deciduous forests. However, few periods of 8-day WUE_{EC} were slightly underestimated during the vegetation season and the typical feature of summer trough in ecosystem WUE was insufficiently captured. Nevertheless, WUE_{MOD} behaved badly

across the four sites. The corresponding R^2 and RMSE ranged from 0.02 to 0.48 and 1.23 to $1.98 \text{ g C kg}^{-1} \text{ H}_2\text{O}$, respectively. Therefore, compared with WUE_{MOD} , WUE_{TG} provided substantially better WUE estimates of temperate deciduous forests and could be used as a new framework for regional extrapolation.

4. Discussion and conclusion

With global environmental issues such as changes in climate and land use/land cover, carbon and water cycles must be deeply understood to propose appropriate ecosystem management (Piao et al., 2007; Chapin et al., 2010; Ito and Inatomi, 2012) and for ecohydrology, which is recently developed interdisciplinary research field. Despite the encouraging performance of the TG model in monitoring the seasonal dynamics in ecosystem WUE of temperate deciduous forests, these WUE estimates still contain plenty of uncertainties and much efforts is needed for improvement.

4.1. Uncertainties in MODIS GPP and ET products

Although remote sensing is the only method that can be used to upscale carbon and water cycles, owing to the defects in the algorithm of MODIS GPP and ET themselves, the indirect WUE estimation remains unsatisfactory. In addition, even WUE_{MOD} performs well at the annual time scale, the compensating errors may be serious at short periods (Figs. 2 and 3). Thus, ongoing examination of GPP and ET products is needed to improve the 8-day variations in ecosystem WUE.

This study revealed that large uncertainties existed in the coupling processes using MODIS GPP and ET products. Such uncertainties can be attributed to the algorithm, various upstream inputs, and biome-specific parameters stored in the Biome Properties Look-Up Table (Yang et al., 2013b, 2015; Tang et al., 2015b). Further analysis must be performed to determine whether GPP or ET contributed more to the observed discrepancies in ecosystem WUE. Therefore, the seasonal patterns of GPP and ET from flux measurements and the MODIS estimates were compared to explore the possible reasons. As shown in Fig. 6, in general, GPP_{MOD} showed a poor agreement whereas ET_{MOD} performed relatively well at the four forest sites except several 8-day periods. Previous studies also confirmed the reliable ET_{MOD} for croplands relying completely on rainfall (Cammalleri et al., 2014; Tang et al., 2015a) and evergreen forests (Liu et al., 2015). The large underestimation of GPP_{MOD} during the vegetation periods may lead to a similar pattern in ecosystem WUE. Fig. 7 illustrated the overall potential of WUE when using both MODIS-derived and tower-based GPP and ET estimates. The strong correlation between GPP and ET across sites demonstrated that carbon and water cycles were tightly coupled. In fact, the slope of the relationship can also be an indicator. Ecosystem WUE across the four sites ranged from 3.31 to $3.77 \text{ g C kg}^{-1} \text{ H}_2\text{O}$ with no apparent distinction. However, the potential was monitored poorly for US-WCr, followed by FR-Fon and IT-Ro2, and relatively satisfactory at US-Bar. The strong positive relationship between ET and GPP implied that higher ET corresponded to a higher carbon uptake of GPP, which also provided possibility to estimate GPP by ET with accurate ecosystem WUE.

4.2. Uncertainties in the MODIS WUE estimates from the TG model

The present study showed the skill in monitoring the variability in ecosystem WUE by exclusive use of time-series MODIS EVI and LST data. However, it remains challenging for accurately predicting the response of WUE to extreme climate events, which was ascribed to the incomplete representation of actual carbon and

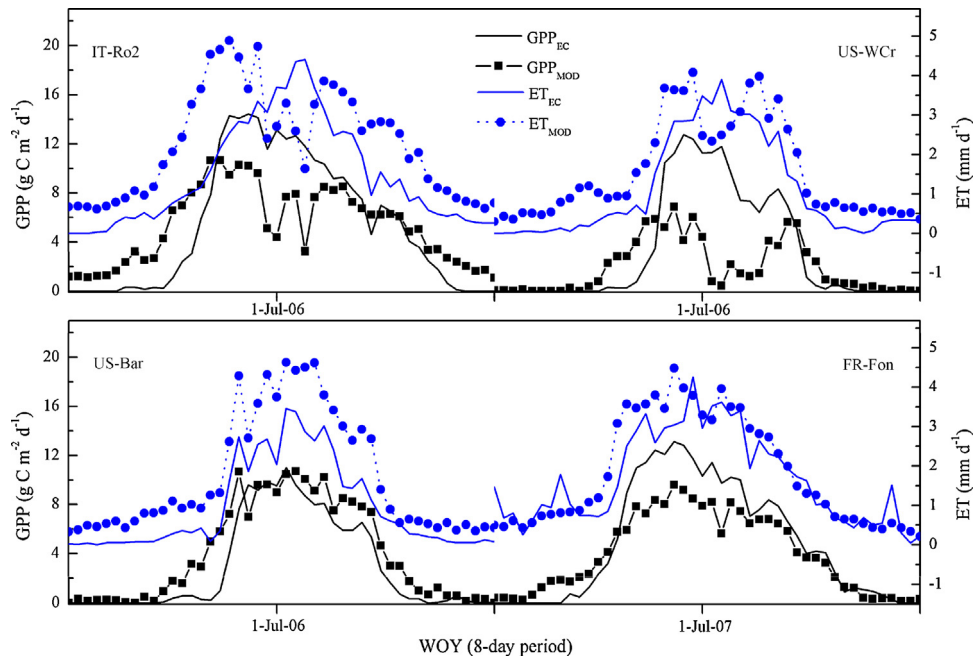


Fig. 6. Seasonal dynamics in 8-day GPP and ET between tower-based measurements (GPP_{EC} , ET_{EC}) and the corresponding MODIS estimates (GPP_{MOD} , ET_{MOD}) at the four flux tower validation sites.

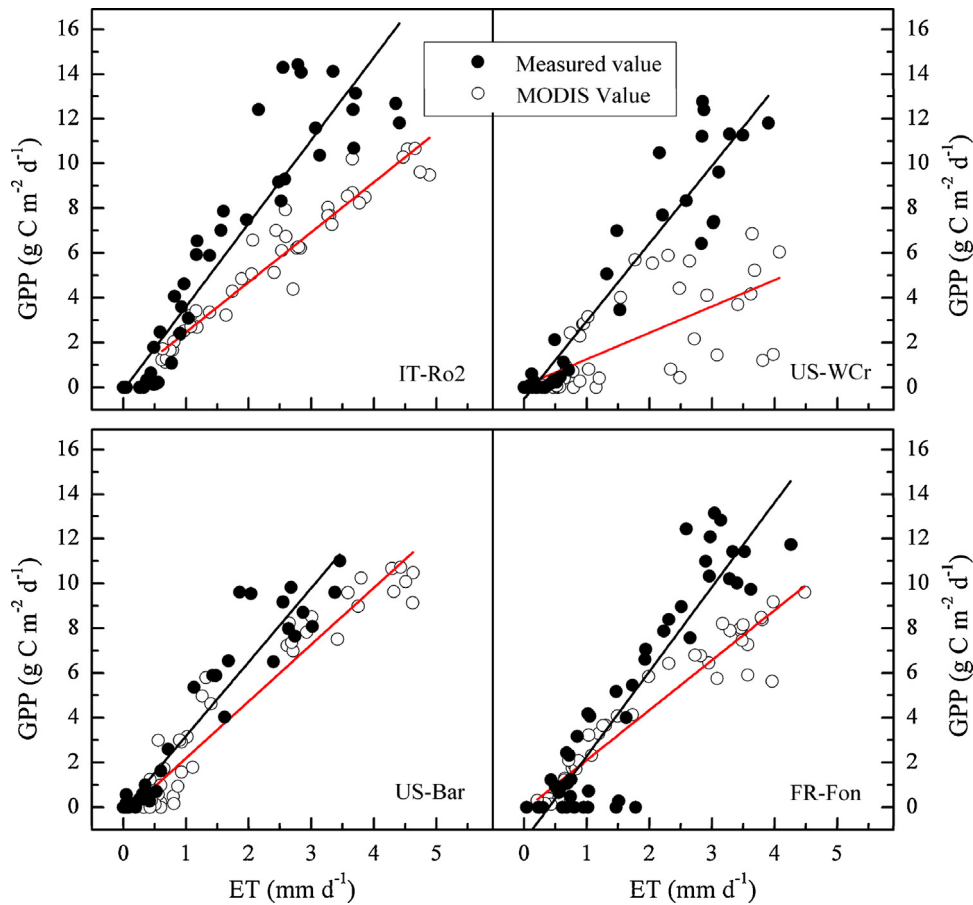


Fig. 7. The relationships between tower-based and MODIS-derived GPP and ET products for the four flux tower validation sites. The slope of the relationship can also be considered as an indicator of ecosystem WUE.

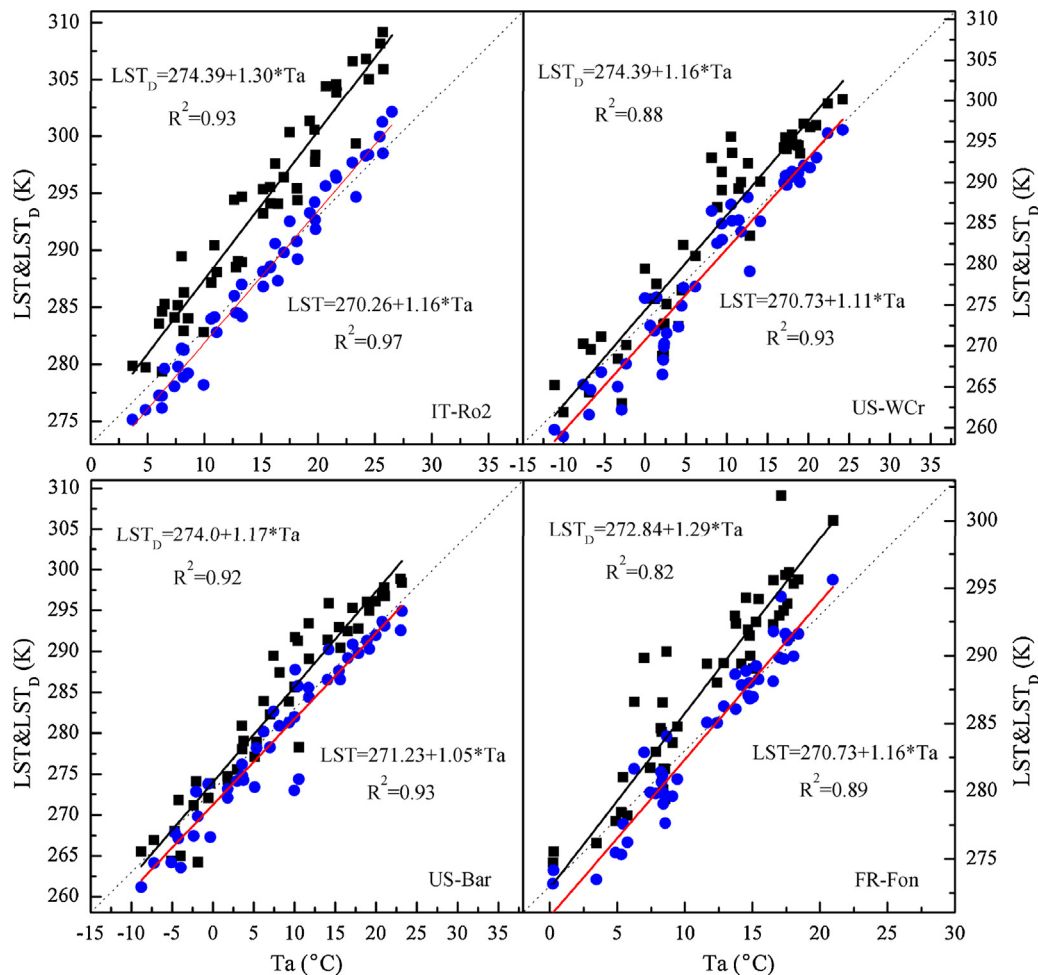


Fig. 8. A linear comparison between observed air temperature (T_a) with MODIS-based LST (combined Terra/Aqua daytime/nighttime acquisitions) and LST_D (combined Terra/Aqua daytime acquisitions).

water cycles, parameters and states in models (Abramowitz and Pitman, 2007). WUE represents interactions between the carbon and water cycles at leaf to ecosystem scales. GPP is controlled by canopy development, nutrient status, sunlight, temperature, ambient humidity, CO₂ concentration, and soil moisture (Zhang et al., 2009; Moreno et al., 2012). ET is the total water vapor flux consisting of evaporation from soil, plant transpiration and evaporation of the intercepted rainfall. It is a complex process related to many variables including relative humidity, temperature, wind speed, soil water content and vegetation status (Wilson and Baldocchi, 2000; Yang et al., 2010; Romaguera et al., 2014). Thus, the use of subsets of these factors to determine the variability in ecosystem WUE, which is typical for the developed model, may limit the precision. There have been considerable interests in using satellite-based LST measurements for explaining biological, hydrological and climatological systems (Sims et al., 2008; Tang et al., 2012b; Wu et al., 2014). LST has also been shown closely related to VPD (Hashimoto et al., 2008; Singh, 2010) and thus may provide a measure of drought stress. As shown in Fig. 8, LST-Day values (LST_D) tended to be generally higher than the mean daily T_a . Fortunately, the combination of Aqua and Terra LST-Day and LST-Night acquisitions into a mean daily value provided a large number of LST observations and a better overall agreement with T_a than LST_D only did. 8-day ground-based near-surface T_a and MODIS-derived LST product distributed closely around the 1:1 line with R^2 ranging from 0.89 to 0.97 at the four sites. This finding revealed a great potential for monitoring spatial variations of near-surface air temperature. Moreover,

Ricciuto et al. (2008) found that reproducing the dynamics of biogeochemical cycles in the transition seasons of spring and autumn was difficult and indicated that the main factors can be ascribed to rapid responses of vegetation growth to temperature change during periods of emergence and senescence. Muraoka et al. (2010) also examined the seasonal and interannual variations in forest canopy LAI that remarkably affected GPP, which suggested the importance of phenology when analyzing and predicting carbon fixation in forest ecosystems. However, the proposed TG model avoided this problem occurred by WUE_{MOD}, which may be correlated with the embedded phenological information in time-series EVI data.

4.3. Uncertainties in the tower-based measurements

Eddy covariance technique provides the optimal method to measure net CO₂ exchange and hydrothermal fluxes for GPP and ET calculation. However, these flux measurements also contained uncertainties including random error and systematic error (Scott et al., 2004; Dragoni et al., 2007). Ideally the systematic error can be amended, but in the case of EC measurements it is still constrained because of the limited understanding regarding various error sources and insufficient background data (Post et al., 2015). After all, GPP is not directly measured by EC tower but is inferred by partitioning NEE into GPP and ecosystem respiration through a light response curve approach (Lasslop et al., 2010). However, in some cases in which the above-canopy fluxes are decoupled from the surface, nighttime respiration may be underestimated and

consequently GPP was overestimated (Aubinet et al., 2002; Heinsch et al., 2006). In addition, Wu et al. (2005) compared ET estimates using the Bowen-ratio energy balance (BREB) method with ET measurements in a temperate mixed forest. The BREB-based estimates of ET were within 6% of the EC estimates over 1-month measurement period. Energy closure ratios is another way to assess validity with a usual range of 0.53–0.99 (Wilson et al., 2002).

Although the TG model is empirical and statistical, fairly good estimates of seasonal variations in ecosystem WUE are provided. Moreover, in many cases, it is far better than the complex MODIS WUE estimates from GPP and ET products, which requires a great number of meteorological and physiological parameters in addition to remote sensing data. Generally, the physical models are favorable for explaining the underlying mechanisms while the empirical models are convenient to extrapolate by the community. Work is ongoing to assess the TG model using more EC sites to develop a robust and general approach for terrestrial ecosystems.

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