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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.

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 CO_2 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 defect; P, natural precipitation.

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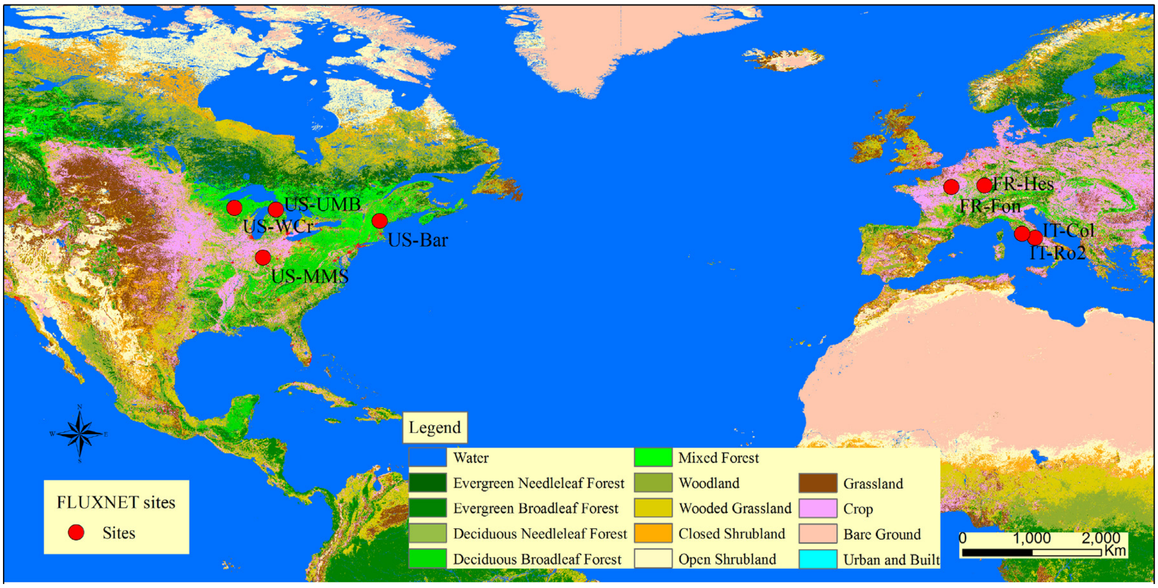

Fig. 1. Geographic locations of the FLUXNET sites.

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 CO_2 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
Calibration sites						
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)
Validation sites						
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)