Daily underlying water use efficiency for AmeriFlux sites

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Abstract Water use efficiency (WUE) is a crucial parameter to describe the interrelationship between gross primary production (GPP) and evapotranspiration (ET). Incorporating the nonlinear effect of vapor pressure deficit (VPD), underlying WUE (uWUE = GPP · VPD0.5/ET) is better than inherent WUE (IWUE = GPP · VPD/ET) at the half-hourly time scale. However, appropriateness of uWUE has not yet been evaluated at the daily time scale. To determine whether uWUE is better than IWUE, daily data for seven vegetation types from 34 AmeriFlux sites were used to validate uWUE at the daily time scale. First, daily mean VPD was shown to be a good substitute for the effective VPD that was required to preserve daily GPP totals. Second, an optimal exponent, \( k^* \), corresponding to the best linear relationship between GPP · VPD and ET, was about 0.55 both at half-hourly and daily time scales. Third, correlation coefficient between GPP · VPD and ET showed that uWUE (\( k = 0.5 \) and \( r = 0.85 \)) was a better approximation of the optimal WUE (\( k = k^* \) and \( r = 0.86 \)) than IWUE (\( k = 1 \) and \( r = 0.81 \)) at the daily scale. Finally, when yearly uWUE was used to predict daily GPP from daily ET and mean VPD, uWUE worked considerably better than IWUE. Comparing observed and predicted daily GPP, the average correlation coefficient and Nash-Sutcliffe coefficient of efficiency were 0.81 and 0.59, respectively, using yearly uWUE, and only 0.59 and ~ 0.83 using yearly IWUE. As a nearly optimal WUE, uWUE consistently outperformed IWUE and could be used to evaluate the effects of global warming and elevated atmosphere CO₂ on carbon assimilation and evapotranspiration.

1. Introduction

Water use efficiency (WUE), defined as the ratio of carbon gain through photosynthesis to water loss through transpiration, is a critical parameter to relate carbon assimilation and evapotranspiration at the ecosystem scale. Knowledge of water use efficiency would help understand the interrelationship between carbon and water cycles in terrestrial ecosystems, and provide valuable information on global carbon, water balance, and vegetation growth. Several empirical models of water use efficiency have been developed, as water use efficiency is correlated with some relatively stable environmental factors, such as water holding capacity of the soil and leaf area index (LAI) [Beer et al., 2007, 2009; Yang et al., 2013]. These models have been used to evaluate intersite variability of water use efficiency and predict regional gross primary production (GPP) and/or evapotranspiration (ET). Water use efficiency has also been used to evaluate the dynamic responses of ecosystems to climate change and elevated atmospheric CO₂ [Guo et al., 2010; Niu et al., 2011; Battipaglia et al., 2013; Keenan et al., 2013], and the responses have been simulated in several process-based ecosystem models [Cramer et al., 2001; Mo et al., 2005; Tian et al., 2010; Zhu et al., 2011; Akihiko and Motoko, 2012]. For example, Kauwe et al. [2013] used 11 ecosystem models such as GCM4, LPJ-GUESS, SDGVM to predict the CO₂ effect on water use efficiency. However, the impact of global change on terrestrial carbon sequestration is uncertain, and explanations of the increasing water use efficiency and declining vegetation growth with rising atmospheric CO₂ concentrations are less than adequate [Perelius et al., 2008, 2011; Andreu-Hayles et al., 2011; Nock et al., 2011; Lèvesque et al., 2014; Xu et al., 2014]. Thus, further researches into water use efficiency should be conducted to address these questions under global change.

The eddy covariance technique has promoted and facilitated research of water use efficiency at different time scales and among different vegetation types, and there are three different formulations of water use efficiency to describe the relationship between GPP and ET at the ecosystem scale, with the effect of vapor pressure deficit (VPD) incorporated in different ways (Table 1). Initially, water use efficiency (WUE) was used to quantify the trade-off between carbon assimilation and water transpiration [Cowan and Farquhar, 1977], and WUE was calculated as the ratio of GPP over ET. Yang et al. [2013] showed that GPP relates to
ET strongly and WUE remains generally invariant at the monthly time scale, whereas a large amount of research has demonstrated that WUE is strongly dependent on VPD at daily or smaller time scales [Abbate et al., 2004; Zhao et al., 2005; Hu et al., 2008]. Inherent water use efficiency (IWUE), derived from the diffusion processes of carbon dioxide and water vapor through stomata between leaves and the atmosphere, was proposed by Beer et al. [2009] to include the effect of VPD on WUE, and the IWUE was validated using data from 43 FluxNet sites across a range of vegetation types. By comparison, the relationship between GPP · VPD and ET is much stronger than that between GPP and ET in terms of the linear correlation coefficient, and IWUE is much less variable than WUE at the daily time scale [Beer et al., 2009]. However, IWUE is not entirely independent of VPD, and Zhou et al. [2014] showed that the relationship between GPP · VPD and ET is in fact significantly nonlinear. Underlying water use efficiency (uWUE), based on IWUE and a simple stomatal model of Lloyd and Farquhar [1994], is formulated to represent the best linear relationship among GPP, ET, and VPD at the half-hourly time scale. The uWUE is shown to be quite close to the optimal WUE by linear correlation analysis, and a linear relationship between GPP · VPD and ET is further supported by a hysteresis model using half-hourly data from 42 Ameriflux sites among seven vegetation types [Zhou et al., 2014]. The three different formulations of WUE are proposed and validated at different time scales, namely WUE at the monthly time scale, IWUE at the daily time scale, and uWUE at the half-hourly time scale (Table 1). An interesting question is whether there is a superior formulation that is appropriate and consistent at varying time scales. As the uWUE is shown to have a stronger linear relationship among GPP, ET, and VPD than WUE and IWUE at the half-hourly time scale, would the uWUE be a suitable and superior formulation when applied to the daily time scale? Water use efficiency at the daily time scale is of great importance and has been widely used in ecosystem vegetation growth models and the remote sensing products. Daily water use efficiency is also the foundation of annual water use efficiency, and the latter is crucial to evaluating the impact of global change on ecosystem water use efficiency in the long term.

A generic model of water use efficiency proposed in Zhou et al. [2014] can be used to explore the optimal relationship among GPP, ET, and VPD at different time scales.

\[
\gamma_{\text{ET}} = \frac{\text{GPP} \cdot \text{VPD}^k}{\text{ET}} \quad (1)
\]

where \(\gamma\) stands for WUE (\(\gamma\)), uWUE (\(\gamma_u\)), and IWUE (\(\gamma_i\)), when \(k\) equals to 0, 0.5, and 1, respectively. At each time scale, an optimal \(k\), henceforth expressed as \(k^*\), is defined as the exponent value in equation (1) that would result in the strongest linear relationship between GPP · VPD and ET in terms of the correlation coefficient. It is demonstrated that \(k^*\) is quite close to 0.5 and a constant value of \(k\) is appropriate at the half-hourly time scale [Zhou et al., 2014]. The question is whether \(k^*\) is scale invariant and an exponent of 0.5 is also suitable at the daily time scale. One of the most important issues with upscaling of water use efficiency is the representativeness of VPD at different time scales. While GPP and ET can be accumulated from half-hourly to daily time scales, VPD cannot. VPD is affected by temperature and relative humidity, and it remains relatively constant for each half hour but varies considerably during a day. Thus, it is important to determine a daily effective VPD that would maintain the same value of uWUE when GPP and ET are accumulated at the daily time scale. Such an effective VPD is required to interpret its effect on water use efficiency at the daily time scale and to quantify the changes in the relationship among GPP, ET, and VPD from half-hourly to daily time scales.

Another issue is how to assess the performance of different formulations of water use efficiency at the daily time scale, and such an assessment should, in our view, consider at least three aspects: (1) linearity among GPP, ET, and VPD; (2) variability of water use efficiency during a growth season; and (3) capacity to predict

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**Table 1. Various Formulations of Water Use Efficiency (WUE) at the Ecosystem Scale**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Formulation</th>
<th>Unit of Measurement</th>
<th>Time Scale</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WUE</td>
<td>(\gamma)</td>
<td>GPP/ET</td>
<td>g C/kg H₂O</td>
<td>Monthly</td>
</tr>
<tr>
<td>Inherent WUE</td>
<td>(\gamma_i)</td>
<td>GPP · VPD/ET</td>
<td>g C hPa/kg H₂O</td>
<td>Daily</td>
</tr>
<tr>
<td>Underlying WUE</td>
<td>(\gamma_u)</td>
<td>GPP · VPD⁰.⁵/ET</td>
<td>g C hPa⁰.⁵/kg H₂O</td>
<td>Half hourly</td>
</tr>
</tbody>
</table>

*The validated time scale for each formulation of WUE is given with a reference. GPP, Gross Primary Production in g C m⁻² d⁻¹; VPD, Vapor Pressure Deficit in hPa; ET, Evapotranspiration in kg H₂O m⁻² d⁻¹.*
daily GPP or ET from a constant water use efficiency. Consistency in water use efficiency implies that WUE is independent of a varying VPD to a large extent, and this is especially important for GPP or ET predictions. A constant water use efficiency for each site has been modeled as a function of two relatively stable environment properties, leaf area index (LAI) and water holding capacity of the soil, and such a constant water use efficiency is shown to be effective in predicting monthly ET and yearly GPP at a regional scale [Beer et al., 2007; Yang et al., 2013]. However, the performance of predicting daily GPP using constant water use efficiency for each site has not yet been evaluated. As crops do change from year to year at some sites, such as the mead-rainfed maize-soybean rotation site, it would be more appropriate to predict daily GPP using constant water use efficiency for each site year instead of a constant value for all years at the site.

The aim of this study was to determine whether the underlying water use efficiency, as defined in equation (1) with $k=0.5$, is superior and consistent at the daily time scale. Our specific objectives were (1) to test whether the effective VPD at the daily time scale could be replaced by the daily mean VPD in calculating water use efficiencies, (2) to evaluate the optimal water use efficiency formulation when applied to daily time scales, (3) to test whether the underlying water use efficiency is a better approximation of the optimal water use efficiency that relates GPP and VPD to ET in comparison of the inherent water use efficiency in terms of linear correlation coefficient and parameter variability at the daily time scale, and (4) to evaluate the prediction performance when the underlying water use efficiency at the annual time scale combined with daily ET and the mean VPD were used to predict daily GPP values.

2. Materials and Methods

2.1. Data

This research was based on half-hourly data from 34 AmeriFlux sites (Table S1 in the supporting information). There were seven vegetation types: cropland (CRO), deciduous broadleaf forest (DBF), grassland (GRA), evergreen needleleaf forest (ENF), woody savanna (WSA), mixed forest (MF), and closed shrubland (CSH) among the 34 sites. The record length for each site ranged from 1 to 13 years, and there were 123 site years in total considered in this study. Data sets provided as Level 4 products (http://public.ornl.gov/ameriflux) were used, including air temperature (°C), latent heat flux (W m⁻²), VPD (hPa), and estimates of GPP (g C m⁻² d⁻¹) derived from the CO₂ flux measurements. Half-hourly values of ET (kg H₂O m⁻² d⁻¹) were calculated from air temperature and latent heat flux, using the method of Donatelli et al. [2006]. The flux data measured using the eddy covariance technique were friction velocity (ustar) filtered, gap filled using quality flags of four categories, namely, the original, most reliable, medium, and least reliable [Reichstein et al., 2005].

The half-hourly data sets were processed and then aggregated to the daily time scale (midnight to midnight). The data processing was performed following four steps. First, defective entries and data on the rainy days and certain number of dry days after the rainy days were excluded. The number of dry days that were excluded depended on the daily precipitation (P) and potential evapotranspiration (PET). Two dry days following a rainy day were excluded when $P$ was larger than twice of PET, otherwise one dry day excluded when $P$ was larger than PET. Only the rainy days were excluded when $P$ was smaller than PET for the day. PET was calculated using the Priestley-Taylor equation [Priestley and Taylor, 1972]. Second, the half-hourly flux data were quality controlled, retaining only those entries with quality flags of the “original” and “most reliable.” Third, only daylight data from 5 A.M. to 9 P.M. were selected, and data with negative net solar radiation or negative GPP, ET, and VPD were excluded. Finally, the half-hourly data were used only for days when there were at least 24 entries and when the average half-hourly GPP for the day was at least 10% of the maximum half-hourly GPP for the site year. The half-hourly data of GPP and ET from available days were then accumulated to daily totals. In order to achieve the four objectives of the paper, the selected data were used as follows: (1) daily mean VPD and the effective VPD when $k$ equal to 0.5 and 1 were calculated to undertake the comparative analysis; (2) half-hourly and daily data on GPP, ET, and VPD were used to analyze the scale effect on water use efficiency; (3) daily GPP, ET, and VPD were used to evaluate the consistency of daily uWUE and IWUE values within a site year; and (4) yearly uWUE and IWUE values were calculated from daily GPP, ET, and VPD to compare their performances in predicting daily GPP values.
2.2. The Effective VPD From Half-Hourly to Daily Time Scales

2.2.1. Derivation of the Effective VPD

To derive a daily effective VPD, let ET\textsubscript{i}, GPP\textsubscript{i}, and VPD\textsubscript{i} be the half-hourly observations for time interval \(i\), and ET\textsubscript{d} and GPP\textsubscript{d} be the daily GPP and ET totals, respectively. That is
\[
ET_d = \sum ET_i \quad (2)
\]
\[
GPP_d = \sum GPP_i \quad (3)
\]
Applying equation (1) for each time interval and summing over all the time intervals in the day, we have
\[
\gamma ET_d = \sum \left[ GPP_i (VPD_i)^k \right] \quad (4)
\]
Let VPD\textsubscript{e} be such an effective VPD at the daily time scale that VPD\textsubscript{e} satisfies equation (1) at the daily time scale, i.e.,
\[
\gamma ET_d = GPP_d (VPD_e)^k \quad (5)
\]
A comparison of equations (4) and (5) would lead to an expression for the effective VPD as follows:
\[
VPD_e = \left[ \sum \frac{GPP_i (VPD_i)^k}{GPP_i} \right]^{\frac{1}{k}} \quad (6)
\]
Thus, an effective VPD should be derived from half-hourly GPP and VPD observations using equation (6), not from the mean VPD directly.

2.2.2. Comparison of the Effective VPD and the Mean VPD

Diurnal variations in GPP, ET, and VPD are similar during days with clear skies. The three variables all increase monotonically from sunrise to their peak values then decrease monotonically to sunset. However, a hysteresis phenomenon exists among their diurnal variations, that is, they reach their peak values at different times, which can be expressed by time lags [Mahecha et al., 2007; O’Grady et al., 2008; Pita et al., 2013]. In general, ET would reach its diurnal peak value at noon, GPP before noon, and VPD after it. The diurnal variations in the three variables and their time lags can be approximated by sinusoidal functions in a hysteresis model below [Zhang et al., 2014; Zhou et al., 2014].
\[
ET = ET_0 \sin(\omega t) \quad (7)
\]
\[
GPP = GPP_0 \sin(\omega t + \alpha) \quad (8)
\]
\[
VPD = VPD_0 \sin(\omega t - \beta) \quad (9)
\]
where \(\omega\) is a constant diurnal frequency for ET, GPP, and VPD, and the peak values of the three variables are ET\textsubscript{0}, GPP\textsubscript{0}, and VPD\textsubscript{0}, respectively. The time lag between ET and GPP is \(\alpha/\omega\), while that between VPD and ET is \(\beta/\omega\). The day time, \(t\), in equations (7)–(9), applies to half of the period, i.e., \(\pi/\omega\). In this paper, we assume that \(t\) starts at \(\beta/\omega\) and ends at \((\beta + \pi)/\omega\) when VPD is zero to ensure that day time VPD is always nonnegative during day time in the generic water use efficiency model (equation (1)).

Daily mean VPD, VPD\textsubscript{d}, can be derived from equation (9) in the hysteresis model.
\[
VPD_d = \frac{\int_{\beta/\omega}^{(\beta + \pi)/\omega} VPD_0 \sin(\omega t - \beta) dt}{\pi} = VPD_0 \frac{2}{\pi} \quad (10)
\]
The effective VPD at the daily time scale, as defined in equation (6), can also be derived from the hysteresis model.
\[
VPD_e = \left[ \frac{\int_{\beta/\omega}^{(\beta + \pi)/\omega} GPP_0 \sin(\omega t + \alpha) \cdot [VPD_0 \sin(\omega t - \beta)]^k dt}{\int_{\beta/\omega}^{(\beta + \pi)/\omega} GPP_0 \sin(\omega t + \alpha) dt} \right]^{\frac{1}{k}} \quad (11)
\]
Let \( I_1 \) be the numerator in equation (11), and \( I_2 \) be the denominator. Define a new variable of integration \( x \) as
\[
x = \left[ \sin(\omega t - \beta) \right]^k, \quad \text{with} \quad k > 0
\]
(12)
Note that as time, \( t \), varies from \( \beta/\omega \) to \( (\beta + \pi/2)/\omega \), and then to \( (\beta + \pi)/\omega \), \( x \) varies from 0 to 1 and then to 0 again. With trigonometric identities, evaluation of \( I_1 \) with respect to \( x \) results in
\[
I_1 = 2\cos(\alpha + \beta) \frac{\text{GPP}_0}{\omega} \frac{\text{VPD}_0}{\lambda} \int_0^1 \frac{x^2}{\sqrt{1 - x^2}} \, dx
\]
or simply
\[
I_1 = 2\cos(\alpha + \beta) \frac{\text{GPP}_0}{\omega} \frac{\text{VPD}_0}{\lambda} \int_0^1 \sqrt{1 - x^2} \, dx
\]
(13)
Evaluation of \( I_2 \) is straightforward:
\[
I_2 = \text{GPP}_0 \frac{2 \cos(\alpha + \beta)}{\omega}
\]
(14)
Combining equations (13) and (14), we can derive an analytic expression for the effective VPD in terms of its peak value, \( \text{VPD}_0 \), and the exponent \( k \) as follows:
\[
\text{VPD}_e = \text{VPD}_0 \left( \int_0^1 \sqrt{1 - x^2} \, dx \right)^{\frac{1}{k}}
\]
(15)
The ratio of the effective over mean VPD from equations (15) and (10) is given as
\[
\frac{\text{VPD}_e}{\text{VPD}_d} = \frac{\pi}{2} \left( \int_0^1 \sqrt{1 - x^2} \, dx \right)^{\frac{1}{k}}
\]
(16)
For \( k = 1 \), the ratio is exactly \( \pi^2/8 = 1.23 \). In general, the ratio needs to be evaluated numerically. As the exponent \( k \) varies from 0.001 to 1, the variation in the ratio is quite small, from 1.15 to 1.23, or \( < 7.0 \%) \) only. When \( k = 0.5 \), as in the case of the underlying water use efficiency, the ratio is 1.20. Assuming the hysteresis model, we have shown analytically that the ratio of \( \text{VPD}_e \) over \( \text{VPD}_d \) is a function of the exponent \( k \) only, and the ratio is practically constant for most values of \( k \). Thus, the effective VPD is essentially proportional to the daily mean VPD. We sought empirical support from observed relationship between the effective VPD and daily mean VPD, and proposed to use the daily mean VPD to predict GPP at the daily time scale using the underlying water use efficiency. In particular, we used a linear regression model through the origin:
\[
\text{VPD}_e = \lambda \text{VPD}_d
\]
(17)
to test whether the effective VPD and the daily mean VPD are well correlated and whether the daily mean VPD can be used instead of the effective VPD for water use efficiency estimation and GPP predictions. When the daily mean VPD is shown to be adequate for GPP predictions at the daily time scale, we can define a daily underlying water use efficiency, \( \gamma_{u,d} \), as follows:
\[
\gamma_{u,d} = \frac{\text{GPP}_d (\text{VPD}_d)^{0.5}}{\text{ET}_d}
\]
(18)
2.3. Validation of the Underlying Water Use Efficiency at the Daily Time Scale
The daily \( u \)WUE formulation was validated for seven vegetation types using data from 123 AmeriFlux site years, and a flow chart for the methodology is shown in Figure 1. First, daily mean VPD and the effective VPD were calculated from half-hourly data, and the parameter, \( \lambda \), was estimated as the slope of the regression equation, i.e., equation (17) for each site year. Second, \( k^* \) relating to the best linear
relationship between GPP · VPD\(^k\) and ET was sought at the half-hourly and daily time scales, using the method in Zhou et al. [2014], to test the scale invariance of \(k\) and to validate uWUE at the daily time scale. The paired \(t\) test and the test for homogeneity of variance were used to evaluate the consistency of the mean and variance of the exponent \(k\) at half-hourly and daily time scales. Third, three different aspects were considered to compare uWUE and IWUE at the daily time scale: (1) the correlation coefficient for the relationship of GPP · VPD\(^{0.5}\) versus ET and GPP · VPD versus ET at the daily time scale, (2) the coefficient of variation, namely the ratio of standard deviation over the mean daily uWUE and IWUE for each year at each site, (3) the discrepancy between daily and yearly water use efficiency in terms of the mean and standard deviation. Finally, the performance of using yearly uWUE to predict daily GPP values was evaluated and compared with yearly IWUE. Yearly uWUE, \(\gamma_{u,y}\), and yearly IWUE, \(\gamma_{i,y}\), were calculated using daily data of GPP, ET, and VPD for each site year, the formulations are shown in equations (19) and (20). Daily GPP, i.e., \(GPP_{u,d}\) and \(GPP_{i,d}\), were predicted using equations (21) and (22) and yearly uWUE and IWUE and daily ET and mean VPD for the site year.

\[
\gamma_{u,y} = \frac{\sum GPP_d \cdot (VPD_d)^{0.5}}{\sum ET_d}
\]

(19)

\[
\gamma_{i,y} = \frac{\sum (GPP_d \cdot VPD_d)}{\sum ET_d}
\]

(20)

\[
GPP_{u,d} = \frac{\gamma_{u,y} \cdot ET_d}{(VPD_d)^{0.5}}
\]

(21)

\[
GPP_{i,d} = \frac{\gamma_{i,y} \cdot ET_d}{VPD_d}
\]

(22)

Table 2. Comparisons of the Effective VPD and Daily Mean VPD, Including the Average of the Coefficient of Determination (\(R^2\)), the Slope of the Linear Fit (\(\lambda\)) in Equation (17), and the Discrepancy (\(D\)) Between the Effective VPD and Daily Mean VPD for the Seven Vegetation Types and the 123 Site Years

<table>
<thead>
<tr>
<th>Site Years</th>
<th>(k = 0.5)</th>
<th>(k = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(R^2)</td>
<td>(\lambda)</td>
</tr>
<tr>
<td>CRO</td>
<td>0.97</td>
<td>1.04</td>
</tr>
<tr>
<td>DBF</td>
<td>0.96</td>
<td>1.00</td>
</tr>
<tr>
<td>GRA</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>ENF</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>WSA</td>
<td>0.97</td>
<td>0.95</td>
</tr>
<tr>
<td>MF</td>
<td>0.98</td>
<td>1.01</td>
</tr>
<tr>
<td>CSH</td>
<td>0.95</td>
<td>1.08</td>
</tr>
<tr>
<td>Average</td>
<td>0.96</td>
<td>1.01</td>
</tr>
</tbody>
</table>

\(a\)The effective VPD was calculated in equation (6) when \(k = 0.5\) and \(k = 1\), respectively.
Prediction performance was assessed using four widely used indicators: (1) the bias, \( B \) (%), (2) the root-mean-square error, RMSE, (3) the correlation coefficient, \( r \), and (4) the Nash-Sutcliffe coefficient of efficiency, \( E_C \) [Nash and Sutcliffe, 1970].

\[
B = 100 \left( \frac{\sum \hat{y} - \sum y}{\sum y} \right) \tag{23}
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum (y - \hat{y})^2} \tag{24}
\]

\[
r = \frac{\sum (y - \bar{y})(\hat{y} - \bar{y})}{\sqrt{\sum (y - \bar{y})^2 \sqrt{\sum (\hat{y} - \bar{y})^2}}} \tag{25}
\]

\[
E_C = 1 - \frac{\sum (y - \hat{y})^2}{\sum (y - \bar{y})^2} \tag{26}
\]

where \( y \) represents the observed daily GPP values, \( \hat{y} \) the predicted daily GPP values, and \( n \) is the total number of observations for the site year. The mean of the observed and predicted values are \( \bar{y} \) and \( \bar{\hat{y}} \), respectively.

3. Results and Discussion

3.1. The Effectiveness of Daily Mean VPD

The linear relationship between the effective VPD and daily mean VPD was evaluated using equation (17) for seven vegetation types and 123 site years. The effective VPD was computed using equation (6) with \( k = 0.5 \) for uWUE and \( k = 1 \) for IWUE. The average coefficient of determination for equation (17) ranged from 0.95 to 0.98 when \( k = 0.5 \) and from 0.94 to 0.97 when \( k = 1 \) for the seven vegetation types, indicating a strong linear relationship between the effective VPD and daily mean VPD (Table 2). The strong linear relationship between VPD\(_d\) and VPD\(_e\) lent empirical support for the proportional relationship derived from the hysteresis model in equation (16).

The mean and the distribution of the slope of the linear fit, i.e., \( \lambda \) for each vegetation type and all the 123 site years as a whole are shown in Table 2 and Figure 2. The slope \( \lambda \) ranged from 0.85 to 1.11 with an average of 1.01 for \( k = 0.5 \) and 1.06 for \( k = 1 \), as shown in Table 2. The dashed lines outside the boxes are the theoretical lambda values from equation (16), i.e., 1.20 for \( k = 0.5 \) and 1.23 for \( k = 1 \).

![Figure 2. Frequency distribution of the slope of the linear fit, i.e., lambda in equation (17) for (a) \( k = 0.5 \) and (b) \( k = 1 \) for the seven vegetation types and the 123 site years (CRO = cropland, DBF = deciduous broadleaf forest, GRA = grassland, ENF = evergreen needleleaf forest, WSA = woody savanna, MF = mixed forest, and CSH = closed shrubland). The dashed lines in the boxes refer to the average lambda values for the seven vegetation types, and the solid lines refer to the median values. The dotted lines outside the boxes are the mean of lambda values for the 123 site years, namely 1.01 for \( k = 0.5 \) and 1.06 for \( k = 1 \), as shown in Table 2. The dashed lines outside the boxes are the theoretical lambda values from equation (16), i.e., 1.20 for \( k = 0.5 \) and 1.23 for \( k = 1 \).](image-url)
from the theoretical lines based on the hysteresis model. The average discrepancy between the effective VPD and the daily mean VPD ranged from 4.7% to 8.8% for $k = 0.5$ and from 1.4% to 11.3% for $k = 1$ for the seven vegetation types, and the average discrepancy was only 1.5% for $k = 0.5$, and 6.1% for $k = 1$ for all the site years (Table 2). The systematic departures from the theoretical values may have resulted from the difference in the diurnal processes of GPP, ET, and VPD and the assumed sinusoidal functions in the hysteresis model. Considering the small variation in $\lambda$ around unity among all the site years, it would be sensible to assume that $\lambda = 1$, and VPD$_e$ equals VPD$_d$ for practical applications. Thus, the effective VPD could be replaced by the daily mean VPD for GPP predictions. We have shown that the daily mean VPD can be used in the generic water use efficiency model at the daily time scale, and this daily mean VPD was used henceforth for water use efficiency calculation in this study.

3.2. The Optimal Water Use Efficiency From Half-Hourly to Daily Time Scales

The optimal exponent, i.e., $k^*$, and the corresponding correlation coefficient for the relationship between GPP · VPD$^{k^*}$ and ET for each site year were calculated at both the half-hourly and daily time scales. Their distributions and comparisons are shown in Table 3 and Figure 4a, and the difference in $k^*$ between half-hourly and daily time scales is shown in Figure 4b for different vegetation types. The average $k^*$ value was about 0.55 using half-hourly and daily data for the 123 site years. There was no obvious difference between the average $k^*$ at the half-hourly and daily time scales, both being close to 0.5, and their difference was less than 0.01 (Table 3). However, the standard deviation of $k^*$ among the 123 site years was larger at the daily time scale than that at the half-hourly time scale. As is shown in the paired t test, the mean of $k^*$ was not significantly different at the 1% level ($p$ value = 0.728). The test for homogeneity of variance, however, showed that there was a significant difference between the variance of $k^*$ at the half-hourly and daily time scales ($p$ value < 0.001). The average $k^*$ for all site years is scale invariant in a

![Figure 3. Comparisons of the daily mean VPD and effective VPD when $k = 0.5$ and $k = 1$ for station US-Goo (GRA) in 2006. The solid line is the 1:1 line, and the dotted lines represent the linear fit between the daily mean VPD and effective VPD. The dashed lines are based on equation (16), and the slopes are 1.20 for $k = 0.5$ and 1.23 for $k = 1$.](image)

**Table 3.** Average ± 1 Standard Deviation of $k^*$ and the Correlation Coefficient ($r$) of GPP · VPD$^{k^*}$ Versus ET at the Half-Hourly and Daily Time Scales for the Seven Vegetation Types and the 123 Site Years

<table>
<thead>
<tr>
<th>Site Years</th>
<th>Half-Hourly Time Scale</th>
<th>Daily Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k^*$</td>
<td>$r$</td>
</tr>
<tr>
<td></td>
<td>$k^*$</td>
<td>$r$</td>
</tr>
<tr>
<td>CRO</td>
<td>0.53 ± 0.08</td>
<td>0.92 ± 0.05</td>
</tr>
<tr>
<td>DBF</td>
<td>0.55 ± 0.12</td>
<td>0.86 ± 0.06</td>
</tr>
<tr>
<td>GRA</td>
<td>0.54 ± 0.13</td>
<td>0.87 ± 0.08</td>
</tr>
<tr>
<td>ENF</td>
<td>0.57 ± 0.10</td>
<td>0.87 ± 0.04</td>
</tr>
<tr>
<td>WSA</td>
<td>0.45 ± 0.16</td>
<td>0.78 ± 0.06</td>
</tr>
<tr>
<td>MF</td>
<td>0.61 ± 0.11</td>
<td>0.85 ± 0.02</td>
</tr>
<tr>
<td>CSH</td>
<td>0.69 ± 0.14</td>
<td>0.88 ± 0.04</td>
</tr>
<tr>
<td>Average</td>
<td>0.55 ± 0.12</td>
<td>0.87 ± 0.06</td>
</tr>
</tbody>
</table>

$^a$The term $k^*$ is the optimal exponent in equation (1) relating to the best linear relationship between GPP · VPD$^{k^*}$ and ET for each site year.
statistical sense, although the changes in the average $k^*$ from half-hourly to daily time scales are different for different vegetation types. At the half-hourly time scale, the average $k^*$ was around 0.5 and more than half of the $k^*$ values lay between 0.4 and 0.6 for four of the seven vegetation types (cropland, deciduous broadleaf forest, evergreen needleleaf forest, and grassland) with the number of site years greater than 20 (Table 3 and Figure 4a). From half-hourly to daily time scales, the change in the average $k^*$ is the smallest for evergreen needle forest and the largest for cropland among the four vegetation types. The average $k^*$ for the other three vegetation types (woody savanna, mixed forest, and closed shrubland) with fewer site years shows greater deviation from 0.5 at the half-hourly time scale and also shows a greater change from half-hourly to daily time scales (Table 3 and Figure 4b). The standard deviation and the range of $k^*$ become larger for each vegetation type from half-hourly to daily time scales, showing high variance at the daily time scale (Table 3 and Figure 4b).

The linear relationship between GPP $\cdot$ VPD$^{k^*}$ and ET becomes weaker from half-hourly to daily time scales on average (Table 3 and Figure 5). Largest changes in the correlation coefficient are generally associated with large changes in $k^*$. The greatest decrease in the average correlation coefficient was 0.07 from 0.92 to 0.85 for cropland, with the average $k^*$ increased from 0.53 to 0.59. The most increase in the correlation coefficient was 0.09 from 0.78 to 0.87 for woody savanna when the average $k^*$ was decreased from 0.45 to 0.33 (Table 3). The change in the average correlation coefficient for the other five vegetation types was smaller than 0.02, and the number of site years with an increased correlation coefficient was close to that with a decreased correlation coefficient (Table 3 and Figure 5). The average correlation coefficient was the largest for cropland at the half-hourly time scale and one of the smallest at the daily time scale, the standard deviation of the correlation coefficient at the daily time scale was as large as 0.10, indicating that the linear relationship between GPP $\cdot$ VPD$^{k^*}$ and ET varied considerably among the 26 site years for cropland at the daily time scale. Although 0.5 is a good approximation for the optimal exponent at both half-hourly and daily time scales, calculated $k^*$ values vary considerably at different time scales and among different vegetation types. As the optimal exponent $k^*$ was derived by maximizing the correlation coefficient between GPP $\cdot$ VPD$^k$ and ET, other environmental factors affecting the relationship among GPP, ET, and VPD were not taken into account, resulting in errors in estimated $k^*$ values, especially at the daily time scale. One of the most important factors is the composition of ET, and the major concern is the ratio of canopy transpiration to ET [Beer et al., 2009; Zhou et al., 2014]. When a linear relationship between GPP $\cdot$ VPD$^k$ and ET is sought within a year, we would expect that for days with low GPP, transpiration contributes only a small portion of ET when the LAI is low. Additionally, the uncertainty in observations may contribute to errors in the estimated $k^*$ as well, especially the uncertainty associated with GPP, which was calculated from the net ecosystem exchange and ecosystem respiration using the Artificial Neural Network method and the Marginal Distribution Sampling method [Papale and Valentini, 2003;
Thus, the water use efficiency would vary within a site year, and a superior formulation for water use efficiency would demand low variance in the water use efficiency at the daily time scale and minimum difference between daily and yearly water use efficiencies. Low variability in the daily WUE and small discrepancy between daily and yearly WUE can be ascertained when the yearly WUE is used to predict daily GPP values.

### 3.3. Comparison of uWUE and IWUE at the Daily Time Scale

Table 4 shows that the relationship between $GPP \cdot VPD^{0.5}$ and ET is better than that between $GPP \cdot VPD$ and ET for all the seven vegetation types at the daily time scale, and the average correlation coefficient for uWUE ($r = 0.85$) is higher than that for IWUE ($r = 0.81$) for the 123 site years. Figure 6 shows a comparison of the correlation coefficient for IWUE and uWUE, and it is quite clear from Figure 6 that the correlation coefficient is mostly high for uWUE than that for IWUE. The change in the correlation coefficient from IWUE to uWUE ranged from 0.15 to 0.35 for all the 123 site years. The average increase in the correlation coefficient was about 0.06 for 97 site years, and the average decrease was 0.02 for only 26 of all the site years, and the decrease in the correlation coefficient occurred when $k^*$ was relatively large (>0.70). The difference in the average correlation coefficient between uWUE ($r = 0.85$) and the optimal WUE ($r = 0.86$) was quite small for all the site years, indicating that uWUE would be a good approximation of the optimal WUE, and the exponent $k = 0.5$ can be used in equation (1) because of the strong linear relationship at the daily time scale. If the daily uWUE evaluated from daily GPP, ET, and VPD observations is a constant during a growth season, there would be a perfect linear relationship between $GPP \cdot VPD^{0.5}$ and ET for the year. A strong linear relationship among daily GPP, ET, and VPD for each site year, as demonstrated with high-correlation coefficient in the paper, would therefore imply that the daily uWUE is nearly constant or less variable for the year. Hence, the yearly uWUE, i.e., equation (19), could be used to predict daily GPP with high accuracy for each site year.

### Table 4. Comparisons of Daily and Yearly uWUE and IWUE for the Seven Vegetation Types and the 123 Site Years

<table>
<thead>
<tr>
<th>Site Years</th>
<th>r</th>
<th>Cv</th>
<th>Mean Daily uWUE</th>
<th>Yearly uWUE</th>
<th>r</th>
<th>Cv</th>
<th>Mean Daily IWUE</th>
<th>Yearly IWUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRO</td>
<td>0.85</td>
<td>0.22</td>
<td>11.24 ± 2.90</td>
<td>11.42 ± 3.03</td>
<td>0.81</td>
<td>0.27</td>
<td>40.57 ± 11.66</td>
<td>41.78 ± 12.42</td>
</tr>
<tr>
<td>DBF</td>
<td>0.84</td>
<td>0.22</td>
<td>9.55 ± 1.60</td>
<td>9.36 ± 1.57</td>
<td>0.79</td>
<td>0.32</td>
<td>28.54 ± 6.32</td>
<td>28.92 ± 6.26</td>
</tr>
<tr>
<td>GRA</td>
<td>0.84</td>
<td>0.24</td>
<td>7.88 ± 1.78</td>
<td>8.05 ± 1.84</td>
<td>0.82</td>
<td>0.32</td>
<td>29.78 ± 7.55</td>
<td>31.15 ± 8.10</td>
</tr>
<tr>
<td>ENF</td>
<td>0.88</td>
<td>0.21</td>
<td>9.96 ± 2.81</td>
<td>9.90 ± 2.73</td>
<td>0.85</td>
<td>0.31</td>
<td>34.49 ± 9.49</td>
<td>35.81 ± 9.57</td>
</tr>
<tr>
<td>WSA</td>
<td>0.84</td>
<td>0.28</td>
<td>9.39 ± 1.35</td>
<td>8.66 ± 1.14</td>
<td>0.66</td>
<td>0.36</td>
<td>39.32 ± 3.25</td>
<td>36.59 ± 2.58</td>
</tr>
<tr>
<td>MF</td>
<td>0.85</td>
<td>0.28</td>
<td>9.07 ± 2.00</td>
<td>8.99 ± 1.86</td>
<td>0.86</td>
<td>0.35</td>
<td>29.49 ± 6.45</td>
<td>30.93 ± 5.97</td>
</tr>
<tr>
<td>CSH</td>
<td>0.86</td>
<td>0.21</td>
<td>6.84 ± 1.44</td>
<td>6.55 ± 1.32</td>
<td>0.83</td>
<td>0.23</td>
<td>20.84 ± 8.28</td>
<td>20.64 ± 8.19</td>
</tr>
<tr>
<td>Average</td>
<td>0.85</td>
<td>0.23</td>
<td>9.52 ± 2.53</td>
<td>9.47 ± 2.56</td>
<td>0.81</td>
<td>0.31</td>
<td>32.87 ± 10.05</td>
<td>33.62 ± 10.32</td>
</tr>
</tbody>
</table>

*The average correlation coefficient ($r$) of $GPP \cdot VPD^{0.5}$ versus ET and $GPP \cdot VPD$ versus ET at the daily time scale, the mean coefficient of variation (Cv) of daily uWUE and IWUE for a year was used to indicate consistency of the daily water use efficiency. Average ± 1 standard deviation of mean daily and yearly uWUE (g C hPa$^{0.5}$/kg H$_2$O) and IWUE (g C hPa/kg H$_2$O) are presented.*
The difference between the mean daily water use efficiency for a year and yearly water use efficiency ranged from \(-0.61\) to \(1.56\) g ChPa\(^{0.5}\)/kg H\(_2\)O for uWUE and from \(-3.80\) to \(4.95\) g ChPa/kg H\(_2\)O for IWUE for the 123 site years. The largest difference was no more than 17% for the yearly uWUE and no more than 14% for the yearly IWUE for these site years, and the difference between the average daily and the average yearly water use efficiency was less than 8% for the seven vegetation types using uWUE and less than 7% using IWUE (Table 4). As is shown in Figure 7, the mean daily uWUE and IWUE are close to yearly uWUE and IWUE, respectively, and daily uWUE values are distributed more tightly around the yearly uWUE with small standard deviations than the IWUE for all the site years, indicating the daily uWUE is less variable in comparison to daily IWUE. The coefficient of variation of the daily uWUE in a year was much smaller than that of daily IWUE, and the average coefficient of variation was 0.23 for daily uWUE and 0.31 for daily IWUE for all the site years, and the average coefficient of variation of daily IWUE was 1.2 ~ 1.5 times larger than that of daily uWUE for the seven vegetation types (Table 4). The variability of uWUE and IWUE in a year affects the accuracy in predicted daily GPP values when daily uWUE and IWUE were replaced by constant uWUE and IWUE for the year. Thus, we have shown that uWUE is not only more suitable than IWUE at the half-hourly time scale but also at the daily time scale, because of the stronger relationship between GPP · VPD\(^{0.5}\) and ET and more consistent daily uWUE values within a year in comparison to IWUE.

### 3.4. Prediction of Daily GPP Values From Yearly uWUE and IWUE

A constant IWUE for individual site has been used to predict annual GPP using mean annual VPD and ET values [Beer et al., 2007]. However, there is a lack of simple and effective model to predict GPP at the daily time scale. Daily uWUE was shown to be more consistent with and closer to the yearly uWUE than IWUE; thus, the yearly uWUE may be more effective in predicting daily GPP using daily ET and mean VPD values, and the model performance can be contrasted with that using IWUE. Yearly uWUE values ranged from \(3.50\) to \(15.83\) g ChPa\(^{0.5}\)/kg H\(_2\)O for the 123 site years, about 25% of the yearly IWUE values, which ranged from \(5.32\) to \(62.31\) g ChPa/kg H\(_2\)O. The average yearly uWUE was \(9.47\) g ChPa\(^{0.5}\)/kg H\(_2\)O, and the average yearly IWUE was \(33.62\) g ChPa/kg H\(_2\)O (Table 4). Among all the seven vegetation types, cropland had the highest yearly uWUE, \(11.24\) g ChPa\(^{0.5}\)/kg H\(_2\)O on average, followed by mixed forest, evergreen needleleaf forest, deciduous broadleaf forest, and the lowest was for closed shrubland, about half of that for cropland (Table 4). Apart from cropland and closed shrub forest, the variation in the mean yearly uWUE is quite small, from \(7.88\) to \(9.96\) g ChPa\(^{0.5}\)/kg H\(_2\)O only (Table 4). The near constancy of the average yearly uWUE indicates the potential to make a first-order prediction of the average GPP from VPD and ET for the five remaining vegetation types. The standard deviation of the yearly uWUE among the 26 site yeas of cropland was as large as \(3.03\) g ChPa\(^{0.5}\)/kg H\(_2\)O, indicating that yearly uWUE may vary considerably among the same vegetation type, even at the same site. For example, US-Ne3 is a mead-rainfed maize-soybean rotation site, the average yearly uWUE was \(15.38\) g ChPa\(^{0.5}\)/kg H\(_2\)O for maize and \(8.68\) g ChPa\(^{0.5}\)/kg H\(_2\)O for soybean. The coefficient of variation was about 0.27 for the yearly uWUE and 0.31 for IWUE for all the 123 site years, indicating that the yearly uWUE is less variable among different site years (Table 4).

The bias in the predicted daily GPP values ranged from \(-3.6\%\) to 5.5% with an average of 0.59% using the yearly uWUE for all the 123 site years, and the average root-mean-square error was 2.88 g C m\(^{-2}\) d\(^{-1}\), indicating that the
yearly uWUE was effective as a predictor of the daily GPP on average. In comparison, the bias in predicted daily GPP using the yearly IWUE was much larger, ranging from 1.4% to 31.9%, and the average bias was about 3.2–12.5%, indicating a systematic overprediction for all the seven vegetation types (Table 5). The average root-mean-square error using the yearly IWUE was 5.30 g C m$^{-2}$ d$^{-1}$, almost twice of that using the yearly uWUE (Table 5). Although the yearly IWUE is effective in predicting yearly GPP [Beer et al., 2007], using the yearly uWUE to predict daily GPP would have smaller bias and smaller root-mean-square error than using the yearly IWUE. The average correlation coefficient between observed and predicted daily GPP values was larger than 0.7 for all the seven vegetation types, and the average Nash-Sutcliffe coefficient of efficiency was almost 0.6 for all the site years (Table 5 and Figure 8). While the majority of the correlation coefficient between the observed and predicted daily GPP (95 out of the 123 site years) was larger than 0.75 using uWUE, and there were only 32 site years using IWUE with the correlation coefficient above 0.75. The performance using the IWUE varied much from site year to site year, especially for deciduous broadleaf forest with negative correlation coefficients for 2 site years. Prediction performance was much improved using the yearly uWUE, and none of the 31 site years had a negative correlation coefficient for deciduous broadleaf forest, and the correlation coefficient for the 2 site years was larger than 0.7, as it can be seen from Figure 8. In terms of the Nash-Sutcliffe coefficient of efficiency, uWUE is much better than IWUE at predicting the daily GPP. The average Nash-Sutcliffe coefficient of efficiency was 0.7 for cropland and 0.64 for grassland, and was 0.59 overall for the 123 site years (Table 5). The average Nash-Sutcliffe coefficient of efficiency using the IWUE was less than zero for all vegetation types, indicating IWUE is no better a predictor of the daily GPP than that predicted using the mean daily GAP as a predictor. Inaccuracy of IWUE is attributed to the fact that the relationship between GPP - VPD and ET is largely nonlinear, and that the daily IWUE is highly variable within a site year. As an example, Figure 9 shows a time series of observed and predicted daily GPP in 2006 at station US-Goo (GRA). It is clear from Figure 9 that the difference between daily and yearly IWUE is much greater than that between daily and yearly uWUE for most days. Daily GPP predicted using IWUE is much larger than observed GPP when daily mean VPD is small, and the yearly IWUE is much larger than the daily IWUE, such as the Julian days from 75 to 142, and the difference between the observed and predicted GPP is much smaller using the uWUE for the same period.
3.5. Discussion of the Two Water Use Efficiency Formulations

IWUE was proposed and has been widely used to estimate regional and continental GPP and to evaluate the responses of terrestrial ecosystems to global change at the yearly time scale [Beer et al., 2007, 2009; Keenan et al., 2013]. IWUE has several important advantages to support its widespread application: (1) IWUE is derived from the physical processes of carbon and water exchanges through stomata between terrestrial ecosystems and the atmosphere; (2) the formulation is simple with only three variables; (3) the relationship among these variables is consistent essentially under steady environmental conditions, and the relationship can respond adaptively to a changing environment; (4) these variables, namely GPP, ET, and VPD, can be easily observed by eddy covariance technique and meteorological instruments at a local scale, and estimated by remote sensing techniques at a regional or global scale; and (5) the formulation could be upscaled to larger time and spatial scales for widespread application. Comparing to IWUE, uWUE developed by Zhou et al. [2014] presents a much stronger relationship among GPP, ET, and VPD at both half-hourly and daily time scales, and is much less variable within a year, in addition to having the same five advantages mentioned above. As such, daily uWUE is much more consistent with the yearly uWUE and is a superior measure of water use efficiency. uWUE could be readily adapted for global change research, such as terrestrial carbon and water cycles in a changing environment. As a key component of the terrestrial carbon balance, GPP plays an important role in ecosystem services and carbon sequestration. The improvement in the accuracy of predicted GPP at the daily time scale would make it possible to predict daily GPP at a regional or global scale combining the eddy covariance technique with remote sensing products, and these will contribute a great deal to the understanding and modeling of global carbon cycle processes.

There were several sources of uncertainties in the analysis using the AmeriFlux data, such as the effect of interception and soil evaporation on ET and the effect of predicted ecosystem respiration on GPP. This analysis was focused on the growth season with relatively high ET and GPP to

### Table 5. Prediction Performances of the Daily GPP Derived From the Yearly uWUE and IWUE Using Equations (21) and (22)

<table>
<thead>
<tr>
<th>Site Years</th>
<th>uWUE</th>
<th></th>
<th></th>
<th>IWUE</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B (%)</td>
<td>RMSE</td>
<td>r</td>
<td>Ec</td>
<td>B (%)</td>
<td>RMSE</td>
</tr>
<tr>
<td>CRO</td>
<td>26</td>
<td>0.3</td>
<td>4.04</td>
<td>0.84</td>
<td>0.70</td>
<td>6.1</td>
</tr>
<tr>
<td>DBF</td>
<td>31</td>
<td>0.5</td>
<td>3.28</td>
<td>0.79</td>
<td>0.54</td>
<td>11.5</td>
</tr>
<tr>
<td>GRA</td>
<td>23</td>
<td>0.4</td>
<td>2.38</td>
<td>0.81</td>
<td>0.64</td>
<td>8.7</td>
</tr>
<tr>
<td>ENF</td>
<td>23</td>
<td>0.8</td>
<td>2.08</td>
<td>0.80</td>
<td>0.57</td>
<td>11.4</td>
</tr>
<tr>
<td>WSA</td>
<td>8</td>
<td>1.9</td>
<td>1.80</td>
<td>0.88</td>
<td>0.60</td>
<td>12.5</td>
</tr>
<tr>
<td>MF</td>
<td>7</td>
<td>0.7</td>
<td>2.67</td>
<td>0.72</td>
<td>0.47</td>
<td>10.3</td>
</tr>
<tr>
<td>CSH</td>
<td>5</td>
<td>−0.2</td>
<td>2.28</td>
<td>0.79</td>
<td>0.41</td>
<td>3.2</td>
</tr>
<tr>
<td>Average</td>
<td>0.6</td>
<td>2.88</td>
<td>0.81</td>
<td>0.59</td>
<td>9.5</td>
<td>5.30</td>
</tr>
</tbody>
</table>

*Four indicators were used, namely the bias (B), the root-mean-square error (RMSE), the correlation coefficient (r), and the Nash-Sutcliffe coefficient of efficiency (Ec), their definitions were given in relation to equations (23) to (26).
reduce these uncertainties. Data on the rainy days and some days following the rainy days were excluded to avoid the effect of wet surface evaporation on ET. Cross-site evaluation of GPP and ecosystem respiration showed that GPP uncertainty was low (less than 10%) based on the flux-partitioning method [Desai et al., 2008], and the AmeriFlux data were processed using the standard data processing procedure which would have constrained the expected uncertainty for GPP estimates. Moreover, all the analysis and comparison between IWUE and uWUE were undertaken using the same data sets with the same amount of uncertainties associated with the estimated ET and GPP. Thus, while uncertainties with the estimated ET and GPP no doubt exist, their impact is likely to be negligibly small in relation to the main findings of this study, i.e., the advantage of uWUE over IWUE.

4. Conclusions

The underlying water use efficiency was demonstrated to be superior and consistent at the daily time scale. Detailed analysis for the seven vegetation types from 34 AmeriFlux sites shows that (1) the effective VPD defined by equation (6) could be replaced by the daily mean VPD for water use efficiency estimation and GPP predictions; (2) a constant exponent of 0.5 in equation (1) is nearly optimal for formulating water use efficiency for all vegetation types both at the half-hourly and daily time scales; (3) the underlying water use efficiency is a better approximation of the optimal water use efficiency than the inherent water use efficiency at the daily time scale, because of the strong relationship between GPP·VPD$^{0.5}$ and ET and the quite consistent daily uWUE values within a site year; and (4) the yearly underlying water use efficiency can be used to predict daily GPP values using daily ET and mean VPD, and the average correlation coefficient was 0.81 and the average Nash-Sutcliffe coefficient of efficiency was 0.59. The underlying water use efficiency could be used as an effective parameter to describe the interrelationship between the carbon and

Figure 9. The observed and predicted daily GPP using (a) yearly uWUE (8.92 g C hPa$^{0.5}$/kg H$_2$O) and (b) yearly IWUE (36.12 g C hPa/kg H$_2$O) for station US-Goo (GRA) in 2006. Daily and yearly uWUE and IWUE are shown as dashed lines.
water coupling in terrestrial ecosystems, and the uWUE will contribute greatly to issues under global change, including climate change impacts on the carbon assimilation and evapotranspiration and the ecosystem responses to elevated atmosphere CO2 concentrations.

Acknowledgments


References