Estimation of Water-Use Efficiency Based on Satellite for the Typical Croplands

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ABSTRACT Water resources become scarce due to the melting of glaciers caused by climate change, and water pollution caused by human activities and overuse of freshwater resources are aggravating this phenomenon. Cropland is an essential part of the terrestrial ecosystem, and it is of great importance to make rational use of the limited water resources to have higher water use efficiency (WUE). The quantitative estimation of the ecosystem WUE and tracking its dynamics of croplands is crucial for addressing the impact of future climate change on crop production. Scaling up field observations of flux towers to a large scale remains a challenge and there are few reports on estimating WUE directly from remote sensing data. This study examined the main environmental factors that contribute to changes in WUE of typical crops, and found that the EVI showed strong correlation with the ecosystem WUE of typical croplands, which can be developed to track ecosystem WUE. This study proposed an alternative method exclusively based on MODIS EVI data analysis with an $R^2$ of nearly 0.90 and a small RMSE, which was much better than the calculations of the MODIS GPP and ET products, and provided an accessible method for modelling the ecosystem WUE to effectively manage water use in croplands.

INDEX TERMS Water use efficiency, cropland, EVI, MODIS.

I. INTRODUCTION

Climate change has significant influence on terrestrial ecosystems, especially in carbon and water relationships [1]. Croplands are essential part of terrestrial ecosystems, which provide food supplies and livelihoods for human beings [2]. Meanwhile, with the increase in the population worldwide, intense competition for water exists among cities, nature, agriculture and industry activities [3]. A healthy and stable farmland ecosystem is conducive to maintaining the ecosystem balance. Recently, appropriate methods have been explored to soundly use water resources and improve agricultural WUE in agricultural production [4]. It is urgent for scientists to discover a proper solution to solve current problems, such as food shortages and compromised food safety [5], [6].

Water-use efficiency (WUE) is defined as capacity of plant to produce biomass while consuming water via evapotranspiration (ET) in plot scale. [7]. WUE is widely regarded as a significant connection between carbon cycle and water cycle in terrestrial ecosystem [8], [9] and it is also characterized as ratio of gross primary production (GPP) over ET [10]. In basin scale, the change in WUE is coupled with the rational use of water, existence tactics and response to changes in the hydrological condition in the basin [6]. The impacts of WUE differ in different scale. Higher WUE improves economic productivity in plot, but with a direct impact on the behavior of the basin as an ecological system. This implies that there is a commitment to local efficiency with respect to the basin sustainability of the basin. Ecosystem WUE of crops show a strong response to the variation. It also varies with the change in vegetation types and environmental conditions [11] which can be affected by several factors, such as temperature, latent
TABLE 1. Description of the flux tower sites of croplands used in this study.

| Crop type          | Site ID | Lat (°) | Long (°) | MAP (mm) | MAT (°C) | Year   |
|--------------------|---------|---------|----------|----------|----------|--------|
| Soybean            | US-Ro1  | 44.714  | -93.089  | 806      | 10.1     | 2012/2 |
| Maize              | US-Ne1  | 41.165  | -96.476  | 790      | 10.1     | 2009-  |
| Paddy rice         | US-Twt  | 38.108  | -121.653 | 421      | 15.6     | 2014-  |
| Winter wheat       | CH-Oe2  | 47.286  | 7.734    | 1155     | 9.8      | 2006-  |

Note: Lat and long represent latitude and longitude, respectively. MAP and MAT represent mean annual precipitation and mean annual temperature, respectively.

heat and water content, which means abnormal temperatures, precipitation or other factors may lead to high or low WUE of plants in certain growing seasons [12], [13].

With global climate change, cropland, as an essential part of terrestrial ecosystems, is confronted with acute threats; the world food reserves are rapidly declining, on account of various environmental issues and urbanization, and the area of crops is decreasing continuously as well [14], [15]. Recently, a method to improve the WUE of croplands has become a hot topic among researchers [4]. Amounts of studies have focused on the function of irrigation projects and technologies in water-deficient areas [16] but there still lack systematic spatio-temporal studies focusing on different crop types. The eddy covariance (EC) system provides the service of field measurements, which makes continuous monitoring a possible solution [17], [18]. The EC system can be combined with remote sensing techniques to observe the WUE of croplands. MODIS GPP and ET algorithms enrich the ecosystem WUE monitoring techniques. Recently, the normalized difference vegetation index (NDVI), the enhanced vegetation index (EVI) and other remotely sensed indices have been used to survey ecosystem indices [19]. The EVI has both high temporal and spatial resolution and wide coverage area [20]. This method is valid for tracking crop growth phenology, evaluating and monitoring cropland seasonal changes [21]–[25]. Thus, we use EVI to model the ecosystem WUE of croplands. The study was conducted: i) to compare the seasonal dynamics among typical crops; ii) to evaluate the capacity to model the ecosystem WUE that was derived from MODIS GPP and ET data; and iii) to explore potential of the EVI in capturing ecosystem WUE.

II. DATA AND METHODS

A. SITE DESCRIPTIONS

We based on four croplands maize, rice, soybean, and winter wheat (Table 1), with one site for each type. The US-Ne1 site is located near Mead, NE with the climate of humid continental. The crops irrigated in this area are continuous maize, which are usually planted in middle of May and ripened in October [26]. The tower began operation in 2001 [27].

The US-Ro1 site is located in Minnesota. This area is temperate continental climate. This site was a conventional-till management corn/soybean annual with soybeans in even years and maize in odd years. This site is rain-fed farming systems and the planting and harvesting season are in late May and October, respectively [9], [28].

The US-Twt is located in the Sacramento-San Joaquin Delta with typical Mediterranean climate - hot, dry summers, and cool, wet winters. The growing season of paddy rice generally begins at the end of April, and the rice is harvested at the end of October to the end of October, and this site is also rain-fed cropland [29], [30].

The CH-Oe2 was part of the CarboEuropeIP project (EU FP6) and the GHG-Europe project (EU FP7), which is located in Oensingen, Switzerland. Eddy covariance flux measurements started in December 2003. The field has been operated since the late 1990s with a 3-year crop rotation. Winter wheat generally cultivated every third year and is the dominant crop in the CH-Oe2 site. Potatoes, winter rapeseed or peas are the second and third crops in the rotation. Wheat is only planted biennially between autumn 2006 and autumn 2010. The irrigation management in the CH-Oe2 site is rain-fed. This study used winter wheat year 2006/2007 and 2008/2009 [31], [32].

B. MODIS PRODUCTS

We obtained the MODIS GPP and ET products to estimate terrestrial water use efficiency. These products have been developed and sequentially improved. Collection 5 MOD17 products were developed to address important errors that Zhao et al. (2005) recognized in the old GPP product (Collection 4) [33]; these errors occurred due to problems in the upstream inputs. A remote sensing-based product, which is based on MODIS and surface meteorological observations, was developed by Mu et al. (2011) to investigate global ET [34]. The synthetic values of 8-day GPP MOD17 and ET MOD16 for the MODIS pixels (with the spatial resolution of 500m) were obtained from the website (https://modis.ornl.gov/documentaiton.html).

The original EVI equation was used in the study which stemmed from blue, red, and near-infrared (NIR) bands and has been proved to be sensitive to vegetation growth [35], [36].

EVI was first used to analyse the relevance with ecosystem WUE of cropland and to develop an approach for quantitative analysis of crop WUE solely based on the EVI. We obtained 8-day composite land surface reflectance (MOD09A1, 500 m resolution) data from the website (http://daac.ornl.gov/MODIS/). The EVI was defined as [21]:

\[
EVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + (6\rho_{red} + 7.5\rho_{blue} + 1)}
\]
where $\rho_{\text{near}}$ is band 2, $\rho_{\text{red}}$ is band 1 and $\rho_{\text{blue}}$ is band 3 of the MODIS spectral reflectance. We introduced the EVI data to analyse the relevance with ecosystem WUE and attempt to identify a selective method to quantitatively determine the WUE of croplands.

C. FLUX MEASUREMENTS AND STATISTICAL ANALYSIS

Analysis was on the basis of the continuous measurement data of the EC system in this study. The flux sites data were derived from AmeriFlux, and the European Fluxes Database Cluster. The EC system consisted of a CO$_2$/H$_2$O gas analyser and a three-dimensional sonic anemometer [37]. The direct measurement of the net ecosystem carbon exchange (NEE) was performed by an EC-based flux tower. By means of non-linear regression, the NEE observations of time series are divided into two parts–total GPP and respiration (Re). The R-based package could be used to fill gaps and partition flux data at https://www.bgcjena.mpg.de/REddyProc/brew/REddyProc.rhtml, which is based on the regression model [38].

WUE has variant definition on different scales and subjects [39]. The WUE of croplands in this study was defined as:

$$WUE = \frac{GPP}{ET} \tag{2}$$

To maintain consistency with the MODIS products, the half-hour WUE of croplands were integrated into an 8-day period. ET (mm d$^{-1}$) was calculated from latent heat (LE, W m$^{-2}$) of observation:

$$ET = \frac{LE}{\lambda} \tag{3}$$

And $\lambda$ represents the energy required to evaporate 1 kg liquid water (approximately 2,454,000 J).

Half-hour flux data were averaged over eight-day values to compare EC-based and MODIS data-based data of GPP, ET and ecosystem WUE of croplands and calculated multi-year mean value or seasonal mean value. We used Pearson correlation analysis to identify main abiotic factors affecting the ecosystem WUE of these four croplands. Linear regression was used to fit the coefficient of determination ($R^2$), root mean square error (RMSE) and scatter-point evaluation results to analyse the connection between the WUE and EVI in crop ecosystems. An $R^2$ value close to 1 and a small RMSE compared to the total variances mean the model executed well.

III. RESULTS

A. SEASONAL VARIATIONS AND ENVIRONMENTAL CONTROLS

The multi-year average values are shown in Table 2. It’s obvious that GPP value of maize (5.083 g C m$^{-2}$d$^{-1}$) is higher than other C$_3$ crops with values less than 5 g C m$^{-2}$d$^{-1}$. On account for the longing flood condition during growth, paddy rice had the highest value of ET with 2.550 mm d$^{-1}$. We demonstrated that the function in the cycle of water and carbon of maize cropland -WUE with a value of 2.966 g C kg$^{-1}$H$_2$O was stronger than winter wheat, paddy rice and soybean with values of 2.318 g C kg$^{-1}$H$_2$O, 1.373 g C kg$^{-1}$H$_2$O and 1.588 g C kg$^{-1}$H$_2$O, respectively.

The seasonal dynamics of the four typical croplands are shown in figure 1. The EC system-based flux data showed that the GPP value gradually increased with crop growth, reached its peak at nearly mid-summer, then started to decrease with the crops mature. However, winter wheat has rather diverse characteristics from other three crops, since it was generally sown in mid-October; its GPP gradually fell to zero after reaching a small peak. Subsequently, GPP of winter wheat gradually increased as the temperature rose and then quickly reached its peak at early summer. The ecosystem WUE has obvious seasonal characteristics and exhibits a changing trend that approximately follows the GPP. The study found the maize site owned the apparent highest peak of GPP at $\sim$25 g C m$^{-2}$d$^{-1}$ and ecosystem WUE of $\sim$6 g C kg$^{-1}$H$_2$O during the growth. ET exhibited similar changing patterns, as the GPP and ET of rice was more prominent than those of other three crops with $\sim$7 mm d$^{-1}$. However, there still exist differences among the same croplands of different observed years, which can be explained by the influence of air temperature ($T_a$), soil temperature ($T_s$) and other environmental factors.

We used Pearson correlation analysis to evaluate the connection between water use efficiency and environmental constraints in the eight-day among croplands (Table 3) and found that the GPP had a stronger decisive status to ecosystem WUE of croplands than ET. $T_a$, $R_g$, as well as $T_s$ were collated strongly with WUE of maize, soybean and wheat cropland. These three factors are regarded as the most important abiotic factors affecting cropland’s growth. As rice was flooded long-term, the abiotic factors had little correlation with its ecosystem WUE. In addition, all four typical crops showed strong correlation with the EVI with values of 0.792, 0.934, 0.676 and 0.618, respectively, which revealed the strong potential of EVI to inverse ecosystem WUE.

B. COMPARISONS BETWEEN EC SYSTEM OBSERVED MODIS-BASED WUE

Calculation of MODIS GPP and ET data is one way to obtain ecosystem WUE but its potential in croplands still needs to be explored. Comparison between EC-based WUE (WUE$_{EC}$) and MODIS data-based WUE (WUE$_{MOD}$) are shown in figure 3, and the correlation between them is

Table 2. Multi-year mean of GPP, ET and ecosystem WUE across the main crop types.

| Crop type  | GPP (g C m$^{-2}$d$^{-1}$) | ET (mm d$^{-1}$) | WUE (g C kg$^{-1}$H$_2$O) |
|-----------|--------------------------|----------------|--------------------------|
| Maize     | 5.083                    | 1.714          | 2.966                    |
| Soybean   | 2.304                    | 1.450          | 1.588                    |
| Paddy rice| 3.502                    | 2.550          | 1.373                    |
| Winter wheat| 4.961                    | 2.140          | 2.318                    |
TABLE 3. Relevance analyses of ecosystem WUE and major abiotic controlling among the four typical croplands.

| Crop types     | GPP (g C·m⁻²·d⁻¹) | ET (mm·d⁻¹) | Rs (W·m⁻²) | Ts (°C) | Tp (°C) | VPD (h·Pa) | EVI |
|----------------|-------------------|-------------|------------|---------|---------|------------|-----|
| Soybean        | 0.965**           | 0.740**     | 0.458**    | 0.526   | 0.610   | 0.277**    | 0.792** |
| Maize          | 0.944**           | 0.811**     | 0.502**    | 0.794   | 0.739   | -0.153     | 0.934** |
| Paddy rice     | 0.836**           | 0.415**     | -0.083     | 0.131   | 0.218   | -0.193     | 0.676** |
| Winter wheat   | 0.867**           | 0.600**     | 0.582**    | 0.381   | 0.282   | 0.135      | 0.618** |

Figure 1. Seasonal variation in GPP, ET and ecosystem WUE of four typical croplands.

Figure 2. Seasonal scatter plots of ecosystem WUE between WUE_EC and WUE_MOD. The black dashed line is 1:1 line and red line represents linear fit.

The multi-year mean WUE_EC of winter wheat (1.912 g C kg⁻¹H₂O) was much more than WUE_MOD (1.470 g C kg⁻¹H₂O). Soybean revealed similar result as winter wheat with the value of 0.875 g C kg⁻¹H₂O and 1.09 g C kg⁻¹H₂O, respectively. In addition, multi-year mean WUE_EC at the maize site was almost twice that of WUE_MOD with the value of 2.892 g C kg⁻¹H₂O and 1.546 g C kg⁻¹H₂O, respectively. Moreover, WUE_EC of paddy rice was only half of that seriously overestimated WUE_MOD with the value of 0.932 g C kg⁻¹H₂O and 2.57 g C kg⁻¹H₂O. These typical croplands generally had similar characteristics—the WUE_MOD seriously overestimated WUE_EC in the early and the latter part of growing period, while substantially underestimated WUE_EC during the peak. Figure 2 shows that WUE_EC and WUE_MOD had poor linear relationship. The R² and RMSE of maize were 0.18 and 1.93, respectively. The R² of soybean was 0.004 and RMSE was 1.46. Cropland of paddy rice and winter wheat had R² with 0.25 and 0.48, respectively and an RMSE with 1.72 and 1.17, respectively. All of the four sites showed the poor performance of WUE_MOD in estimating WUE_EC. Thus, we indicated that the potential of MODIS GPP and ET products to precisely estimate WUE of croplands is still challenging.

C. TRACKING WUE DYNAMICS USING MODIS EVI DATA

Table 3 shows highly correlation between the EVI and WUE of croplands; furthermore, time-series MODIS EVI data can easily be obtained that imply the possibility of observing WUE in a tower-based region. This measurement can reduce the unsureness of indirect observation of GPP and ET products. We developed a model (WUEBI) solely based on the EVI to monitor the seasonal dynamics of croplands. Maize (equation (4)) and soybean (equation (5)) performed well with an R² of -0.872 and 0.843 (as is shown in figure 4), respectively, which indicated high accuracy at both sites.

\[
WUE_{BI} = 7.847 \times EVI - 0.558 \quad (4)
\]
\[
WUE_{BI} = 7.675 \times EVI - 1.307 \quad (5)
\]
However, the model still needs to be further verified on a regional scale. Figure 5 and figure 6 exhibit a comparison of the ecosystem WUE from the flux site (WUE_{EC}) with MODIS estimates from calculation of GPP and ET data (WUE_{MOD}) and from time-series EVI data (WUE_{BI}) at the maize and soybean sites during the three-year growing period. In the estimation of MODIS products from the calculations of GPP and ET data, the R² was 0.04, and the RMSE was 1.46. The R² was 0.84 and RMSE was 0.55, in the time-series EVI data inversion at the soybean site. The R² was 0.18, and the RMSE was 3.70, in the MODIS estimates from the calculation of the GPP and ET data, while the R² was 0.873 and RMSE was 0.864, in the time-series EVI data inversion of maize site. Figure 7 exhibited seasonal patterns of WUE_{EC}, MODIS estimations (WUE_{BI}) from EVI data and calculation from MODIS products data among maize and soybean EC observation during the three-year growing period. The WUE_{BI} agreed well with the WUE_{EC} except for a certain period. The study indicated that the time-series EVI had a better performance than the MODIS GPP and ET data in predicting the WUE_{EC}.

IV. DISCUSSIONS

Detecting the ecosystem WUE of croplands at the spatio-temporal scale has important significance in comprehending carbon-water cycle process and exploring solutions to improve the ecosystem WUE of croplands. This study evaluated the predictive ability of the MODIS GPP, ET and EVI products in estimating the ecosystem WUE of typical croplands. Figure 8, figure 9 and figure 10 compared the seasonal dynamics in GPP and ET between the EC-system measurement and MODIS products among four typical croplands. During the three-year period, GPP_{MOD} matched poorly to the EC-based observation at all four typical croplands—maize (R² values of 0.35), soybean (0.60), paddy rice (0.34) and winter wheat (0.37), with, and RMSE values of 6.90, 2.35, 4.45, 4.62 g m⁻² d⁻¹. The ET_{MOD} at three cropland
sites—maize, soybean and winter wheat, showed better performances in predicting the ET\textsubscript{EC} with R\textsuperscript{2} values of 0.82, 0.73 and 0.78, respectively, and with RMSE values of 0.81, 0.66, and 0.81 mm d\textsuperscript{-1}, respectively. However, owing to the initial flood condition of paddy rice, the MODIS ET product did not perform well in predicting the EC-based evapotranspiration with an R\textsuperscript{2} an RMSE of 0.62 and 2.12 g m\textsuperscript{-2} d\textsuperscript{-1}, respectively. The large discrete residual still exists, which affects the consistency between the model and observed GPP and ET. This means that even if all model or observation errors or uncertainties can be eliminated, the model and observed values cannot match accurately [40]. The result of this study is consistent with findings of the previous study that croplands exhibited large GPP RMSE with the value of 4.80 g m\textsuperscript{-2} d\textsuperscript{-1}, and ET was slightly underestimated with an RMSE of 0.88 mm d\textsuperscript{-1} [41]. The mismatch between the GPP and ET based on EC system and MODIS also relates to the footprint. The observation tower usually uses approximately 1 km\textsuperscript{2} as its footprint while it there also remains some uncertainties related to errors in gap filling, measuring, variation in the wind speed and directions, and atmospheric turbulence. [42].

The 1 km resolution of MODIS GPP/ET products makes achieving accurate observations difficult. Previous studies suggested that the accuracy of the MODIS land cover product is ~65-80% [43]. Thus, the MODIS observed region may include some land cover types, such as steppe or other crops planted in these adjacent areas.

Figure 11 shows the linear relationship between the WUE\textsubscript{EC} and the EVI data in paddy rice and winter wheat flux sites during a three-year growing period. Paddy rice and winter wheat did not perform well, with an R\textsuperscript{2} of 0.449 and 0.523, respectively. Many scientists have developed models to monitor paddy rice fields. Peng et al. (2014), based on the MODIS NPP algorithms and calibrated models using MODIS annual NPP product, combined the model with the MODIS GPP product to estimate paddy rice fields, applied these models to paddy rice fields in Liling County, China [44], and obtained an RMSE of less than 5%. Son et al. (2014) improved the MODIS EVI and NDVI data and compared and analysed the data of MODIS EVI and NDVI to estimate the large-scale production of MRD from 2002 to 2011 [45]; the study carried out objectively with EMD and quadratic model. MODIS EVI data for large-scale estimation of rice and winter wheat still needed to be improved according to the irrigated condition of paddy rice and interannual growth of winter wheat.

This study showed great potential for MODIS EVI data in determining the ecosystem WUE of croplands during the growing period, especially in maize and soybean fields. However, we must recognize that climate influence, community composition, bionomic effect and other disturbances are great obstructions in monitoring the ecosystem WUE, especially in a large scale [46], [47]. To achieve the accurate monitoring of the ecosystem water use efficiency of croplands, future studies should focus more on the combined environmental
conditions and different crop growing characteristics with the MODIS land cover product. The water use efficiency of crop fluctuates during its growth and its trend is not necessarily absolutely linear; thus, more nonprior nonlinear models could be explored to more accurately predict the ecosystem WUE of croplands.

V. CONCLUSION
This study took four typical croplands, maize, soybean, rice and winter wheat, and analysed: 1) the interannual variations among these croplands. It was found that the C₄ crop, maize, had a higher multi-year mean ecosystem WUE value of 2.892 g C kg⁻¹ H₂O, followed by winter wheat, paddy rice and soybean with values of 1.912 g C kg⁻¹ H₂O and 0.875 g C kg⁻¹ H₂O, respectively. 2) Seasonal dynamics. The GPP value increased as the growing of the crop, then arrived at the summit at nearly mid-summer, then started to decrease with crop ripening. Winter wheat was an exception, which was generally sown in mid-October and whose GPP gradually fell to zero after reaching a small peak, then gradually increasing as the temperature rose, and then quickly reaching its peak in early summer. The ecosystem WUE exhibited a changing trend that was approximately similar to the GPP. The study found the maize site owned the apparent highest peak of GPP of ∼25 g C m⁻² d⁻¹ and an ecosystem WUE of ∼6 g C kg⁻¹ H₂O in the growth season. ET exhibited the similar patterns of change to GPP. The ET of rice was more prominent than that for the other three crops with ∼7 mm d⁻¹. 3) Abiotic factors that affect cropland’s growth. It was found that the WUE of croplands was determined more by GPP than ET. Rg, air temperature and soil temperature were high correlations of the WUE among four typical croplands. The EVI showed strong correlation with the maize, soybean and winter wheat WUE. 4) The MODIS GPP, ET product and time-series EVI data in performing ecosystem WUE. The study proposed an alternative method, which was exclusively based MODIS EVI data and performed much better than the calculation of MODIS GPP and ET products. Thus, this study provided a predictive method for the EVI to track the ecosystem WUE of typical croplands.

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