Detection of Vegetation Light-Use Efficiency Based on Solar-Induced Chlorophyll Fluorescence Separated From Canopy Radiance Spectrum

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***Abstract*—Photosynthetic light-use efficiency (LUE) is an important indictor of plant photosynthesis, but it is not yet assessable by remote sensing. The recent research on the separation of solar-induced chlorophyll fluorescence (ChlF) from the hyperspectral data indicates the possibility of detecting LUE. In this study, we presented a novel solution for monitoring LUE from hyperspectral data. Experiments at leaf level and canopy level were carried out on winter wheat (C3 plant functional type) on 18 April, 2008 and summer maize (C4 plant functional type) on 5 July, 2008 by synchronously measuring daily canopy radiance spectra and leaf or canopy LUE. The solar-induced chlorophyll fluorescence signals at 760 nm and 688 nm were separated from the reflected radiance spectra based on Fraunhofer lines in two oxygen absorption bands. The results showed that LUE was inversely related to the relative chlorophyll fluorescence. The leaf-level LUE models for winter wheat were built based on relative ChlF at bands of 688 nm ($R^2 = 0.78$) and 760 nm ($R^2 = 0.64$), whereas correlation coefficients of the canopy-level LUE models for summer maize on relative ChlF at the same bands were 0.63 and 0.77, respectively.**

***Index Terms*—Fluorescence, Fraunhofer line, hyperspectral, photosynthesis, photosynthetic light use efficiency.**

I. Introduction

PHOTOSYNTHETIC light-use efficiency (LUE) is an important indictor of plant photosynthesis and a key parameter for remote-sensing based models for monitoring vegetation productivity [1], [2]. Currently, plant LUE can be detected by *in situ* measurement. At leaf scale, LUE can be calculated from the net photosynthetic rate by measuring the exchange of Co_2 in a leaf holder using a photosynthesis instrument [3]. At the canopy or landscape scale, eddy covariance flux towers have the capability to provide near-continuous measurements of gross ecosystem production (GEP), thus LUE can be calculated from Co_2 and flux exchange between the plant canopy and atmosphere by the eddy covariance micrometeorological method [4]–[6].

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Remotely sensed spectral reflectance data are unique in their ability to provide consistent large-scale observations that can be related to ecological phenomena [7]. For example, net primary productivity (NPP) is related to plant photosynthetic activity and can be estimated from remotely sensed images by observing the patterns of light absorption [2], [8], [9]. As a technique in quantifying light absorption, remote sensing has emerged as the primary tool for large-scale NPP monitoring and constituted one of the few actual observations of carbon cycling processes at the regional or global levels. Regional- and global-scale NPP studies require accurate estimation of both APAR and LUE. Monteith (1972) developed methods for estimating plant productivity from observation of absorbed photosynthetically active radiation (APAR) and LUE [1]. Although spatial and temporal variations in APAR can be consistently quantified through remote sensing techniques [10], photosynthetic efficiency has not been well assessed by remote sensing [11]. Because LUE is known to exhibit both spatial variation across vegetation types [9], [12] and temporal variation at individual sites [13], [14], a common approach is to incorporate information about vegetation type and/or temperature/water availability conditions into LUE calculations [2]. One such technique is the Carnegie–Ames–Stanford Approach (CASA) model for estimating NPP from remote sensing data. CASA is a widely recognized NPP model that downregulates photosynthetic efficiency in response to short-term adverse temperatures or dry soil conditions [8], [9]. Direct estimation of LUE from space would benefit LUE-based models that use inputs from remote sensing to estimate terrestrial productivity. Some LUE models based on vegetation indexes (e.g., PRI, EVI, NDVI) from MODIS and Spot Vegetation images were well validated using the flux tower data [5], [15]. Furthermore, Zhang *et al.* (2005) suggested that only the PAR absorbed by photosynthetic pigments (APARchl) enabled photosynthetic processes, and LUE based on APARchl could provide a more physiologically realistic parameter than the more commonly used LUE based on the PAR absorbed by canopy [16]. And their estimates of APARchl provided more realistic gross primary production (GEP) and LUE from flux tower data than its based on the PAR absorbed by canopy [6].

Emission of chlorophyll fluorescence competes with photochemical energy trapping (conversion) in reaction centers resulting in fluorescence quenching when trapping in the reaction center is effective. The complementary relation between fluorescence and photochemical yield has made it possible to monitor a sensitive non-invasive probe in photosynthesis using fluorescence [17]–[19]. The effect of chlorophyll fluorescence emission on the apparent vegetation reflectance spectrum has recently been investigated [20]–[22]. Although the observed vegetation reflectance inevitably includes contributions from both reflected and fluoresced radiations, many researches have proved that it is possible to separate solar-induced ChlF radiation from observed apparent vegetation reflectance. For example, the solar-induced ChlF signals at 656 nm, 687 nm, and 760 nm were successfully separated from the observed apparent vegetation reflectance based on the Fraunhofer-line principle [21]–[24]. Although the intensity of the ChlF emission is relatively low, it is commonly used to track leaf photosynthetic activity, and is considered a rapid, noninvasive probe for photosynthetic activity [17], [25]. Therefore, we propose a more direct remote sensing method to monitor LUE by the separated solar-induced ChlF radiation.

To test whether the solar-induced ChlF is correlated with LUE, two diurnal change experiments were designed for winter wheat (C3 plant functional type) and summer maize (C4 plant functional type). The leaf-level net photosynthetic rates and the canopy-level net CO2 flux values were acquired for both crops. The LUE values from the leaf-level net photosynthetic rates and the canopy-level CO2 flux values were correlated to the separated solar-induced ChlF signals. The results proved that LUE can be detected more directly using the solar-induced ChlF.

II. Materials and Experiments

Maize (C4 plant functional type) and winter wheat (C3 plant functional type) were selected to acquire canopy spectra and photosynthetic parameters.

A. Leaf-Level Experiment for Winter Wheat

1) Study Site: A diurnal variation experiment was designed for winter wheat (C3 plant functional type) to acquire the leaf-level net photosynthetic rates and canopy spectra. The experiment was performed at Beijing Academy of Agriculture and Forestry Sciences (39.942°N, 116.277°E) on 18 April 2008, when the winter wheat was at the jointing stage (the flag leaf is fully emerged from the whorl). The experimental area had normal fertilizer management and uniform growth with a size of about 100×100 m^2. The leaf area index (LAI) was 5.8 and the vegetation coverage was nearly 100%, which suggested the good growth status.

2) Spectral Measurement: All canopy spectral measurements were taken from a height of 1.3 m from the canopy (2 m above the ground) using an ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Boulder, CO, USA). The spectrometer was fitted with a 25° field-of-view bare fiber-optic cable and operated in the 350–2500 nm spectral region with a sampling interval of 1.4 nm between 350 and 1050 nm and 2 nm between 1050 and 2500 nm. The spectral resolution (or FWHM) was 3 nm for the region 350–1000 nm and 10 nm for the region 1000–2500 nm. The fiber-optics was fixed at the southern end of a horizontal pole, which was fixed by a tripod in the north–south direction. All the canopy and panel radiance spectra were taken every 30 min from 9:00 to 17:30. The minimum solar zenith angle was about 29° on 18 April 2008, and the field of view of the fiber optics was 25°. Because the fiber optics was fixed at the south end of the horizontal pole, the spectral measurements in the diurnal experiment were not influenced by the shadow of the pole and the fiber.

3) The Leaf-Level Photosynthesis Measurement: The photosynthetic parameters were measured by a portable photosynthesis measuring system (LI-6400, Li-Cor, Inc., USA) under natural illumination, and were carried out synchronously with the spectral measurement. Measurements were conducted for the selected five flag leaves every 30 min from 9:00 to 17:30. These measured photosynthetic parameters included net photosynthetic rate (Pn), stomatal conductance (Gs), transpiration (Ts), intercellular Co_2 concentration (Ci), atmospheric Co_2 concentration (Ca), leaf temperature (TL), relative humidity (RH), photosynthetically active radiation (PAR), etc.

B. Canopy-Level Experiment for Summer Maize

1) Study Site: Another diurnal variation experiment was designed for summer mazie (C4 plant functional type) to acquire the canopy-level net Co_2 flux values and the canopy spectra. The experiment was performed on 5 July 2008 at Yingke Irrigation Area, Zhangye, Gansu Province (38.858°N, 100.407°E). The experimental field had normal fertilizer management and uniform growth with a size of 360×350 m^2. The LAI was 5.3 and the vegetation coverage was about 90%.

2) Spectral Measurement: The canopy spectral measurements were taken from a height of 2.3 m from the canopy (4 m above the ground) using an ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Boulder, CO, USA). The fiber optics was fixed at the southern end of a horizontal pole, which was fixed by a stand in the north-south direction. All the canopy and panel radiance spectra were taken every 30 min from 10:00 to 16:00 and every 60 min from 16:00 to 20:00.

3) CANOPY-Level Co_2 Flux Measurement: An open-path eddy covariance (EC) system was installed at a tower to record the net ecosystem exchange of Co_2 (NEE, mg $Co_2 \cdot m^{-2} \cdot s^{-1}$), latent heat (LE, $W \cdot m^{-2}$), and sensible heat (H, $W \cdot m^{-2}$) by a CR5000 datalogger (CSI). Each tower included a fast-response 3-D sonic anemometer (CSAT3, CSI) and an open-path gas analyzer (LI-7500, LICOR). The CSAT3 and LI-7500 were mounted at the height of 4 m above the ground. The half-hour NEE of Co_2 was calculated from the covariance between vertical wind velocity $(m \cdot s^{-1})$ and Co_2 concentration $(mg \cdot m^{-3})$ fluctuations using Reynolds decomposition rules [26]. A DYNAMET Weather Station was also fixed at the tower to record the weather parameters, such as PAR, temperature, rain, and winds.

III. Methods

A. Principles to Detection LUE From ChlF

Chlorophyll, the major leaf pigment, predominantly absorbs the visible light, mainly blue and red. When there is no non-photochemical quenching, chlorophyll fluorescence is inversely correlated to photosynthesis, the process that converts Co_2 to biomass using sunlight as the energy source. As the visible part of the sunlight incident on a leaf is absorbed by the leaf pigments such as chlorophylls and carotenoids, the non-absorbed

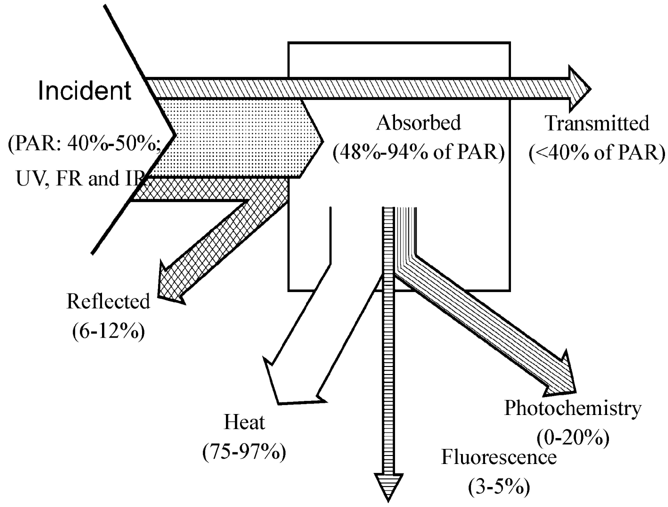

Fig. 1. Different processes occurring to the energy reaching leaf surface [27].

part of light (mainly green quanta) is reflected and transmitted (as illustrated in Fig. 1).

The absorbed energy is channeled into heat, photochemistry, and fluorescence. In the process, roughly 20% of energy is taken up by the leaf through the absorption of light under the optimum condition, and the energy is converted into photochemical energy internally. The remaining energy is dissipated as ChlF (ca. 3%–5%) and heat (ca. $>75\%$). ChlF is inversely related to the photosynthetic activity when there is no non-photochemical quenching; it decreases with increasing photosynthesis (photosynthetic quantum conversion) and *vice versa* [18]. The decrease of the photosynthetic activity by various types of stress makes ChlF a valuable tool in characterizing the health state of a plant.

B. Derivation of Photosynthetic Light-Use Efficiency

The definition of LUE can vary, because studies use net primary production (NPP) in the numerator or gross primary production (GPP) [5], [28]. The amount of absorbed light that plants can trap from the sun is referred to as GPP. When ecosystem photosynthesis is calculated with a process model, it is referred to as GPP. In this study, LUE is defined as the ratio of GPP to APAR. GPP is the product of three terms [6]: 1) the light use efficiency, which is a measure of the PAR conversion efficiency into photosynthetically fixed Co_2; 2) the fraction of absorbed photosynthetically active radiation (fPAR) of the canopy; and 3) the incident PAR where

$$\mathrm{GPP} = \mathrm{LUE} * \mathrm{fAPAR} * \mathrm{PAR}.$$

1) Derivation of LUE at the Leaf Scale Experiment: At the leaf scale experiment, we assumed that NPP equals to GPP during the measuring time and most of the incident PAR on green leaf was absorbed (almost 90%) [29], [30]. The leaf's absorbed light was approximated by the PAR values recorded by the LI-6400 measuring system. The LUE at the leaf scale experiment was derived as

$$\mathrm{LUE}(\%) = \frac{Pn(\mu\mathrm{mol\ Co_2 \cdot m^{-2} \cdot s^{-1}})}{\mathrm{PAR}(\mu\mathrm{mol \cdot m^{-2} \cdot s^{-1}})} \times 100\%. \quad (1)$$

2) Derivation of LUE at the Canopy Scale Experiment: At the canopy scale experiment, fPAR was measured using a Sunscan Canopy Analysis System according to the method of [31], with a value of 0.891. The LUE at the canopy scale experiment was derived as

$$\mathrm{LUE}(\%) = \frac{\mathrm{GPP}}{\mathrm{fPAR} * \mathrm{PAR}} * 100\%. \quad (2)$$

An indirect method in measuring GPP is to determine the mass of carbon that a plant absorbs during the photosynthesis. However, plants also respire; they emit Co_2 as well as take it in. The respiration (RE) can be calculated separately for growth (Rg) and maintenance (Rm) components. It is necessary to separate net ecosystem Co_2 exchange (NEE) from the photosynthetic and respiration fluxes. The growth respiration (Rg) is assumed to be about 25% of NEE if GPP is greater than respiration [32]. We employed a conventional method, in which the maintenance respiration (Rm) is expressed as an empirical function of microclimatic variables. Temperature sensitivity of Rm is often expressed by Q_{10}, defined as respiration rate increase with every 10 °C increase in temperature $(\mathrm{Q}_{10} = 2)$. The Q_{10}-based formula has commonly been used to calculate soil or ecosystem respiration at local to global scales [33], [34]. We also used nighttime RE-temperature relationship to determine nighttime Rm [35]:

$$\mathrm{Rm}(T) = \mathrm{Rm}_0 \times Q_{10}^{(T-25)/10} \quad (3)$$

where Rm_0 is the maintenance respiration when the air temperature is 25 °C. As the nighttime Rg and GPP can be neglected, the nighttime NEE can be approximated as Rm. Rm_0 was regressed with the nighttime NEE and air-temperature data, resulting in a value of 13.242 with R^2 of 0.52 $(\mathrm{n} = 18)$.

If the soil's heterotrophic respiration is neglected, GPP can be calculated as

$$\mathrm{GPP} \approx \mathrm{NEE} + \mathrm{RE} = \mathrm{NEE} + \mathrm{Rg} + \mathrm{Rm}. \quad (4)$$

The daily variation curves of PAR, GPP, NEE, and RE are given in Fig. 2. The results show that GPP, NEE, and RE track closely with PAR. RE covers about 45% of GPP, and stays at a higher level until 18:00 when GPP starts to decrease rapidly. NEE covers about 55% of GPP and decreases to 0 or a negative value when PAR is smaller than 200 $\mu\mathrm{mol \cdot m^{-2} \cdot s^{-1}}$, indicating that maintenance respiration is the dominant contribution to flux under conditions of low illumination.

C. Separation of ChlF Signal Based on the Fraunhofer Lines In-Filling Method

The amount of chlorophyll fluorescence emitted by a leaf under natural sunlight only accounts for up to 1% or 2% of the absorbed light in the visible part of the spectrum [19], [21]. It is difficult to quantify because the signal is obscured by the reflected light. However, at certain wavelengths where the solar spectrum is attenuated (Fraunhofer lines), the fluorescence signal may be quantifiable.

Fraunhofer lines are dark absorption lines in the solar spectrum, including those at 486, 527, 589, 656, 688, and 760 nm. All these bands can be detected if the signal-to-noise ratio

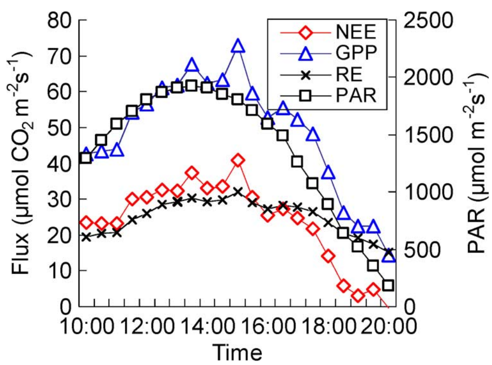

Fig. 2. Daily changes of net primary productivity, gross primary productivity, and respiration.

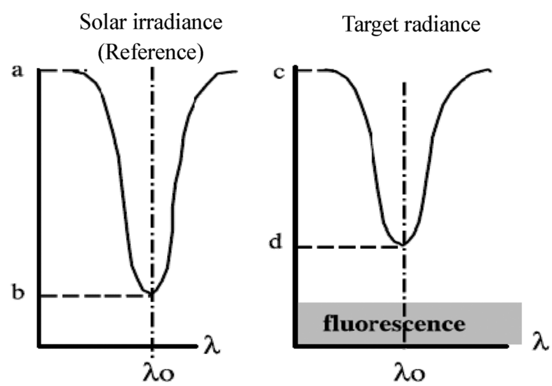

Fig. 3. Detecting vegetation fluorescence from Fraunhofer lines [21].

(SNR) and spectral resolution of the spectral instrument is sufficiently high. The two oxygen absorption bands (688 nm and 760 nm) located closer to the chlorophyll fluorescence peaks can be selected to monitor the chlorophyll fluorescence emission under daylight excitation by the Fraunhofer lines in-filling method [21], [24], [36].

The principle of the Fraunhofer lines in-filling method is and shown in Fig. 3. The fluorescence flux f can be calculated as [21], [37]

$$f = \frac{(a \times d - c \times b)}{(a - b)} \tag{5}$$

where a and b represent the detected irradiance from the reference panel in and out of the oxygen-absorption feature. Similarly, c and d represent the detected radiance from the target at the border and at the bottom of the band. The solar-induced fluorescence at 688 nm and 760 nm was calculated according to (5). For the 688 nm O_2 Fraunhofer line, the bands in and out of the oxygen absorption feature were set as 684 nm and 688 nm sampling bands of the ASD spectrometer, where a and b were the detected irradiance from the reference panel at the 684 nm and 688 nm sampling bands of the ASD spectrometer, and c and d were also the reflected radiance from the canopy at the 684 nm and 688 nm sampling bands. Similarly, the bands in and out of the 760 nm oxygen-absorption feature were set as 756 nm and 760 nm sampling bands of the ASD spectrometer.

ChlF radiation is only a small part of the observed apparent vegetation reflectance, and the relative ChlF is defined as the ratio of ChlF radiation to the canopy irradiance at the border band of the Fraunhofer line. According to (5), the relative ChlF, fr, can be calculated as

$$fr = \frac{f}{a} = \frac{(a \times d - c \times b)}{[(a - b) * a]}. \tag{6}$$

IV. Results and Analysis

A. Relation Between PAR and the Separated ChlF

Photosynthetic processes, including photochemical process (LUE) and chlorophyll fluorescence, are determined by genotypes and also by external environmental factors, such as temperature, water, nutrition, or disease.

In the two diurnal experiments, solar-induced ChlF radiation was mostly determined by PAR. The solar-induced ChlF radiation calculated according the Fraunhofer lines in-filling method was correlated to PAR. The relations between the solar-induced ChlF radiation and PAR of the two experiments are given in Fig. 4 and Fig. 5. The two figures show a positive linear relation between PAR and the separated ChlF radiation at 688 nm and 760 nm. The correlation coefficients (R^2) are 0.79 at 688 nm and 0.80 at 760 nm for winter wheat, and 0.89 at 688 nm and 0.99 at 760 nm for summer maize. The solar-induced ChlF intensity detected by the Fraunhofer lines in-filling method is a radiance signal. More incident photons were irradiated on a leaf, more chlorophyll fluorescence photons will be yielded. Therefore, the positive relation between the solar-induced ChlF and PAR was reasonable, which was also observed by other researches [21], [38]–[40].

The relative solar-induced ChlF was also correlated to PAR. The statistical results show a positive linear relation between PAR and the relative separated ChlF at 688 nm and 760 nm. The correlation coefficients (R^2) are 0.72 at 688 nm and 0.62 at 760 nm for winter wheat, and 0.70 at 688 nm and 0.86 at 760 nm for summer maize. The results suggest the self-protective mechanism of ChlF at a high irradiance level.

We also found a negative linear relation between LUE and PAR. The correlation coefficients (R^2) are 0.78 at 688 nm and 0.64 at 760 nm for winter wheat, and 0.63 at 688 nm and 0.77 at 760 nm for summer maize.

B. Relation Between LUE and the Separated ChlF

During photosynthesis, part of the energy captured by chlorophyll is dissipated as fluorescence within the wavelength of 650–800 nm with peaks at 690 and 740 nm. Chlorophyll fluorescence, combined with non-photochemical quenching (NPQ), is an expression of the balance between light harvested (absorption) and light utilized in the photosynthetic process [19], [41]. The 690 nm fluorescence signal from leaves and crops is therefore widely employed by physiologists and agronomists as a diagnostic tool for detecting crop stress.

In principle, fluorescence is very closely related to the efficiency of light utilization because it represents ‘wasted’ energy. If the incident light and NPQ are fixed, ChlF is inversely related to the photosynthetic activity; i.e., it decreases with increasing photosynthesis (photosynthetic quantum conversion) and *vice versa* [18].

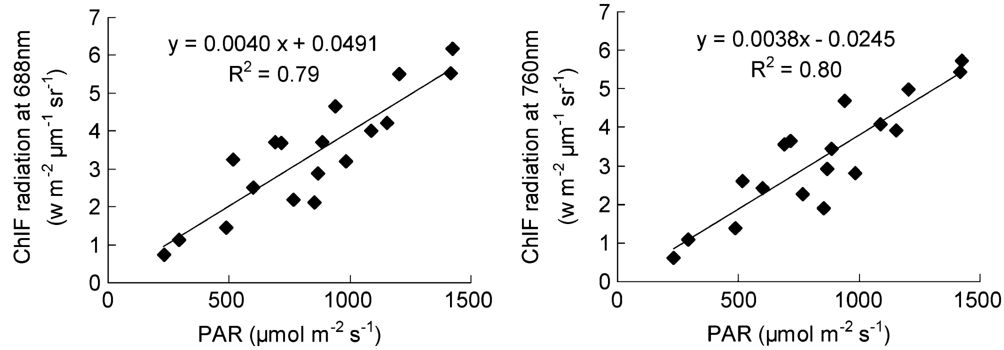

Fig. 4. The relations between PAR and ChlF signals at 760 nm and 688 nm for wheat.

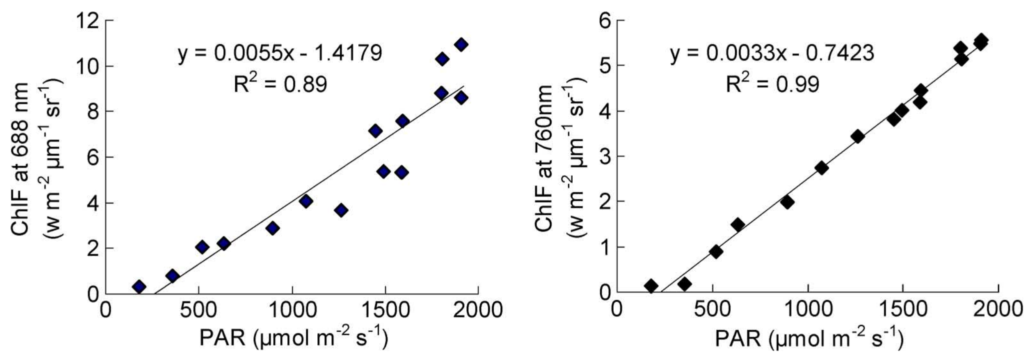

Fig. 5. The relations between PAR and ChlF signals at 760 nm and 688 nm for maize.

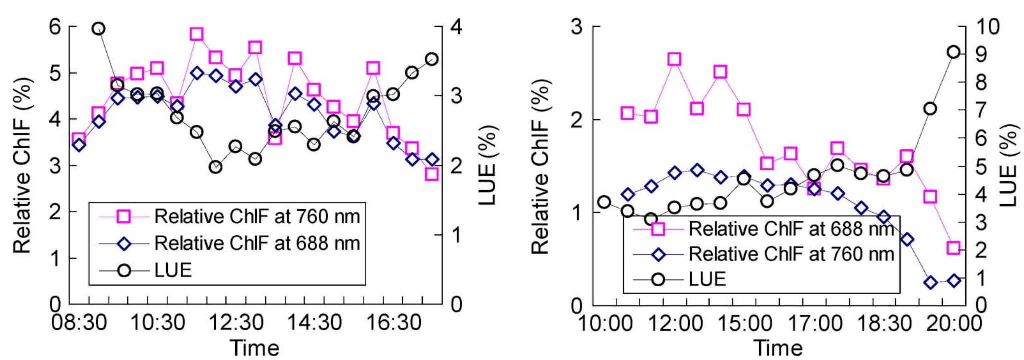

Fig. 6. The daily changes of LUE and the relative ChlF signals at 760 nm and 688 nm for wheat (left) and maize (right).

As shown in (1) and (2), LUE is defined as the number of moles of carbon fixed per mole of absorbed light. Therefore, the relation between the relative ChlF and LUE should be more reasonable and practical because the influence of PAR is eliminated.

Fig. 6 shows the daily changes of LUE and the relative ChlF at 688 nm and 760 nm for winter wheat and summer maize. These results demonstrated that the relative ChlF was higher at noon and lower in the morning or afternoon, which was inversely related to the diurnal changes of LUE.

The relative ChlF values at 760 nm and 688 nm were correlated to LUE (Fig. 7 and Fig. 8). There is a significantly negative relation between the relative ChlF and LUE at the leaf level for winter wheat, with R^2 of 0.78 at 688 nm and 0.64 at 760 nm, respectively. A similar significantly negative relation was also found between the relative ChlF and LUE at the canopy level for summer maize, with R^2 of 0.63 at 688 nm and 0.77 at 760 nm, respectively. These results demonstrate the feasibility and reliability to use solar-induced ChlF signals separated at Fraunhofer lines in the estimation of LUE.

V. Conclusions and Discussions

Photosynthetic efficiency is very important and not yet generally assessable by remote sensing. On the one hand, LUE is known to exhibit both spatial variation across vegetation types and temporal variation at individual sites. On the other hand, chlorophyll fluorescence (ChlF) is a direct indicator for plant physiology, and reflects the photochemical process and efficiency. Thus, it is possible to determine LUE by monitoring solar-induced ChlF radiation using remote sensing technology.

In this study, two diurnal experiments were carried out on winter wheat and summer maize to obtain the diurnal changes of canopy radiance spectra, LUE, and PAR. Experimental data reported here demonstrates that the solar-induced fluorescence

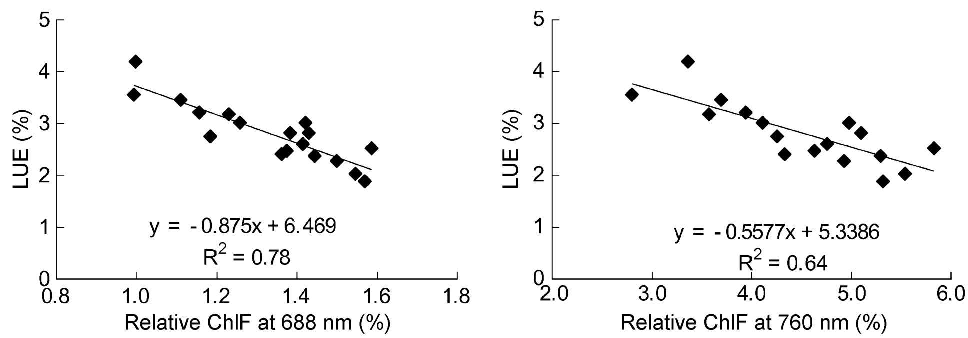

Fig. 7. The relations between LUE and the solar-induced ChlF at 760 nm and 688 nm for wheat.

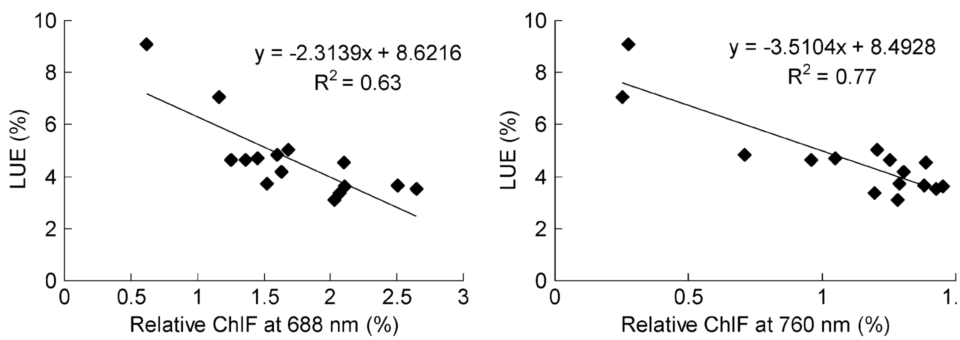

Fig. 8. The relations between LUE and the solar-induced ChlF at 760 nm and 688 nm for maize.

spectra are observable in canopy radiance spectra through the two Fraunhofer absorption features at 688 nm and 760 nm. The separated ChlF signals were significantly and negatively correlated to LUE. The leaf-level LUE models for winter wheat were based on the relative ChlF at the 688 nm $(\mathrm{R}^2 = 0.78)$ and 760 nm $(\mathrm{R}^2 = 0.64)$. The canopy-level LUE models for summer maize were also built based on the relative ChlF at 688 nm $(\mathrm{R}^2 = 0.63)$ and 760 nm $(\mathrm{R}^2 = 0.77)$.

These results demonstrate that it is feasible to determine LUE from hyperspectral data if the separated ChlF signals at the Fraunhofer lines can be derived. However, NPQ is also an important regulatory process in photosynthesis, strategically aimed to diminish any damage, which may be caused by high light intensities. The complementary and competitive relationship between fluorescence and photosynthesis (and by association LUE) is only observed when non-photochemical quenching is not operating. Changes in the ChlF reflect the changes in quantum yield of photochemical reaction and also thermal dissipation of the excitation energy. Only when the ChlF signals combined with NPQ, LUE can be completely determined. Therefore, the LUE models based on ChlF were limited by the disturbance of NPQ.

Furthermore, the negative correlation between solar-induced ChlF and LUE may still affected by the variations in vegetation species, physiological statuses, and environmental conditions. Furthermore, these relationships may not applicable to airborne or spaceborne remote sensing data, because the atmospheric absorption of the up-welling radiation at the two oxygen bands has not been eliminated.

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