J. Agr. Sci. Tech. (2016) Vol. 18: 387-398

Estimating and Validating Wheat Leaf Water Content with Three MODIS Spectral Indexes: A Case Study in Ningxia Plain, China

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ABSTRACT

Water content plays an important role in the process of plant photosynthesis and biomass accumulation. Many methods have been developed to retrieve canopy leaf water content from remote sensing data. However, the validity of these methods has not been verified, which limits their applications. This study estimates the Leaf Water Content (LWC) of winter wheat with three most widely used indexes: Normalized Difference Water Index (NDWI), Simple Ratio (SR), and Shortwave Infrared Perpendicular Water Stress Index (SPSI), as well as MODIS short wave and near infrared data, and then compares remote sensing estimates of vegetation water content with field-measured values measured in concurrent dates. The results indicate that the three indexes are significantly correlated with the LWC of winter wheat at the 0.01 significance level. They all have good accuracy with higher than 90%. The indexes derived from MODIS bands 6 and 2 were better than those from bands 7 and 2 for measuring wheat leaf water content, and the correlations of the former two (NDWI and SR) were stronger than that of *SPSI*.

Keywords: Near infrared band, Remote sensing, Short wave infrared band. Spectral characteristic index, Validation.

INTRODUCTION

Several vegetation properties affect its spectral signature, some of which are diagnostic of vegetation health, for instance, water and nutrients (Ustin and Gamon, 2010; Ghasemloo *et al.*, 2011; Darvishsefat *et al.*, 2011). Kramer (1983) pointed out that the influence of water stress on plant growth and output is much larger than that of any other factor. Specially, accounting for 40-80% weight in the plant canopy, water is essential to the process of plant photosynthesis and biomass accumulation (Pan, 2004). The canopy leaf water content can reflect the status of plant physiology, thus, its monitoring and diagnosis with remote sensing is of great significance for agriculture, forestry, and ecology of the environment, as well as for evaluating vegetation drought (Zhang *et al.*, 2007). Crop water stress can cause a series of leaf

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[DOR: 20.1001.1.16807073.2016.18.2.6.6]

changes in the space extension attitude, the shape of the structure, color, and thickness, etc., further leading to the spectral reflectance changes of the leaf and canopy (Mamnouie *et al.*, 2006; Eslam, 2009; Paul and Danson, 2004; Mousivand *et al.*, 2014). Therefore, diagnosing the water content of leaf and plant with crop spectral characteristics has become the focus in agricultural remote sensing (Wang *et al.*, 2008b).

Generally, three methods have been developed for monitoring crop canopy water content with remote sensing technologies. The first method estimates canopy water content indirectly using soil moisture content (Xue *et al.*, 2003). Due to the big variations in crop water use over soil conditions, crop species and cultivation modes, this method cannot reflect crop water deficit independently, thus, it does not meet the requirement of determining crop water deficit status timely and accurately in practice (Xue *et al.*, 2003). The second method uses canopy temperature to compute crop transpiration, such as the reference temperature method (Tanner, 1963), Crop Water Stress Index (CWSI) and so on (Zhang, 1987; Qi *et al.*, 2005). Although it has been an important method to measure plant water stress, crop transpiration is strongly influenced by environmental conditions. That is, the relation between plant water content and transpiration is determined by some complex meteorological and biophysical parameters, not by a single factor. Accordingly, the applications of this method are limited (Zhao, 2010). Unlike the former two methods, which estimate the canopy water content indirectly, the third method monitors water content directly by radiative transfer models (Jacquemoud *et al.*, 2000; Zarco-Tejada *et al.*, 2003) or with spectral feature indexes (Jackson *et al.*, 2004; Chen *et al.*, 2005; Ghulam *et al.*, 2007, 2008; Yilmaz *et al.*, 2008; Wu *et al.*, 2009; Hunt *et al.*, 2011; Mirzaie *et al.*, 2014), because spectral indexes are direct measures of vegetation moisture in the sense that they try to capture and maximize the sensitivity of vegetation reflectance to moisture content. Studies on mechanism of remote sensing indicate that Short Wave Infrared (SWIR) is more sensitive to vegetation liquid water than visible light and near infrared bands, but vegetation water is also influenced by factors of leaf internal structure and dry matter, while NIR and SWIR bands commonly used in the vegetation water inversion can eliminate these effects (Ceccato *et al*., 2001). Therefore, spectral indexes based on NIR and SWIR bands are helpful to monitor crop water content directly (Kramer, 1983). In the shortwave infrared band of 1.3 ~ 3.0 μm range, there are three valleys of water absorption in 1.45, 1.95, and 2.6-2.7 μm, due to the water absorption of the leaf cell sap and cell membrane. The different shape and characteristics of vegetation reflectance spectral curve in different bands lay the physical basis for identifying or distinguishing from other features in remote sensing images (Mei *et al*., 2001). Spectral (vegetation) index methods use the combination of some specific bands or band reflectance of vegetation to estimate vegetation content. The environmental impacts of terrain, soil, cloud shadows, and atmospheric conditions on vegetation can be minimized or eliminated by choosing band combinations with some physical basis, for example, bands normalization or simple ratio (Li *et al*., 2009; Tadesse *et al.*, 2005). Tian *et al*. (2000) and Wang *et al*. (2001) measured the wheat leaf water content and established a linear relation between wheat leaf relative water content and spectrum characteristic absorption peaks depth and area near 1.45 μm. The results showed that the water shortage situation of wheat can be diagnosed by spectral reflectance. But, as the atmospheric moisture absorption band, the 1.45 μm spectrum is not within the atmospheric window, hence, it is difficult to obtain the high quality data of this band using aerial remote sensing images. Therefore, this method is more suitable for precision agriculture in the high

[DOR: 20.1001.1.16807073.2016.18.2.6.6]

spectrometric determination of crop leaf water on the ground. Ratio type methods, for instance, Simple Ratio (Jordan, 1969) and Water Index (Peñuelas, 1993), have been proposed for remote sensing of vegetation water content. Tian *et al*. (2004) presented the statistical method to study the correlation between wheat canopy reflected characteristic and leaves and plant water status under the condition of different soil water and nitrogen. They also developed a new vegetation water index of $(\rho_{610}/\rho_{560})/((\rho_{810}-\rho_{610})/(\rho_{810}+\rho_{610}))$ to predict water status of wheat. (Here ρ560, ρ610 and ρ810 is the vegetation spectral reflectance of 560 nm, 610nm and 810 nm, respectively) But vegetation index is on the basis of ground survey data, and does not eliminate the influences of atmosphere, soil and other factors, thus, more work are needed to test the accuracy of the index. Shortwave Infrared Perpendicular Water Stress Index (SPSI) was first developed by Ghulam *et al*. (2007) and proved to estimate vegetation water content better.

Due to the relative complexity of radiative transfer models, the most widely used method for monitoring crop water content directly is the spectral characteristic indexes constructed by Short Wave Infrared (SWIR) and Near Infrared (NIR) bands (Jackson *et al.*, 2004; Chen *et al.*, 2005; Ghulam *et al.*, 2007, 2008; Yilmaz *et al.*, 2008; Wu *et al.*, 2009; Jr Hunt, *et al.,* 2001; Mirzaie *et al.*, 2014). Many indexes have been developed, such as Normalized Difference Index of the near Infrared (NDII) (Hardisky, 1983), Normalized Difference Water Index (NDWI) (Gao, 1996), and Vegetation Drought Index (VDI) (Maki *et al.*, 2004), by using NIR and SWIR of wide band or narrow band, among which NIR is used as reference band, and SWIR as moisture determination band. Moreover, a spectrum inversion model of plant water content can be constructed based on the red edge width of canopy spectral (Wang *et al.*, 2008b). Therefore, this method is more practical for monitoring irrigation and crop water. Here, NDVI was not adopted because the vegetation response can reach saturation easily and reflect the situation of vegetation later. Enhanced Vegetation Index (EVI) can better reflect the vegetation condition by adding blue band in comparison with NDVI, while it does not consider the shortwave bands which are more sensitive to vegetation water. Although many studies on selecting appropriate bands have been done to define indexes for estimating the leaf water content, there is still a lack of work on whether the existing methods can reflect the leaf water content effectively, and whether the estimated leaf water content is accurate enough for practical applications. This lack limits the applications of the presented methods, thus, it is necessary to conduct some experiments to answer these questions.

The present study aimed to estimate the wheat leaf water content using three most widely used methods and MODIS data, and then build series of models to explore the relationships between the three indexes from MODIS data and collected values from ground survey. The goal of the paper is to validate and compare the feasibility and availability of the three indexes with time series data in north-west China, and find out which index and which shortwave infrared band is better to measure the leaf water content and how they are correlated with the real the leaf water content.

MATERIALS AND METHODS

Study Area

The study area was located in Ningxia Huizu autonomous region of China, which is a representative semi-arid region, with annual precipitation and evaporation of about 200 mm and 1,600 mm, respectively. The south part of Ningxia is drier than the north part, due to the lower precipitation and higher evaporation in the southern part, and the proximity of the northern part to the Yellow River. For this study, two 1 km×1 km plots of winter wheat in Guyuan City (Kujing Village), and two plots of similar

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size in Yongning County (one is in Wanghong area, and the other in Dongfang area) were selected. Each plot contained five sample points (Figure 1), and the geographic information of five sample sites was thus recorded by Global Positioning System (GPS) within a 1 km^2 scale (corresponding to MODIS pixels). In each site, ten pieces of upper leaves of each cluster wheat plants (about ten or more plants) were collected in a numbered plastic bag. The wheat leaf water content was determined by collecting leaf clippings, after fresh weight measurement using electronic balance, clippings were dried by oven at 80°C for 24 hours to determine its dry weight, and then leaf water content was calculated (Ping *et al.*, 2007). To match MODIS imagery pixel, the leaf water contents of the five sample points were averaged to represent the water information of the entire plot.

The study aimed to investigate the temporal variation in leaf water content in Yongning and Guyuan. The ground truth measurements were conducted synchronously with the Terra-MODIS satellite of 50 m satellite positional accuracy (Wolfe *et al.*, 2002) over cross. We collected wheat leaf at about 10:00-11:00 am on the dates in Table 1 and determined their water content by oven drying method and, consequently, obtained the trial dataset. The trial dataset was divided into two parts: the regression dataset used for building the models, and the validation dataset for testing the models. In other words, for each two plots of Yongning and Guyuan, one was used to

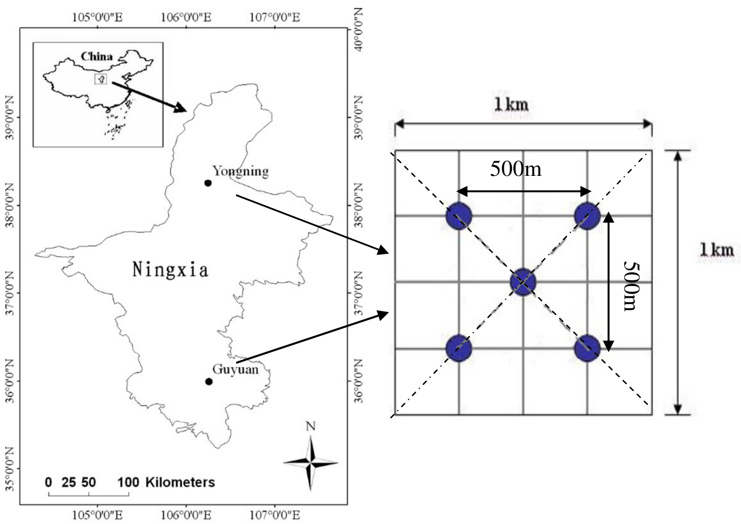

Figure 1. Location of the study area, Ningxia Huizu autonomous region of China.

Table 1. Dates of ground synchronous observation trial in Ningxia, China.

No	Regression date	Site	Validation date	Site
1	2009-05-22	Wanghong	2009-05-22	Wanghong
2	2009-05-26	Wanghong	2009-05-26	Wanghong
3	2009-05-29	Wanghong	2009-05-29	Wanghong
4	2009-05-22	Dongfang	2009-06-17	Wanghong
5	2009-05-26	Dongfang	2009-05-22	Dongfang
6	2009-05-29	Dongfang	2009-05-29	Dongfang
7	2009-06-14	Dongfang	2009-06-14	Dongfang
8	2009-06-17	Dongfang	2009-05-31	Kujing
9	2009-05-31	Kujing	2009-06-08	Kujing
10	2009-06-08	Kujing	2009-06-13	Kujing
11	2009-06-13	Kujing	2009-06-30	Kujing
12	2009-06-30	Kujing		

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construct the regression models, and the other to test these models. Ten wheat plants were chosen to measure leaf water content.

The MOD09 data product of 500 m resolution provided the estimates of the surface spectral reflectance with seven bands. The data was corrected for the effects of atmospheric gases, aerosol, and thin cirrus clouds (Vermote and Vermeulen, 1999). MOD09GA includes quality control descriptions of the data and has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts. From the NASA website (http://edcimswww.cr.usgs.gov/pub/imswelcome/), the MOD09 products (005 version) were downloaded freely in SIN (Sine) projection with HDF format, and then re-projected onto an Albers equal area projection in GeoTIFF format using MRT (MODIS Re-projection Tool). All images were acquired under cloud-free condition.

Methodology

With the convenience and availability of spectral indexes mentioned in the introduction, this study used the following widely used spectral indexes to estimate the vegetation water content with MODIS data.

(1) *NDWI* (Normalized Difference Water Index; Gao, 1996). SWIR and NIR bands are sensitive to vegetation water content, thus, they are used to eliminate the effects of atmospheric disturbances, and build *NDWI* index [Equation (1)].

$$NDWI = \frac{R_{NIR} - R_{SWIR}}{R_{SWIR} + R_{NIR}} \qquad (1)$$

Where, R_{SWIR} and R_{NIR} refer to the atmospherically corrected reflectance of NIR and SWIR bands, respectively.

(2) *SR* (Simple Ratio; Jordan, 1969). It is used to minimize or eliminate the influences of environmental part by the ratio of SWIR to NIR.

$$SR = \frac{R_{SWIR}}{R_{NIR}} \qquad (2)$$

(3) *SPSI* (Short wave infrared Perpendicular water Stress Index; Ghulam *et al*., 2007). The NIR-SWIR feature space is helpful to select the soil line and build the index. *SPSI* index is defined as follows:

$$SPSI = \frac{1}{\sqrt{M^2+1}}(R_{SWIR} + R_{NIR}) \qquad (3)$$

Where, M is the baseline slope of $NIR-SWIR$, and R_{SWIR} and R_{NIR} are the atmospherically corrected reflectance of NIR and SWIR bands, respectively.

RESULTS AND DISCUSSION

Vegetation water content estimation models using *NDWI, SR, and SPSI* indexes were constructed by the moisture-sensitive band SWIR and the reference band NIR. MODIS data was chosen as it has three (5-7th) short wave infrared bands. In this study, since the data of band 5 had severe stripe noise in China, only bands 6 and 7 were used, whose center wavelengths were 1,640 and 2,130 nm, respectively. Therefore, six indexes $NDWI_{6,2}$, $NDWI_{7,2}$, $SR_{6,2}$, $SR_{7,2}$, $SPSI_{6,2}$, $SPSI_{7,2}$ were obtained in total, and they were compared and tested to determine which of the two SWIR bands and which type of index could provide better results for leaf water content estimation, so as to apply better in practice.

The regression dataset of the ground truth values and the six indexes extracted from MODIS images were used to fit the six models between them. The R^2 of the six models were 0.59, 0.56, 0.61, 0.57, 0.51, 0.44, respectively, after the regression test. As shown in Figures 2, 4, and 6, the six indexes were correlated with the leaf water content, as all the six correlations are significant at the level $\alpha = 0.01$ (P< 0.01). However, although they all are computed from the same bands, *SPSI* may be better according to its principle and definition. It was obvious that the four indexes of *NDWI*, *SR* have stronger correlations with leaf water content than that of *SPSI*. However, it is not

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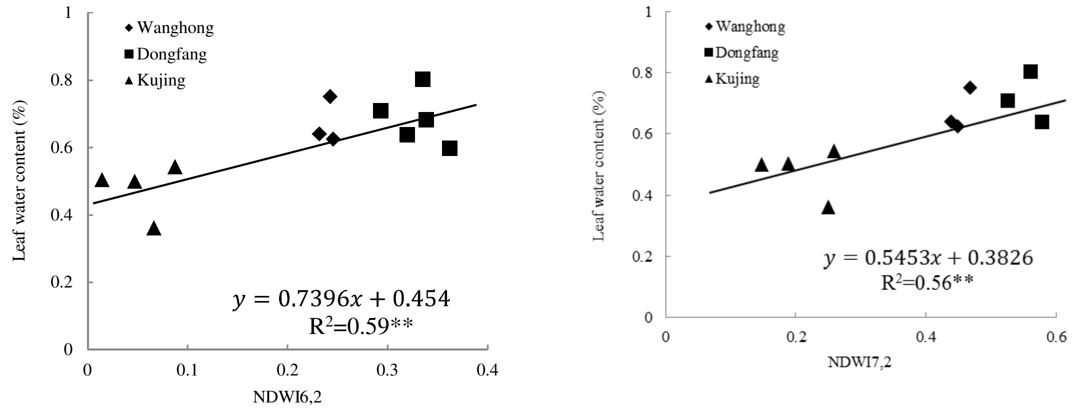

Figure 2. Relations between remotely sensed $NDWI_{6,2}$, $NDWI_{7,2}$ and measured wheat leaf water content.

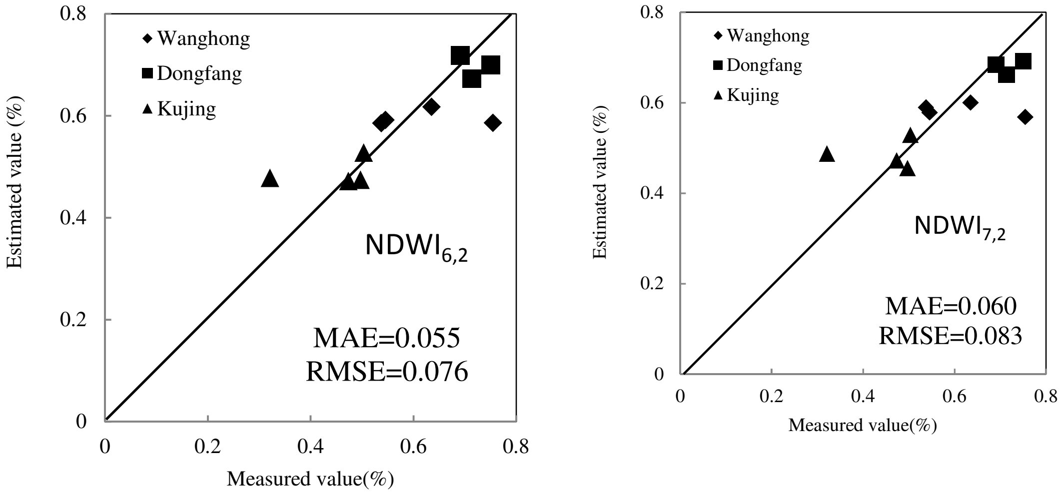

Figure 3. Validation of $NDWI_{6,2}$, $NDWI_{7,2}$ for estimating wheat leaf water content with measured value.

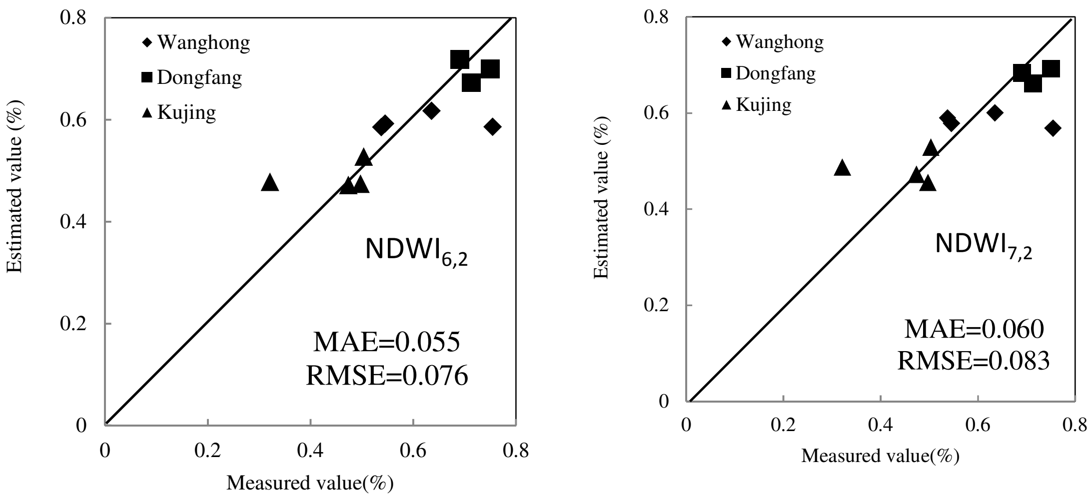

Figure 4. Relations between remotely sensed $SR_{6,2}$, $SR_{7,2}$ and measured wheat leaf water content.

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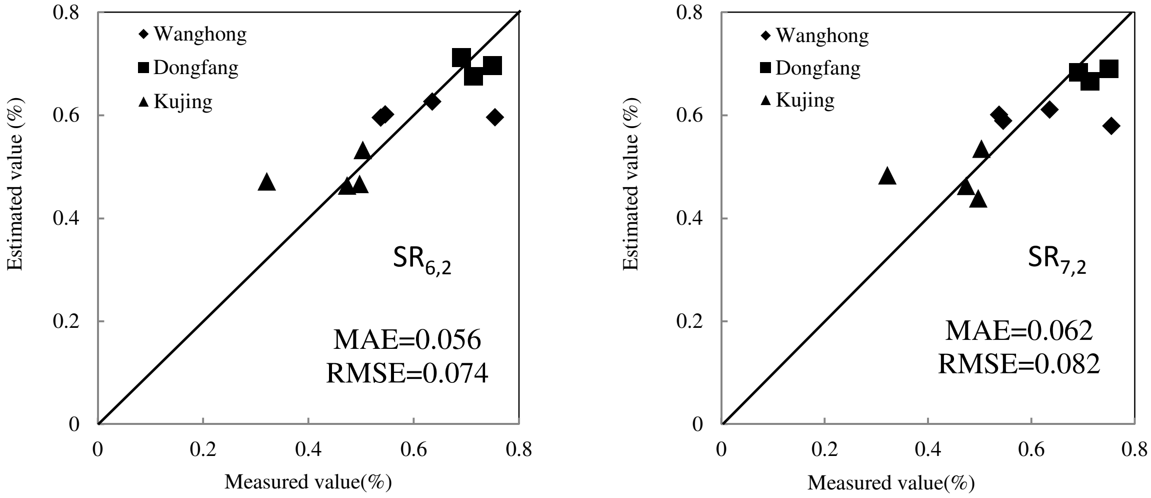

Figure 5. Validation of $SR_{6,2}$, $SR_{7,2}$ for estimating wheat leaf water content with measured values.

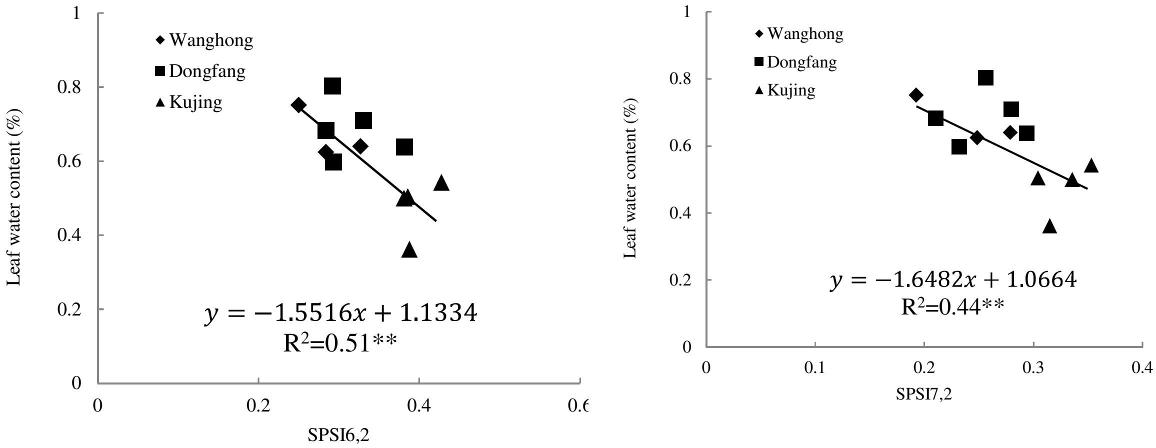

Figure 6. Relations between remotely sensed $SPSI_{6,2}$, $SPSI_{7,2}$ and measured wheat leaf water content.

clear whether this conclusion is true in most places or only in this field, thus, much work is required in future study. For instance, the conclusion needs to be tested in more study areas. In addition, we found that the correlations between the three type indexes of bands (6, 2) and wheat leaf water content were slightly better than that of bands (7, 2), demonstrating that MODIS band 6 was more suitable to measure leaf water content than band 7. This is consistent with the sensitivity studies of Bowyer and Danson (2004), and Wang *et al*. (2008a).

Similarly, the six fitted models were tested by using the validated dataset of the ground-truthing values. The results are shown in Figures 3, 5, and 7, respectively. It can be seen that the *MAEs* (Mean Absolute Errors) of the six models were 0.055, 0.060, 0.056, 0.062, 0.084, and 0.080, respectively; while *RMSEs* (Root Mean Square Errors) were 0.076, 0.083, 0.074, 0.082, 0.107, and 0.102, respectively. Moreover, the inversion error of leaf water content index was basically not larger than 0.1. Namely, the inversion accuracy is above 90%. In three sites of Wanghong, Dongfang and Kujing, from these figures, we find that the measured and estimated values of wheat leaf water content in Kujing are lowest, indicating that Kujing is drier than other two sites. We also found that the inversion accuracies of *NDWI* and *SR* were higher than that of *SPSI*, and the accuracies of bands (6, 2) were better than

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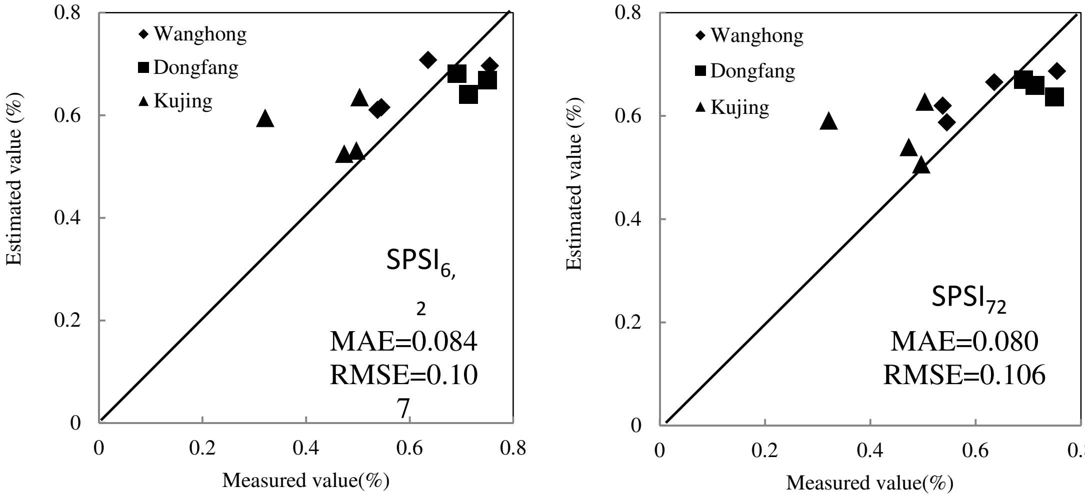

Figure 7. Validation of *$SPSI_{6,2}$ and $SPSI_{7,2}$* for estimating wheat leaf water content with measured values.

that of bands (7, 2). It should be pointed out that the retrieved values were scarcely lower than the observed water content values, partly because the trial covered time was too short to obtain enough data. Therefore further work is needed to demonstrate it.

Comparing the coefficients of the six models, it could be found that: (1) $NDWI_{6,2}$ and $NDWI_{7,2}$ are positively significantly correlated with the leaf water content, while the other four indexes are negatively significantly correlated with the leaf water content. Therefore, the larger the indexes $NDWI_{6,2}$ and $NDWI_{7,2}$, the higher the leaf water content; and the larger the indexes $SR_{6,2}$, $SR_{7,2}$, $SPSI_{6,2}$ *and* $SPSI_{7,2}$, the less the leaf water content, (2) The correlations of indexes (6, 2) with leaf water content are slightly higher than that of indexes (7, 2), indicating that MODIS band 6 is more sensitive than band 7 for wheat leaf water content.

However, since the observations were conducted in the small field of Ningxia, and the range of leaf water content does not include the low value of less than about 0.35%, its applications in other arid regions needs more tests. Moreover, due to the limitation of experiments, this study only measured the leaf water content, more studies are needed to determine the water content of plant stem and stalk, and then to calculate the vegetation overall water content according to certain weight function, like the study of Jackson *et al.* (2004). In addition, the differences in water content between different crops are large, so is the estimation correlation. Therefore, the research will involve more major crops, including corn, rice, etc.

CONCLUSION

The spectral characteristic index constructed by SWIR bands is one of the most widely used methods for monitoring crop water content. The three indexes *NDWI, SR,* and *SPSI* were adopted to estimate leaf water content of winter wheat in Ningxia Plain, China, and were combined with MODIS remote sensing data and the *in situ* data to fit and test the relationships between the indexes and leaf water content.

The results indicated that they had acceptable correlations with leaf water content which is extremely significant at the 0.05 level. The correlations of *NDWI* and *SR* with leaf water content were stronger than that of *SPSI*. The MODIS band 6 is better than band 7 for estimating wheat leaf water content.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (41101313 and 41201331), the High Resolution Earth Observation Systems of National Science and Technology Major Projects (E05-Y30B02-9001-13/15-1), the National High Technology Research and Development Program of China (863 Program) (2013AA122003), Science and Technology Develop Project of Shandong Province (2012GSF11713). We also thank the editors and anonymous reviewers for insightful comments.

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برآورد و راستی آزمایی محتوای آب برگ گندم با استفاده از سه نمایه طیفی MODIS: مطالعه موردی در دشت نینگژیا در چین

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چکیده

آب موجود در گیاه نقش مهمی در فرایند فتوسنتز و تجمع زیستوده دارد. در این رابطه، روش های مختلفی برای تعیین آب برگ پوشش گیاهی با استفاده از داده های سنجش از دور درست شده است. با اینهمه، اعتبار این روش ها راستی آزمایی نشده است و این موضوع کاربرد آن ها را محدود کرده است. درپژوهش حاضر، آب موجود در برگ (LWC) گندم زمستانه با سه نمایه که به طور گسترده ای استفاده می شوند برآورد شده است. این نمایه ها عبارت بودند از : اختلاف نمایه آب نرمال شده (NDWI)، نسبت ساده(SR)، و نمایه تنش آب تابش های عمودی مادون قرمز موج کوتاه (SPSI) و داده های موج کوتاه و نزدیک مادون قرمز MODIS . در ادامه کار، برآورد های به دست آمده از سنجش از دور با اعداد اندازه گیری های مزرعه ای آب موجود در پوشش گیاهی، در تاریخ های همزمان مقایسه شد. نتایج نشان داد که سه نمایه مزبور به طور معناداری (درحد 0/01) با LWC گندم زمستانه همبستگی داشتند. و صحت همگی بیش از ۹۰٪ بود. همچنین، در اندازه گیری آب موجود در

برگ گندم زمستانه، نمایه های به دست آمده از باندهای ۶ و ۲ MODIS بهتر از باندهای ۷ و ۲ بود و همبستگی دو نمایه اخیر(NDWI و SR) قوی تر از همبستگی با SPSI بود.

[DOR: 20.1001.1.16807073.2016.18.2.6.6]