Determining the Canopy Water Stress for Spring Wheat by Using Canopy Hyperspectral Reflectance Data in Loess Plateau Semi-Arid Regions

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Abstract

Crop water stress significantly reduces crop yield. Several studies have employed optical and remote sensing methods to obtain non-damage monitoring crop water content to understand the agriculture drought process. In this paper, the spectral information (i.e., the canopy absorption feature at the 350 nm to 2500 nm band range) from the field experiments was used to estimate and identify the canopy water stress. Five different levels of water treatments exist in the spring wheat field in the semi-arid regions of Loess Plateau, Northwest China. The hyperspectral reflectance, soil moisture content, soil water potential, canopy water content, amount of chlorophyll, leaf area index, and environmental parameters were measured. The relationship between canopy reflectance and canopy water content were analyzed at different water stress levels. In addition, various spectral indices were tested by measurements. Results showed that a high correlation exists in semi-arid water index-1, semi-arid water index-2, and red edge normalized difference vegetation index thus denoting that these indices can indicate
water stress effectively. We can conclude that canopy reflectance can identify crop water stress and can be used to develop a certain index for monitoring agriculture drought.

**KEYWORDS:** Water stress; canopy hyperspectral reflectance; spring wheat; spectral indices; semi-arid regions

## 1. INTRODUCTION

Water scarcity is a major constraint for crop yield and vegetation development in semi-arid regions. In Loess Plateau, Northwest China, rainfall is scarce, and soil erosion and water loss are severe. These two constraints decrease soil moisture, which can decline crop production. The area was constantly hit by drought. The climate change model predicts that drought in this area will be more severe in the coming decades.\[1\]. Drought reduces crop yield, which, in turn, affects people’s lives. Timely irrigation can prevent drought disasters. An accurate estimation of crop water content is significant in irrigation management and drought assessment.\[2\]. Vegetation water content can express plant growth status. The estimation of vegetation water content from canopy level is central to understanding drought processes. This approach is also recognized as a key element in understanding plant biosphere processes and can assist in the monitoring of plant drought in semi-arid rainfed agriculture regions.\[3\].
When crops suffer from water stress, they aim to decrease evapotranspiration\cite{4} and manifest several symptoms, including leaf wilting, photosynthetic ally reduction, stunted growth, and leaf area reduction. These symptoms show the significant effects of drought on crop growth. Therefore, the early detection of crop water stress is critical to minimize loss of productivity. The timely identification of water stress by the color of leaves or other early symptoms was reported in many studies\cite{5-7}.

Compared with other methods, remote sensing can better obtain water stress because it can offer more important spectral details of the crop growth status in the 400 nm to 2500 nm spectral range. High crop canopy reflectance occurs in the near infrared (NIR) and shortwave-infrared (SWIR) regions. Meanwhile, photosynthetic pigments absorb energy only in the visible (VIS) and red-edge spectral regions\cite{8-9}. The amount of reflection and absorption is largely influenced by water and dry matter in leaves\cite{10-11}. Therefore, understanding how water and other factors affect the signal measured in the solar spectrum (400 nm to 2500 nm) is important. Portable spectroradiometers can be used to measure spectral characteristics to estimate leaf properties or canopy properties. The gravimetric water content (GWC, %)\cite{12} is the main parameter describing the amount of water in vegetation, especially at the canopy level. Liquid water strongly absorbs solar radiation in the NIR band (720 nm to 1000 nm) and SWIR band (1000 nm to 2500 nm); solar spectrum shows a series of absorption features. Many experiments have advanced the estimation of plant water content by using hyperspectral remote sensing. A
correlation between NIR and SWIR and plant water content was reported in laboratory studies \[13-14\].

A number of studies have searched for the optimal model and wavelengths to measure plant water content \[15,16\]. Water absorption features at 970, 1200, 1450, and 1950 nm have been given special attention. Gao and Goetz \[17\] and Roberts \[18\] designed a spectrum-matching technique in the 860 nm to 1080 nm region to estimate water vapor and vegetation liquid water. Most researchers have attempted to build spectral vegetation indices that are composed of bands located at absorption peaks and flanks. Some examples of these indices include the plant water index \[11\], normalized difference water index (NDWI) \[10\], and maximum difference water index \[19\]. The equivalent water thickness and moisture stress index (expressed as the ratio of reflectance values at 1600 nm to reflectance values at 820 nm) have shown good relationship \[20\]. In another study, Aldakheel and Danson \[21\] showed that changes occur in the leaf internal structure during dehydration, which affects reflectance of plant canopy across the entire 400 nm to 2500 nm spectrum. The reflectance corresponding to the change was used to model the water stress of leaves and canopies.

At the canopy level, radiative transfer models have been used to simulate the effect of water content on reflectance \[22,23\]. Some researchers proposed empirical relationships between vegetation water content and spectral indices. For instance, Dawson et al. \[24\]
showed that the water index (WI) proposed by Penuslas et al.\textsuperscript{[2]} and the NDWI proposed by Gao\textsuperscript{[10]} were related to the quantity of water per unit area in the canopy. SWIR reflectance has been employed for water stress monitoring\textsuperscript{[1,25]} due to its sensitivity. The normalized difference infrared index (NDII) and simple ratio water index (SRWI) have provided good correlations with canopy water content (CWC)\textsuperscript{[8,26]}.

Other studies have found that some indices based in the visible and red edge regions could provide water stress information. Suárez et al. used the photochemical reflectance index (PRI) to capture water stress\textsuperscript{[5,6]}, whereas Dobrowski et al.\textsuperscript{[27]} used reflectance or indices based on the red edge region to capture water stress, which induced change in chlorophyll fluorescence. Similarly, Gitelson\textsuperscript{[28]} suggested the red edge normalized difference vegetation index (red edge NDVI) However, given the canopy structure, background, and view geometry, the spectral indices for monitoring water stress show uncertainties in different regions and plants. Some investigations have been performed on crops other than spring wheat. As a consequence of the different measurement conditions and different crop, some degree of disagreement exists in the selection of wavebands. Thus, further study is required on the water stress indices of spring wheat in semi-arid areas. In addition, limited studies were reported on the semi-arid region of Loess Plateau.

This study is the first to investigate the change of CWC and chlorophyll (Chl) content of spring wheat in different water-stressed levels. We then analyze the effects of water stress on reflectance at the crop canopy level in the semi-arid regions of Loess Plateau,
Northwest China, on the basis of three years of field experiments. Furthermore, we investigate the relationship between canopy hyperspectral reflectance and soil water potential (SWP) as well as soil relative moisture (SRM) and CWC. Finally, we analyze the relationship of the spectral index and CWC in three years. We have developed two new indices, namely, semi-arid water index-1 (SAWI-1) and semi-arid water index-2 (SAWI-2), to detect water stress in semi-arid regions in Northwest China. We have combined information from both the NIR and SWIR regions to maximize the sensitivity of the CWC of spring wheat in semi-arid regions. This work developed new indices for crop drought in semi-arid regions and may improve the accuracy of crop drought estimation and monitoring in agriculture irrigation and drought management.

2. METHODOLOGY

2.1 Study Areas

The experiments were conducted in 2008, 2011, and 2012 in Dingxi County (104°35′24"E, 35°33′36"N, elevation 1920 m) of Gansu Province, Northwest China. Dingxi County is located in the western Chinese Loess Plateau, with semi-arid continental monsoon climate characterized by cold and dry winters and warm and wet summers. The annual mean precipitation is 450 mm with great inter-annual variations. The average monthly air temperature ranges from −7.4 °C to 27.5 °C, with mean annual temperature of 6.3 °C (weather record from 1960 to 2000). Pan evaporation is 1400 mm. The monthly average precipitation in the growing season of 2008, 2011, and 2012 is 465,
405, and 629 mm, respectively. The predominant gray calcareous soil developed on loess parent material with silt texture has a relatively thick profile. Spring wheat is one of the main crops in the study area.

2.2 Experimental Design

An arid agricultural meteorology station is located about 10 km from Dingxi City. Experiments were carried out in the station. Five water stress treatments were designed: 1) D0: rainfed field; 2) D1: severe drought, soil relative moisture <30%; 3) D2: moderate drought, 30% < soil relative moisture < 40%; 4) D3: light drought, 40% < soil relative moisture < 50%; 5) D4: no drought, soil relative moisture > 50%. Each treatment has three replicated measurements. Each measurement was carried out in a 3 m × 3 m plot. A total of 15 plots were employed in the study. Spring wheat was selected as the study object, and the same management practices were implemented for all plots (i.e., timing, pest, and disease control).

2.3 Field Data Collection

2.3.1 Spectral Measurements

An ASD field spectroradiometer (Analytical Spectral Devices, Boulder CO, USA) with measuring reflectance in the 350 nm to 2500 nm spectral range was used to measure canopy reflectance. The spectrum is characterized by a 3 nm spectral resolution and a 1.4 nm sampling interval across the 350 nm to 1050 nm spectral range and by a 10 nm
spectral resolution and 2 nm sampling interval across the 1050 nm to 2500 nm spectral range. All canopy spectral measurements were taken from a height of 1.0 m above the canopy under clear sky conditions between 1000 and 1400 h (Beijing local time). Spectral reflectance was recorded in the 350 nm to 2500 nm range with a 25° field of view. The spectroradiometer was calibrated before and after each plot reading by using a spectralon white reference panel (Labsphere, Inc., North Sutton, NH, USA). Five scans were averaged in every measurement, and five points were measured in every plot. The spectrometer was programmed to automatically calculate the average of 25 readings taken at each sampling point. The spectral regions of 1350 nm to 1420 nm and 1800 nm to 1960 nm were eliminated from the analysis because they are strongly affected by atmosphere water absorption. By using ViewSpec Pro version 6.0 software to assemble and interpret data, we converted and imported files into statistical software for further analysis.

2.3.2 Physiological Parameter And Water Content Measurements

The leaf area index (LAI) was measured with LAI-2000, and the Chl of spring wheat leaf was measured with the portable Chlorophyll Meter SPAD502 (Minolta Corporation, New Jersey, USA). Soil water content was obtained with the conventional oven-dry method. The SWP and leaf water potential were measured in midday by using WP4 dew point potentiometer (Decagon Devices, Inc., Washington, USA). Crop water content was measured using the drying method. Specifically, fresh weight (FW) was recorded using
an analytical balance. The samples were dried at 72 °C in an oven, until constant weight (dry weight, DW) was reached. Fuel moisture content (FMC) was used to express crop water content, which can be calculated as follows[^29]:

\[
FMC = \frac{FW - DW}{FW (or DW)} \times 100\%.
\]

The leaf water content per unit leaf area or equivalent water thickness (EWT, g/cm\(^2\)) is defined as the ratio of the leaf water content to the leaf area. EWT is a hypothetical thickness of a single layer of water averaged over the whole leaf area[^30]:

\[
EWT = \frac{FW - DW}{A},
\]

where \(A\) is the leaf area. At canopy level, CWC can be represented by the equivalent water thickness of the canopy (\(EWT_{\text{canopy}}\)), which is expressed as follows[^31]:

\[
EWT_{\text{canopy}} = \text{LAI} \times EWT.
\]

### 2.4 Spectral Indices Selected In This Study

The spectral indices used in this study are presented in Table 1. The first three indices (NDWI, SRWI, and WI) are primarily related to the water content of the plant[^8, 10, 11]. The NDVI was primarily related to leaf biomass and canopy structure[^32]. Optimized soil-adjusted vegetation index (OSAVI) has been successfully built to investigate the effects of scene components on indices calculated from pure crown pixels and from aggregated soil[^11]. Red edge NDVI was related with changes in the Chl of the vegetation. PRI and NDII are indices used in recent years to monitor water stress[^11, 27]. A series of semi-arid water indices (SAWI) were used in the current study region.
3. RESULTS AND DISCUSSION

3.1 Response Of Spring Wheat To Water Stress

The variation of CWC and Chl are shown in Figure.1a and Figure.1b, when they are in different water status during the growth stage of spring wheat. CWC varies significantly with different treatments except in the milking stage. Chl decreases with the increase of water stress level. Similar results were observed by Colombo\textsuperscript{[12]}, Ceccato\textsuperscript{[4]} and Brazil\textsuperscript{[35]} reported the EWT\textsubscript{canopy} instead of vegetation water content at the canopy level and found that CWC decreased with water stress. In the same treatment, CWC changes with different growth stages but D1. This finding suggests that EWT\textsubscript{canopy} should be more sensitive at low levels of drought stress for spring wheat. CWC is the highest in heading and blooming stages, which in the two stages drops from 0.06 g·cm\textsuperscript{-2} to 0.01 g·cm\textsuperscript{-2} in five treatments (Fig. 1). Generally, the CWC is the immediate response to soil water stress at the canopy level and is thus mainly used to describe crop water stress in this study. D0, defined as the drought level for rained field spring wheat, is different in the experiment years. Fig. 1 presents the average D0 values in three years. Meanwhile, Chl (here expressed with the measured SPAD value) is a significant indicator of water stress and fluctuates during the growth season. Therefore, the Chl response of spring wheat to water stress is unclear because the Chl response has time hysteresis. Given that the Chl response is later than the CWC, the SPAD values obtained in the study are not variable for early water stress. Fang\textsuperscript{[36]} studied the relationship between Chl and soil water
content. They concluded that Chl remained stable in the water stress status in arid regions. However, some studies reported that Chl increased when soil water content decreased [37].

3.2 Water Stress Prediction Using Canopy Reflectance

The variation of spring wheat canopy hyperspectral reflectance in five treatments has similar trends in the growth stage. However, the spectral response for water stress is more evident in the heading stage than in the growth stage. Thus, we use the hyperspectral reflectance in the heading stage to identify the water stress level. Fig. 2 shows the variation of the reflectance spectrum of spring wheat canopy in different soil moisture status. Significant changes were observed in the SWIR region (1300 nm to 2500 nm), as expected. Significant changes occurred in the NIR (700 nm to 1300 nm) and VIS (400 nm to 700 nm) regions because of severe drought (26% SRM) and no drought stress (70% SRM). VIS and SWIR reflectance increases with the decrease of soil water content, but NIR reflectance increases with the increase of soil water content, which contradicts what has been largely reported for NIR reflectance [2,7,11,38]. Our result may be influenced by soil background. A large proportion of bare land appears because the canopy coverage of spring wheat in water stress status is low in semi-arid regions.

Significantly high reflectance (Fig. 2) in the blue and red regions of the VIS region at high water stress level suggests that leaf water deficit reduces photosynthetic pigment concentration. The result is similar to that found in cotton, wheat, and satsuma mandarin
trees\textsuperscript{39–40}. Reflectance in the VIS region is predominantly controlled by primary photosynthetic pigments\textsuperscript{41}. This finding could be corroborated with the high coefficient of determination values (Fig. 3). Nevertheless, the Chl content showed no sensibility to water stress (Fig. 1); thus, the reason is unclear. In our study, the water absorption wave band in the 970 and 1200 nm range is not notable to water stress. This finding is different from the results reported for water status in other plants\textsuperscript{42}. The reflectance in the SWIR region is the most stable and sensitive to water stress in three-year measurements and in different growth stages. This finding is consistent with the studies of Tian\textsuperscript{42} and Abuwasit\textsuperscript{9}. Many researchers used SWIR combined with NIR to build many spectral indices for monitoring the vegetation water status because SWIR is stable and is sensitive to vegetation water status \textsuperscript{4,10,18,26,31}. Yi used the NDWI index to monitor vegetation water content for cotton\textsuperscript{39}, and Dzikiti used the NDWI index to monitor vegetation water content for citrus trees\textsuperscript{43}. Chen estimated water content by using NDII and NDWI\textsuperscript{44}. Fourty and Baret\textsuperscript{22} reported that the wavelengths at 1530 and 1720 nm seem to be the most appropriate for assessing vegetation water.

### 3.3 Correlation Between Water Content And Spectral Reflectance Of Spring Wheat Canopy

Linear correlation was performed between spring wheat canopy reflectance and CWC as well as SWP and SRM. Spectral reflectance and the three parameters are negatively correlated in the 350 nm to 730 nm, 1410 nm to 1830 nm, and 1930 nm to 2400 nm range.
spectral range and are positively correlated in the 730 nm to 1310 nm spectral range. Fig. 3 indicates that two distinct bands showed the highest correlation values. The correlation coefficients for SWP, SRM, and CWC are respectively 0.93, 0.75, and 0.81 at 780 nm and are −0.94, −0.78, and −0.79 at 1750 nm (Fig. 3). Several indices were developed using two bands in SWIR with different combinations. However, the bands and their combinations were different among indices. The indices in the study are not the same as those of earlier studies [2,10]. We used 780 and 1750 nm bands to build two indices, i.e., SAWI-1 and SAWI-2. NDWI and SRWI used 860 and 1240 nm bands [8,10]. Hardisky [26] reported NDII built with 820 and 1645 nm bands.

3.4 Testing Spectral Indices

Hyperspectral vegetation indices using only a limited amount of data are important and useful in the detection of plant water stress. Therefore, many spectral indices have been developed (Table 1). We selected CWC (defined with canopy equivalent water thickness) to test these indices listed in Table 1 by using datasets from 2008, 2011, and 2012 (Table 2). We found that traditional indices, such as NDVI, red edge NDVI, NDII, and SRI, had good relationship with CWC for three-year measurements. Traditional water indices, such as WI and NDWI, showed good performance in 2008 and 2012, but poor performance in 2011. SAWI-1 and SAWI-2 showed good and stable relationship with CWC in three-year measurements. SAWI-2 performed best in 2008, whereas SRI performed best in 2011 and 2012. Through three years of observations, we found that SAWI-2 is the best index. The
relationship between the spectral indices and CWC were weaker in 2012 compared with that in other years. SAWI-1 and SAWI-2 performed better than other indices. The new indices proposed in this study were found more superior to other indices. The differences in the performance of these indices may be caused by varying environmental conditions. The metrological conditions in 2011 are not the same as that in the other two years.

NDVI and OSAVI are standardized indices that utilize the characteristic features of the vegetation spectrum. Vegetation has low reflectance in the red region of the spectrum due to scattering caused by internal leaf structure. A significant difference exists in the reflectance at the VIS and NIR regions for no water stress and severe drought stress in our study (Fig. 2). To some degree, OSAVI decreases the effection from soil background Therefore, the adjusting coefficient of OSAVI in semi-arid regions should be improved.

Water indices, including NDWI, WI, and SRWI, are shown to be unstable in the three-year experiments. However, the cause of this instability is unclear. The data on the water indices in our study area do not agree with the results in earlier studies [2,10,39]. Compared with other indices, NDII and SRI performed better in the current study. The spectral band of these two indices is similar and near the band in our study. PRI is often used to determine water stress [5, 6]. However, PRI and water stress have low relationship in 2008 and 2012. Barton and North [45] demonstrated that PRI is highly affected by soil background when LAI<3. LAI is not higher than 3 in the water stress status of the study; therefore, PRI performs poorly in our study area.
The indices proposed in this study (SAWI-1 and SAWI-2) showed strong relationship with CWC ($r$ ranging from 0.606 to 0.886). The superior performance of SAWI-1 and SAWI-2 could be due to the fact that the bands selected showed maximum linear correlation with the water parameters (Fig. 3). The advantage of SAWI-1 and SAWI-2 is stable in every experiment year.

SAWI-1 and SAWI-2 were used to identify crop drought grade on the basis of the relationship between drought level and two indices for three-year measurements. We estimated the drought grade of the “rained” treatment for three years. The drought grade in 2008 and 2011 is severe drought. In 2012, the drought grade for the “rained” treatment is no drought in the booting and filling stages and moderate drought in the heading stage. The correlation coefficients ($r$) by SAWI-1 were 0.77, 0.78, and 0.81, respectively, for 2008, 2011, and 2012. The correlation coefficient ($r$) by SAWI-2 were 0.83, 0.79, and 0.83, respectively, for 2008, 2011, and 2012. This result indicates that the SAWI-1 and SAWI-2 may be ideal indices for spring wheat drought monitoring in the semi-arid region of Loess Plateau, Northwest China. Fig. 4 presents the average samples in the three experimental years.

4. CONCLUSION

We can draw the following conclusions from the study:
(1) CWC is sensitive to water stress of spring wheat in semi-arid rainfed regions of Loess Plateau. CWC varies significantly with different water stress levels and decreases with the increase of water stress level. At the same water stress, CWC changes with different growth stages.

(2) The response of canopy reflectance to water stress is not the same in NIR, VIS, and SWIR. VIS and SWIR reflectance increased with decreasing water content, and NIR reflectance increased with increasing water content.

(3) Hyperspectral data from the study revealed that the narrow bands at 780 and 1750 nm are sensitive to the water parameters of spring wheat. Two indices (i.e., SAWI-1 and SAWI-2) were developed in these study. These indices performed better and were more stable than the other indices and hence have the potential to detect the drought stress status of spring wheat in the semi-arid regions of Loess Plateau, Northwest China. This study focused on an arid agricultural station in Dingxi City to build spectral indices that can help enhance agricultural activities in the entire Chinese Loess Plateau.

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Table 1 Spectral reflectance indices used to estimate canopy water content and water stress in this study.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Name</th>
<th>Formula</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDWI</td>
<td>Normalised Difference Water Index</td>
<td>((R_{860} - R_{1240})/(R_{860} + R_{1240}))</td>
<td>Gao et al. (1996) [10]</td>
</tr>
<tr>
<td>SRWI</td>
<td>Simple ratio water index</td>
<td>(R_{860}/R_{1240})</td>
<td>Zarco-Tejada et al. (2003) [8]</td>
</tr>
<tr>
<td>WI</td>
<td>Water index</td>
<td>(R_{900}/R_{970})</td>
<td>Peñuelas et al (1997) [11]</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
<td>((R_{800} - R_{670})/(R_{800} + R_{670}))</td>
<td>Rouse et al. (1973) [32]</td>
</tr>
<tr>
<td>Red edge NDVI</td>
<td>Red Edge Normalised Difference Vegetation Index</td>
<td>((R_{750} - R_{705})/(R_{750} + R_{705}))</td>
<td>Gitelson (1994) [12]</td>
</tr>
<tr>
<td>PRI</td>
<td>Photochemical Reflectance Index</td>
<td>((R_{570} - R_{531})/(R_{570} + R_{531}))</td>
<td>Gamon et al. (1992) [33]</td>
</tr>
<tr>
<td>NDII</td>
<td>Normalized difference infrared index</td>
<td>((R_{820}-R_{1645})/(R_{820}+R_{1645}))</td>
<td>Hardinsky et al. (1983) [26]</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------------------------------</td>
<td>-----------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>OSAVI</td>
<td>Optimized Soil-Adjusted Vegetation Index</td>
<td>((1+0.16)(R_{800}-R_{670})/(R_{800}+R_{670})+0.16)</td>
<td>Rondeaux (1996) [34]</td>
</tr>
<tr>
<td>SRI</td>
<td>Simple Ratio Index</td>
<td>(R_{900}/R_{680})</td>
<td>Rouse et al. (1973) [32]</td>
</tr>
<tr>
<td>SAWI-1</td>
<td>Semi-Arid Water Index-1</td>
<td>(R_{780}/R_{1750})</td>
<td>This study</td>
</tr>
<tr>
<td>SAWI-2</td>
<td>Semi-Arid Water Index-2</td>
<td>((R_{780}-R_{1750})/(R_{780}+R_{1750}))</td>
<td>This study</td>
</tr>
</tbody>
</table>

\(R\), Reflectance at corresponding wavelength (nm) depicted as subscript.
Table 2 Correlation coefficients (r) between the spectral indices and canopy water content of spring wheat in three years.

<table>
<thead>
<tr>
<th>Index</th>
<th>2008 n=28</th>
<th>2011 n=33</th>
<th>2012 n=45</th>
<th>All ( n=116 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDWI</td>
<td>0.575*</td>
<td>0.096</td>
<td>0.562**</td>
<td>0.007</td>
</tr>
<tr>
<td>SRWI</td>
<td>0.612*</td>
<td>0.029</td>
<td>0.573**</td>
<td>0.135</td>
</tr>
<tr>
<td>WI</td>
<td>0.876*</td>
<td>-0.06</td>
<td>0.554**</td>
<td>0.046</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.754*</td>
<td>0.745**</td>
<td>0.545**</td>
<td>0.482**</td>
</tr>
<tr>
<td>Red edge</td>
<td>0.819*</td>
<td>0.779**</td>
<td>0.503**</td>
<td>0.512**</td>
</tr>
<tr>
<td>NDVI</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRI</td>
<td>-0.178</td>
<td>-0.839**</td>
<td>-0.485**</td>
<td>-0.241**</td>
</tr>
<tr>
<td>NDII</td>
<td>0.876*</td>
<td>0.646**</td>
<td>0.574**</td>
<td>0.517**</td>
</tr>
<tr>
<td>OSAVI</td>
<td>0.734*</td>
<td>0.724**</td>
<td>0.526**</td>
<td>0.461**</td>
</tr>
<tr>
<td>SRI</td>
<td>0.854*</td>
<td>0.886**</td>
<td>0.626**</td>
<td>0.402*</td>
</tr>
<tr>
<td>SAWI-1</td>
<td>0.871*</td>
<td>0.619**</td>
<td>0.606**</td>
<td>0.554**</td>
</tr>
<tr>
<td>SAWI-2</td>
<td>0.886*</td>
<td>0.649**</td>
<td>0.568**</td>
<td>0.559**</td>
</tr>
</tbody>
</table>

#* significant (P<0.05)  ** significant (P<0.01)
Figure 1. Change of mean canopy equivalent water thickness (1a) and chlorophyll (1b) of spring wheat in three years under different water stress levels (D0, rained; D1, severe drought; D2, moderate drought; D3, light drought; D4, no drought).
Figure 2. Mean canopy reflectance spectra of spring wheat at different water stress levels.
Figure 3. Linear correlation coefficient (r) between canopy spectral reflectance and soil relative moisture, canopy equivalent water thickness, and soil water potential.
Figure 4. Average sample analysis in three experiment years.