Article

Ground Hyper-Spectral Remote-Sensing Monitoring of Wheat Water Stress during Different Growing Stages

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Abstract: Monitoring agricultural drought via ground hyper-spectral remote sensing has always been a hot topic in the fields of agriculture and meteorology. In this study, a greenhouse experiment was conducted on wheat subjected to water stress during its different growth stages, namely tillering, jointing, and milk maturity. An instrument (HOBO ware PRO) used to continuously measure soil moisture was employed to measure the soil water content (SWC). An analytical spectral device (ASD) was utilized to obtain the spectral curve of wheat subject to different water treatment methods. The canopy temperature was obtained using thermal infrared sensors (METER SI-400). The relationships between the SWC, wheat drought stage, canopy temperature, and spectral response characteristics were elucidated. The results showed that the significant differences in spectral characteristics were due to water stress during the different growth stages of wheat. Red-edge parameters of red-valley position (RVP) and red-edge position (REP) both changed by 21 nm for the tillering-stage drought and the jointing-stage drought; however, the RVP and REP values for the milk maturity stage drought and the treatment under no water stress changed by 2 nm. Further, it was proved that the red-edge blue-shift phenomenon was affected not only by the different wheat growth processes, but also by the water stress at different growth stages. Red-edge reflectance clearly reflects wheat water stress at different growth stages. From SWC and canopy temperature analysis results, SWC and canopy temperature had a significant difference between wheat drought at different growth stages, and the canopy temperature at the jointing stage drought had the strongest change. The water index (WI) based on eleven vegetation water indexes exhibited a good performance for distinguishing wheat water stress at different growth stages. In conclusion, ground-based hyperspectral remote sensing can provide a large amount of high temporal and spectral resolution data on vegetation and its surrounding environment, making it an important technical tool for wheat drought monitoring, which has a great significance on the monitoring and early warning of wheat drought, reducing drought-related yield losses, and ensuring food security.

Keywords: hyper-spectral; greenhouse experiment; water stress; red edge; blue shift

1. Introduction

Crop canopy hyper-spectral analysis is a remote-sensing technology used for non-destructive testing, which is effective for monitoring the growth, yield, and stress of crops [1–3]. Using hyper-spectral imaging to estimate wheat water stress is significantly important for large-scale wheat drought monitoring [4]. A massive information source for spectral curves can be obtained from the reflectivity, reflection peak, and absorption valley positions; the absorption width and depth; the spectral derivative; the absorption area; and the symmetry, slope, and characteristic index [5–7]. The hyper-spectral characteristics for wheat water stress mainly focus on the perspective of the spectrum, the selection of characteristic bands using the differential or ratio method, red-edge information, and parameter extraction from spectral characteristic [8,9]. The red edge of the crop is defined
by the sharp change in the canopy reflectance of the leaves between 680 and 750 nm. The red edge is formed because of the multiple scattering of the near-infrared band inside the leaves and the absorption of visible light by chlorophyll [10,11]. The position of the red edge is considered to be closely related to the moisture and nitrogen contents in the leaf, the leaf area index (LAI), and the chlorophyll content in the vegetation [12–14]. Liu et al. indicated that the amount of red and blue shifts from the red edge can be used to monitor crop water stress and phenological characteristics [8]. He et al. proved that the red edge of a crop is an indicator of crops suffering from water stress [13].

The vegetation water index (VWI) is an effective method used for the parameter extraction of spectral characteristics for describing the level of vegetation drought; it is not only widely used in leaf-scale measurements and field-scale experiments, but also in long-term large-scale crop water monitoring combined with remote-sensing technology [15,16]. These indexes are usually calculated using the spectral values of the vegetation water absorption band, such as the visible light and near-infrared bands with different scales [17]. VWIs for field-scale and leaf-scale experiments can be measured with a spectrometer, and VWIs for satellite-scale experiments can be calculated via satellite imaging. Some related VWIs have been proposed since the 1990s. For example, field-scale VWIs include the WI [18], WI/NDVI [19], and RDI1450 [20]; leaf-scale VWIs include the MSI [21], R975 [22], and RDI [23]; and satellite-scale VWIs include the NDWI [19], SRWI [24], NDII [25], and GVMI [26]. These indexes differ with regard to the data obtained, equipment used, and the resulting wave widths; their accuracy, sensitivity, and uncertainty should be analyzed according to different application scenarios.

Drought is a natural disaster caused by short-term climatic anomalies and is characterized by its high frequency, impact, duration, and damage compared to other agricultural disasters [27]. Agricultural droughts are considered to be the most complex natural hazards, affecting the largest number of people but with little understanding of the mechanisms [28]. Many scholars suggest that the main drivers affecting drought are meteorology, physical properties of the soil, and agricultural management, etc. The development of ground-based hyperspectral sensors has become an effective means of acquiring parameters of crops and their surroundings, and is important for monitoring crop drought. Judging from existing research, the jointing, booting, and heading stages are the key growth stages of wheat, and these three growth stages afford the most significant differences with regard to wheat phenology characteristics [29–31]. This study is novel as we designed a greenhouse experiment for these three growth stages of the wheat exposed to drought and subsequently obtained useful crop/environment information using the ground-based hyperspectral monitor method, aiming to reveal the mechanism of drought in different wheat growth stages. The primary objectives of this study were: (1) designing the jointing, booting, and heading stages of the wheat exposed to drought, which was followed by collecting and analyzing related data; (2) comparing the spectral characteristics (water absorption bands and red-edge parameters), soil moisture, and canopy temperatures for each treatment, which were collected using ground-based remote-sensing sensors; and (3) calculating and comparing the eleven VWIs and finding the best VWIs to characterize wheat drought based on wheat canopy hyper-spectral. The great significance of this study is to reveal the responses of the wheat exposed to drought in different wheat growth stages, and accumulate technical experience to advancing the development of ground-based hyperspectral remote sensing on wheat drought monitoring.

2. Materials and Methods

2.1. Experiment Design

The experiment was conducted in the greenhouse of the Chinese Academy of Agricultural Sciences, Beijing (116.33° E, 39.97° N) from October 15 2019 to March 18 2020. The soil was sourced from the Langfang Experimental Station of the Chinese Academy of Agricultural Sciences (116.76° E, 39.55° N); it exhibited a sandy loam texture and the clay fraction was 5.43%. For the soil organic carbon content of 3.91 ± 0.78 g/kg, the initial
The total nitrogen content was 0.45 ± 0.07 g/kg, the initial ammonium nitrogen content was 1.44 ± 0.18 mg/L, and the initial soil pH was 7.4. The wheat variety was Jimai No. 38. Four controlled trials were set up, including the jointing, booting, and heading stages under water stress, along with a trial with no water stress for comparison. Subsequently, 30 kg/ha of nitrogen fertilizer was applied on each group; however, no top dressing was applied to ensure that the wheat growth was affected by nitrogen stress. Insecticides and herbicides were sprayed evenly on Nov 30. Each set followed different water management strategies and irrigation details, as listed in Table 1. Information on the wheat phenology of this trial is as follows. The wheat was planted on 15 October 2019; the wheat germinated on 6 November and in the tillering phase from 6 to 24 November 2019; the jointing stage lasted from 25 November 2019 to 30 January 2020; and the wheat flowered and filled in the last days of the jointing stage, and in milk maturity stage from 30 January to 20 March 2020.

Table 1. The amount of irrigation once a week per time for different sets (unit: mL). Date format (yyyy.mm.dd).

| Remarks                     | Before Tillering Stage (2019.10.15–11.06) | Tillering Stage (2019.11.06–11.24) | Jointing Stage (2019.11.25–2020.01.30) | Milk Maturity Stage (2020.01.30–03.20) |
|-----------------------------|--------------------------------------------|------------------------------------|-----------------------------------------|---------------------------------------|
| S1  Tillering stage drought  | 2000                                       | 500                                | 2000                                    | 2000                                  |
| S2  Tillering stage drought  | 2000                                       | 500                                | 2000                                    | 2000                                  |
| S3  Jointing stage drought   | 2000                                       | 2000                               | 500                                     | 2000                                  |
| S4  Jointing stage drought   | 2000                                       | 2000                               | 500                                     | 2000                                  |
| S5  Milk maturity stage drought | 2000                                   | 2000                               | 500                                     | 2000                                  |
| S6  Milk maturity stage drought | 2000                                   | 2000                               | 500                                     | 2000                                  |
| S7  No water stress          | 2000                                       | 2000                               | 2000                                    | 2000                                  |
| S8  No water stress          | 2000                                       | 2000                               | 2000                                    | 2000                                  |

An ASD FieldSpec Pro spectrometer (Analytical Spectral Devices, Inc., Boulder, CO, USA) was used to measure the wheat canopy spectral. The spectrometer had a spectral range of 350–2500 nm, with a 3 nm sample footprint size in the 350–1000 nm region and a 10 nm sample footprint size in the 1000–2500 nm region. The spectrometer automatically interpolated the final result to 1 nm. Wheat spectra were measured twice for each group during the experimental period, namely on Jan 9 and Mar 9. Furthermore, spectral data for different periods of drought were obtained. We measured wheat spectrums on sunny days, preferably between 10:00 and 14:00 a.m. when the light conditions were the best before irrigation [32]. When we measured the spectral, the distance between the sensor and the wheat canopy was kept at about 15 cm. Whenever one spectral acquisition operation was performed, the ASD acquired five continuous spectral profiles for one sample. Five sets of acquisition operation were obtained for one sample, and 25 spectrum profiles were averaged as the final spectrum of the canopy. Then, the average spectra of the two groups were used as the spectrum observation data of one group. A continuous observation instrument (HOBO ware PRO) was used to obtain soil water content, and the sampling interval was set to 5 min. The canopy temperature was obtained using the thermal infrared sensors (METER SI-400), which can continuously record the canopy temperature and ambient temperature every 1 min. Observations of soil moisture and canopy temperature were taken after the wheat entered the tillering stage (November 6, 2019). To facilitate analysis and mapping, we averaged the soil moisture and canopy temperature observations to 1 day. The data quality and instrument error of the above instruments have been verified in a previous experiment [32].

2.2. Red-edge Parameters

The red edge is a steep and nearly straight bevel between 660 nm and 770 nm and occurs due to the strong absorption of vegetation chlorophyll in the red band and the multiple scattering of the radiation in the near-infrared band inside the blade [33,34]. The
1st derivative of reflectance is commonly used to describe the red-edge parameters and estimate the position of the red edge (Equation (1)).

\[ R'(\lambda_i) = \frac{R(\lambda_i) - R(\lambda_{i-1})}{\lambda_i - \lambda_{i-1}} \]  

(1)

where \( R \) represents the reflectance, \( R' \) represents the 1st derivative for reflectance, \( \lambda \) represents the wavelength, and \( i \) represents the spectral channel.

Six red-edge parameters were used in this study to study the response of spectral characteristics of wheat during the different growing stages of drought. The seven red-edge parameters included the red-valley position (RVP), the red-valley reflectance (RVR), the red-edge position (REP), the red-edge reflectance (RER), the red-edge width (REW), and the red-edge amplitude (REA) [35]. The definitions and equations for the 6 red-edge parameters are listed in Table 2.

| Items                    | Abbreviation | Definition                                                                 | Equation                  | Unit |
|--------------------------|--------------|----------------------------------------------------------------------------|---------------------------|------|
| Red-Valley Position      | RVP          | The wavelength value corresponding to the minimum reflectance within the red band. | \( \lambda_{\text{Max}(R(\lambda))} \) | nm   |
| Red-Valley Reflectance   | RVR          | The minimum reflectance within the red band.                               | \( \text{Min}(R(\lambda)) \) | –    |
| Red-Edge Position        | REP          | The wavelength value corresponding to the maximum value of the first derivative spectrum. | \( \lambda_{\text{Max}(R'(\lambda))} \) | nm   |
| Red-Edge Reflectance     | RER          | The reflectance value at the band of the maximum value of the 1st derivative. | \( R(\lambda_{\text{Max}(R'(\lambda))}) \) | –    |
| Red-Edge Width           | REW          | The distance from the red-valley position to the red-edge position.        | \( \text{REP-RVP} \)     | nm   |
| Red-Edge Amplitude       | REA          | The maximum value of the first derivative of reflectance with red band.    | \( \text{Max}(R'(\lambda)) \) | –    |

2.3. Vegetation Water Indexes (VWI)

Eleven types of vegetation water indexes (VWIs) were applied in this study to quantify drought change for different drought stages. The equations and references for the eleven VWIs are listed in Table 3. Most of the VWIs were calculated via two hyper-spectral bands that exhibited sensitivity for the water content in crops. We collected eleven VWIs, which not only included the leaf-scale and field-scale VWIs, but also the satellite-scale VWIs; this was aimed at comparing and verifying the applicability of different scales of VWIs in a greenhouse experiment. Although various vegetation water indexes were scale-limited, we tried to investigate if these indexes have good performances at the canopy scale, so we did not stick to the index-scale limitations when we calculated indexes.
Table 3. Equations and references of the vegetation water indexes.

| Index | Equation | Scale | Reference |
|-------|----------|-------|-----------|
| 1 WI  | $\frac{\rho_{900}}{\rho_{970}}$ | Field | [18] |
| 2 WI/NDVI | $\frac{\rho_{900}}{\rho_{970}} \frac{\rho_{800} - \rho_{680}}{\rho_{800} + \rho_{680}}$ | Field | [19] |
| 3 R975 | $\frac{\sum_{i=1}^{960} \rho_i}{\sum_{i=920}^{940} \rho_i + 1}$ | Leaf | [22] |
| 4 MSI | $\frac{\rho_{1600} - \rho_{1200}}{\rho_{1600} + \rho_{1200}}$ | Leaf | [21] |
| 5 DRI | $\frac{\rho_{816} - \rho_{2218}}{\rho_{816} + \rho_{2218}}$ | Leaf | [23] |
| 6 RDI1450 | $\frac{\rho_{max} - \rho_{min}}{\rho_{max}}$ | Field | [20] |
| 7 NDWI | $\frac{\rho_{800} - \rho_{1200}}{\rho_{800} + \rho_{1200}}$ | Satellite | [19] |
| 8 SRWI | $\frac{\rho_{800}}{\rho_{820}}$ | Satellite | [24] |
| 9 NDII | $\frac{\rho_{820} - \rho_{1650}}{\rho_{820} + \rho_{1650}}$ | Satellite | [25] |
| 10 R5/R7 | $\frac{\rho_{510}}{\rho_{2218}}$ | Leaf | [36] |
| 11 GVMI | $\frac{(\rho_{820} + 0.1)(\rho_{1600})}{(\rho_{820} + 0.02)} - (\rho_{820} + 0.02)$ | Satellite | [26] |

3. Results

3.1. Wheat Spectral Characteristics

The spectrum curve and the first derivative for the reflectance curve for different growth stages of drought are shown in Figures 1 and 2. The oscillations centered at 1350, 1850, and 2400 nm were due to the influence of the water vapor in air, which were related to the moisture content of the air on the day of the spectral measurement. Owing to the varying moisture content in the air for different spectrum measurement periods, noise intensities were also observed to be different. As shown in Figure 1a, the curve representing the milk maturity stage drought and the treatment under no water stress was almost overlaid because the wheat had not reached the milk maturity stage by Jan 9, and the watering gradient was the same as that of the control group without water stress. The spectrum characteristics for the tillering stage drought and jointing stage drought were quite different, as shown in Figure 1a. The reflectance of the tillering stage drought was smaller than the reflectance values of the jointing stage drought in the blue band of 350–450 nm and in the near-infrared band of 800–2300 nm. The reflectance under no water stress was observed to be the smallest of the three groups. The differences in spectrum characteristics for the four comparison groups are shown in Figure 1b. In the near-infrared band, the decreasing order of reflectivity for different stages was the tillering stage drought, the jointing stage drought, the milk maturity stage drought, and no water stress. As these results indicate that crop reflectance in the near-infrared band was closely related to the structure of chloroplasts, the upper limit of the water content of wheat leaves may be proportional to the time of drought. However, in the blue and green bands, the reflectivity of the four control groups had no obvious regularity.
The first derivative of reflectivity was of great significance for confirming the red-edge position, reflecting the wheat spectral characteristics and red-edge parameters. As shown in Figure 1c,d, the first derivative of the spectrum fluctuated in the following ranges: 450–750 nm, 950–1150 nm, 1350–1550 nm, 1850–1950 nm, and 2300–2350 nm. The shape of the first derivative was mainly determined by the spectral characteristics of the vegetation reflectance and observation conditions. When the first derivative was positive in a
certain band, the reflectivity gradually increased in this band; otherwise, the reflectance gradually decreased.

3.2. Soil Water Content Tendency

The variation in the soil water content for each group is shown in Figure 2. The blue points in the top of the curves represent the irrigation time, which led to these variations. There were three irrigation cycles during the wheat tillering stage, ten during the wheat jointing stage, and six during the milk maturity jointing stage. After irrigation, the soil water content immediately increased and then decreased gradually over the next 3–5 days. The water stress test group also received a small amount of irrigation to prevent wheat annihilation due to drought. The soil water contents of the experimental group subjected to drought treatment in different growth periods were extremely significant. The soil water content of the experimental group with the least irrigation in each growth period maintained the lowest soil water content. However, the soil water content in the no-water-stress group maintained a high level of soil water content.

3.3. Wheat Spectral Characteristics

To observe the variations in the red edge and the red-edge parameters for different wheat treatments, the red-edge band at 660–770 nm was discussed separately (Figure 3). The calculation results and numerical changes in the six red-edge parameters are shown in Tables 4 and 5. The red-valley position (RVP) and red-edge position (REP) decided the red-edge starting position. From the tillering stage to the milk maturity stage, the RVP continued to decrease and the REP continued to increase with time, indicating that a blue shift phenomenon appeared for the red edge. There were two main reasons for the occurrence of this phenomenon: the phenology of wheat and the water stress during the growth stages [13]. In addition, the values for REP and red-edge width (REW) for the tillering stage drought and jointing stage drought were larger than those for the milk maturity stage and no-water-stress groups, which indicates that the blue shift of red edge was more obvious during the tillering stage drought and jointing stage drought. Red-valley reflectance (RVR) reflected the minimum value of red-edge reflectivity. RVR decreased for each group during the wheat growth periods and did not show obvious differences between the four groups, which means that RVR was affected by the influence of wheat phenology, and RVR was not sensitive to water stress. The red-edge reflectance (RER) was the most obvious index among the four comparison groups, indicating that RER could better reflect the spectral response characteristics of drought in different growth periods. The change in the red-edge amplitude (REA) value was small during the wheat growth periods, and there were small differences between the four comparison groups.
3.4. Canopy Temperature Characteristics Analysis

In order to reduce the influence of ambient temperature on canopy temperature, we introduced the concept of the difference between canopy temperature and ambient temperature (DCTAT) to analyze canopy temperature results. Due to the transpiration of the crop, the canopy temperature of wheat was usually lower than the ambient temperature and the DCTAT value was usually negative. During wheat tillering stage, the DCTAT value ranged between $-7.8$ and $-1.3$ °C (Figure 4a), and the canopy temperature in the water-stress experimental group (green line) was, on average, $0.72 \pm 0.56$ °C higher than...
in the no-water-stress experimental group. During the wheat jointing stage, the DCTAT value ranged between $-9.92$ and $0.76 \degree C$ (Figure 4b), and the canopy temperature in the water-stress experimental group (blue line) was, on average, $1.36 \pm 0.44 \degree C$ higher than in the no-water-stress experimental group. During the wheat milk and maturity stage, the DCTAT value ranged between $-13.49$ and $0.80 \degree C$ (Figure 4c), and the canopy temperature in the water-stress experimental group (grey line) was, on average, $0.67 \pm 0.78 \degree C$ higher than in the no-water-stress experimental group. A higher DCTAT represents a higher canopy temperature, a higher canopy temperature indicates weaker transpiration in wheat, and weaker transpiration reflects a higher intensity of water stress on wheat. Comparing water stress treatment DCTAT results with those of no-water-stress treatment during wheat different growth periods above, we found that the largest changes in canopy temperature of wheat under water stress occurred at the jointing stage.

### 3.5. Vegetation Water Index Analysis

The VWI used in this study was widely shown to perform well in characterizing the crop water content, and the hyperspectral data of wheat from ground-based observations are a reliable source for calculating the VWI. Using two spectral observation data with 200 spectral curves from Jan. 9 and Mar. 5 for four different experiment groups, six vegetation water indexes were calculated to study variations in VWIs (Figure 5 and Table 6). The main basis for determining whether VWI can characterize different stages of drought in wheat is whether there are significant differences in VWI values calculated at different times for each control, and whether such differences have regularity (including a comparison between samples exposed to drought at different growth stages, and between drought samples and no-water-stress samples). Compared with the no-water-stress test group, the differences in the WI curve slopes for different water sets showed significant differences and regularity, which implied that the WI might be able to classify different growth stages of drought for wheat. Water stress in different stages tends to cause permanent damage to the wheat, which could be distinguished by the WI at the leaf scale.

#### Table 6. Results with each VWI for different drought stages.

| Date   | WI Tillering Stage Drought | Jointing Stage Drought | Milk Maturity Stage Drought | No Water Stress |
|--------|-----------------------------|-------------------------|-----------------------------|-----------------|
| Jan. 9 | 1.06                        | 1.09                    | 1.04                        | 1.04            |
| Mar. 5 | 1.04                        | 1.04                    | 1.03                        | 1.09            |
| Jan. 9 | 1.37                        | 1.49                    | 2.06                        | 2.07            |
| Mar. 5 | 2.16                        | 2.41                    | 3.24                        | 4.16            |
| Jan. 9 | 0.96                        | 0.94                    | 0.97                        | 0.97            |
| Mar. 5 | 0.98                        | 0.96                    | 0.97                        | 0.90            |
| Jan. 9 | 0.58                        | 0.52                    | 0.61                        | 0.61            |
| MSI    |                             |                         |                             |                 |
| Mar. 5 | 0.54                        | 0.55                    | 0.59                        | 0.43            |
| Jan. 9 | 0.43                        | 0.47                    | 0.43                        | 0.43            |
| DRI    |                             |                         |                             |                 |
| Mar. 5 | 0.51                        | 0.52                    | 0.48                        | 0.62            |
| Jan. 9 | 0.94                        | 0.95                    | 0.98                        | 0.96            |
| RDI1450|                             |                         |                             |                 |
| Mar. 5 | 0.92                        | 0.94                    | 0.95                        | 0.97            |
| Jan. 9 | 0.10                        | 0.13                    | 0.06                        | 0.06            |
| NDWI   |                             |                         |                             |                 |
| Mar. 5 | 0.08                        | 0.09                    | 0.07                        | 0.06            |
Table 6. Cont.

| Date   | Tillering Stage Drought | Jointing Stage Drought | Milk Maturity Stage Drought | No Water Stress |
|--------|-------------------------|-------------------------|----------------------------|----------------|
| SRWI   | Jan. 9                  | 1.22                    | 1.31                       | 1.12           | 1.13           |
|        | Mar. 5                  | 1.18                    | 1.21                       | 1.16           | 1.12           |
| NDII   | Jan. 9                  | 0.24                    | 0.28                       | 0.20           | 0.20           |
|        | Mar. 5                  | 0.26                    | 0.35                       | 0.26           | 0.22           |
| R5/R7  | Jan. 9                  | 1.52                    | 1.56                       | 1.66           | 1.65           |
|        | Mar. 5                  | 1.81                    | 2.08                       | 1.87           | 1.81           |
| GVMI   | Jan. 9                  | 0.30                    | 0.35                       | 0.28           | 0.28           |
|        | Mar. 5                  | 0.33                    | 0.43                       | 0.33           | 0.30           |

Figure 4. Difference between canopy temperature and ambient temperature (DCTAT). (a–c) represent the tillering stage, jointing stage, and milk maturity stage, respectively. No data were attributed to sensor damage or equipment overhaul. (Date format: yyyymmdd).
drought samples and no-water-stress samples. Compared with the no-water-stress test group, the differences in the WI curve slopes for different water sets showed significant differences and regularity, which implied that the WI might be able to classify different growth stages of drought for wheat. Water stress in different stages tends to cause permanent damage to the wheat, which could be distinguished by the WI at the leaf scale.

Figure 5. The slope change in eleven VWIs on two observation dates (Jan. 9 and Mar. 5) for different growth stages drought for wheat.

Except for WI/NDVI and R5/R7, the other five leaf/field-scale VWIs (WI, R975, MSI, RDI, and RDI1450) can better distinguish wheat water stress and the absence of it via slope variability. For RDI1450 and the WI, when the slope was greater than 0, it represented that the wheat had not suffered water stress during the growth period, and when the slope was less than 0, it represented that the wheat had suffered water stress. For R975 and MSI, when the slope was less than 0, it represented that the wheat had not suffered water stress during the growth period, and when the slope was greater than 0, it represented that the wheat had suffered water stress. For RDI, the increase in slope decreased, indicating that the wheat suffered water stress.

However, WI/NDVI and R5/R7, which were both leaf/field-scale VWIs, showed no significant differences between the water-stress groups and the no-water-stress group. All the satellite-scale VWIs (including NDWI, SRWI, NDII, and GVMI) did not exhibit
good performance in distinguishing water-stressed and non-water-stressed wheat. This result proved that VWIs had certain requirements for researching different scales; this is reinstated by the fact that satellite-scale VWIs could not be applied at the leaf/field scale. However, leaf-scale and field-scale VWIs exhibited a certain degree of applicability for each of the scales.

4. Discussion

4.1. Advantages of Ground-Based Hyperspectral Monitor Wheat Drought

With the development of ground-based remote-sensing sensors, higher temporal and spectral resolution sensors emerged, covering various wavelength bands, such as visible light, near-infrared, mid-infrared, far-infrared, and microwave [37]. A variety of vegetation parameters monitored tends to diversify, such as the leaf area index, chlorophyll, chlorophyll fluorescence, plant water content, etc. A wide range of environmental parameters can be monitored to assist in drought monitoring, such as temperature, canopy temperature, soil moisture, water vapor pressure, wind speed, air pressure, etc. [38,39]. With this large number of precise multi-parameter observations, we can better clarify the mechanisms of drought in winter wheat by analyzing the interrelationships between the various vegetation and environmental parameters [40]. In this study, for example, by designing comparative experiments in the greenhouse with wheat subjected to drought at different growth stages, we collected a large amount of raw data on canopy temperature, soil moisture, and canopy spectra. We observed differences in soil moisture and canopy temperature in different comparison samples, and observed the interrelationship between different irrigation quantities, canopy temperature, and soil moisture. The spectral measurements of the wheat canopy were used to observe the differences in spectra between the different samples, and the changes in the red-edge parameters. Vegetation moisture indexes were calculated from the vegetation hyper spectrum to select the most suitable index for evaluating the wheat drought at different growth stages. These results demonstrate the importance of ground-based hyperspectral remote sensing in the study of drought mechanisms in wheat. This refined access to data and the ability to analyze qualitatively and quantitatively is irreplaceable to other research methods.

4.2. Enlightenment for Large-Scale Drought Monitoring

Observing the spectral characteristics of drought and analyzing the water stress spectrum changes at different growth stages for wheat is important for clarifying the drought mechanism of wheat, which has great significance for guiding scientific irrigation, realizing crop growth monitoring, improving crop yield, and ensuring food security [41,42]. Research on wheat spectrum based on the greenhouse-controlled variable experiment has accumulated rich data and valuable methodology experience for large-scale wheat drought monitoring. With the rapid developments in remote-sensing technology in recent years, the spatial resolution, temporal resolution, and spectral resolution of remote-sensing sensors have greatly improved, resulting in the continuous development of large-scale, timely, and accurate wheat cropping monitoring. In particular, the use of hyper-spectral remote-sensing sensors is increasingly popular and can easily obtain remote-sensing images with high resolutions for wheat in each growth stage. Based on the spectral response characteristics of wheat, wheat growth with different drought periods can be classified. Combined with accurate soil moisture monitoring technology, meteorology, and field wheat observation data, a deeper understanding of drought mechanisms and a better arrangement of irrigation events can be achieved while minimizing yield losses. However, solving the applicability of hyper-spectral research at the leaf/field scale and the satellite scale is a difficult problem in the field of hyper-spectral drought monitoring.

5. Conclusions

In this study, we designed a greenhouse experiment with three different growth stages (tillering, jointing, and milk maturity stage) to study drought in wheat for mechanisms
of wheat drought. A variety of ground-based continuous-record remote-sensing sensors were used to monitor key vegetation and environmental parameters during wheat growth periods, which was an effective way to collect precise data automatically, continuously towards wheat drought. The monitored parameters included ambient temperature, canopy temperature, soil moisture, and wheat canopy spectral. The collected observations were statistically analyzed to understand the different changing conditions of soil moisture and canopy temperature for different water strategies samples, as well as using canopy spectral to calculate red-edge parameters and some commonly used vegetation moisture indices to characterize wheat drought at different growth stages from a quantitative and qualitative perspective. This study is of great significance for understanding the drought mechanism of wheat and the spectral response characteristics of drought at different growth stages. It also provided a valuable experience for large-scale remote sensing for the monitoring of wheat under drought conditions to increase wheat yield and ensure food security. The main conclusions drawn from this study are as follows:

1. SWC and canopy temperature had a significant difference between wheat drought at different growth stages, and canopy temperature at the jointing stage drought had the strongest change (−9.92 to 0.76 °C).

2. The wheat at different growth stages showed significant differences in spectral response characteristics during the drought period. The red-edge parameters and vegetation water indexes can better show the spectral characteristic differences.

3. Owing to the wheat phenology and water stress during growth periods of wheat with different water stress treatments, the changes in RVP and REP can constitute a red-edge blue shift. The value of blue shift was 21 nm for the tillering stage drought and jointing stage drought, which were significantly larger than those of the milk maturity stage drought (2 nm) and the treatment with no water stress (2 nm).

4. Among the red-edge parameters, RER was the most optimum to reveal the red-edge characteristics for wheat at different growth stages.

5. Based on eleven vegetation water indexes (VWIs), the WI exhibited a good performance for distinguishing wheat water stress at different growth stages.

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