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Spectral analysis of winter wheat leaves for detection and differentiation of diseases and insects

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ABSTRACT

Yellow rust (*Puccinia striiformis* f. sp. Tritici), powdery mildew (*Blumeria graminis*) and wheat aphid (*Sitobion avenae* F.) infestation are three serious conditions that have a severe impact on yield and grain quality of winter wheat worldwide. Discrimination among these three stressors is of practical importance, given that specific procedures (i.e. adoption of fungicide and insecticide) are needed to treat different diseases and insects. This study examines the potential of hyperspectral sensor systems in discriminating these three stressors at leaf level. Reflectance spectra of leaves infected with yellow rust, powdery mildew and aphids were measured at the early grain filling stage. Normalization was performed prior to spectral analysis on all three groups of samples for removing differences in the spectral baseline among different cultivars. To obtain appropriate bands and spectral features (SFs) for stressor discrimination and damage intensity estimation, a correlation analysis and an independent *t*-test were used jointly. Based on the most efficient bands/SFs, models for discriminating stressors and estimating stressor intensity were established by Fisher's linear discriminant analysis (FLDA) and partial least square regression (PLSR), respectively. The results showed that the performance of the discrimination model was satisfactory in general, with an overall accuracy of 0.75. However, the discrimination model produced varied classification accuracies among different types of diseases and insects. The regression model produced reasonable estimates of stress intensity, with an R^2 of 0.73 and a RMSE of 0.148. This study illustrates the potential use of hyperspectral information in discriminating yellow rust, powdery mildew and wheat aphid infestation in winter wheat. In practice, it is important to extend the discriminative analysis from leaf level to canopy level.

1. Introduction

Diseases and insects cause reduced crop yields every year, posing a significant risk to food production worldwide (Strange and Scott, 2005). In dealing with crop diseases and insects, application of an appropriate amount of fungicide/insecticide is important. Misuse and overuse of fungicide/insecticide could result in failure of disease/insect control, and even soil contamination (Sankaran et al., 2010). With the capability of observing the ground surface in a spatially continuous manner, remote sensing provides an alternative to conventional means for disease and insect surveys. As plant stress may be characterized using specific responses in the visible (VIS), near infrared (NIR) and shortwave infrared (SWIR) spectral domains, it is possible to detect or map plant response to diseases/insects with remotely sensed data (Sankaran et al., 2010; Escalante-Ramírez, 2012).

To conduct remote sensing of crop diseases/insects, it is important to identify bands or spectral features that are sensitive to specific stressors. Delwiche and Kim (2000) assessed the spectral characteristics of fusarium head blight disease in winter wheat, and found that the reflectance at 550, 568, 605, 623, 660, 697, 715 and 733 nm are the best indicators of disease presence. Moshou et al. (2004) reported that the reflectance at 680, 725 and 750 nm could be used to detect yellow rust in winter wheat. Yang et al. (2005) identified that the band centered at 694 nm can be used to detect greenbug infestation. Graeff et al. (2006) successfully distinguished powdery mildew and take-all disease infected wheat leaves from normal wheat leaves with reflectance at 490, 510, 516, 540, 780, and

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Abbreviations: VIs, vegetation indexes; SFs, spectral features; FLDA, fisher's linear discriminant analysis; PLSR, partial least square regression; VIS, visible; NIR, near infrared; SWIR, shortwave infrared; PM, powdery mildew; YR, yellow rust; AH, aphid; DI, damage index.

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1300 nm at an early stage. Apart from the original bands, vegetation indices were also shown to be useful in diagnosis of plant diseases and insects, given that most VIs can enhance spectral features at specific positions through certain transformations (e.g. subtraction, dividing, and normalization). It was found that yellow rust could be detected using NDVI (Normalized Difference Vegetation Index) or PRI (Photochemical Reflectance Index) (Bravo et al., 2003; Huang et al., 2007). In detection of aphid infestation, Mirik et al. (2007) proposed an index called AI (Aphid Index) to indicate the abundance of Russian wheat aphids in the field.

As studied above, most studies so far focus on spectral response or detection of one specific disease or insect; they seldom consider spectral mixing between different diseases or insects. However, in practice, different diseases and insects often occur simultaneously in the field, posing a challenge to their detection and discrimination. For example, serious diseases and insects (including powdery mildew yellow rust and aphids) of winter wheat in northern china tend to occur simultaneously during the jointing to grouting stages because their geographical regions overlap. To avoid possible spectral mixing among these diseases and insects, prior to estimation of their severity, it is necessary to compare spectral responses and identify spectral features that are able to differentiate these conditions. However, in reviewing the literature it was found that this comparison of spectral signatures was generally missing. To address this issue, hyperspectral measurements were made for all three types of diseases and insects together.

The objectives of this paper are: (1) to understand the difference of spectral responses among PM (powdery mildew), YR (yellow rust) and AH (aphid) at leaf level on winter wheat; (2) to identify efficient spectral features for differentiating the three stressors; and (3) to develop a discriminant model for differentiating PM, YR and AH, and a regression model for estimating their severities.

2. Materials and methods

2.1. Data acquisition

2.1.1. Study area and disease inoculation

The experiment was conducted at Beijing Xiaotangshan Precision Agriculture Experimental Base, China (40°10.6′N, 116°26.3′E) during the wheat growing seasons in 2011 and 2012. Three different wheat cultivars, Jingshuang16, Jing9843, and Zhongmai16, were used in the experiment, and they were susceptible to PM, YR and AH, respectively.

To introduce YR and PM pathogens to wheat plants, an inoculation technique was used. Given that aphids tend to occur naturally in the experimental field every year, no pesticide treatment was used to allow aphid infestation. For each disease/insect treatment, three replicates were set with a unit plot in size of 5 m × 5 m. In addition, three control plots were also used as a reference containing exactly the same cultivars but with the use of pesticides to prevent infections. To avoid cross infection among different types of diseases/insects, the distance between each treatment plot was no less than 20 m. In both years, the PM and YR showed visible leaf symptoms beginning in the early grain filling stage. The AH also exhibited clear symptoms at this stage. Symptoms of the three stressors are shown in Fig. 1. For this reason, the early grain filling stage was chosen for data collection in this study on May 23 in 2011 and May 16 in 2012.

2.1.2. Leaf sampling and spectral measurement

Leaf spectral measurements were taken using a FieldSpec® UV/VNIR spectroradiometer (ASD Inc., Boulder, Colorado, USA) over the 350–2500 nm wavelengths, coupled with an ASD Leaf Clip, an accessory of the ASD spectroradiometer. The device included a built-in light source, which allowed for indoor measurements. The spectrum of a white Spectralon reference panel (99% reflectance) was measured once for every 10 leaf measurements. To convert the radiance signals to spectral reflectance, a calibrated white panel was used. The dark reference panel was placed behind the leaf when taking measurement given it can absorb transmitted lights. This avoids possible disruption from multiple transmitted lights. Leaf reflectance was generated by dividing the sample radiance with the radiance of the white Spectralon with a multiplication of the reflectance of white reference:

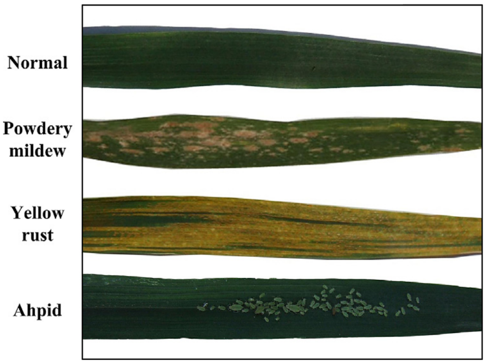

Fig. 1. Normal leaves and leaves infected with powdery mildew, yellow rust and aphid of winter wheat.

$$\mathrm{Ref}_{(\mathrm{target})} = \frac{\mathrm{Rad}_{(\mathrm{target})}}{\mathrm{Rad}_{\mathrm{white\ reference}}} \times \mathrm{Ref}_{\mathrm{white\ reference}} \times 100\% \qquad (1)$$

where $\mathrm{Ref}_{(\mathrm{target})}$ is the reflectance of the observing target; $\mathrm{Rad}_{(\mathrm{target})}$ is the radiance of the observing target; $\mathrm{Rad}_{(\mathrm{white\ reference})}$ is the radiance of the white panel; and $\mathrm{Ref}_{(\mathrm{white\ reference})}$ is the reflectance of the white panel.

For each leaf, 15 readings were recorded and then averaged to obtain a spectral curve for the leaf. A digital color photo was also taken immediately after each spectral measurement with a white paper background to facilitate later determination of disease severity. For YR, PM and AH treatments, a total of 66, 33 and 50 spectral measurements were made for infected leaf samples, whereas 26, 14 and 16 measurements were made for non-infected leaf samples, respectively. For calibration and validation of the models in each group, samples were randomly split into sub-groups representing 60% and 40% of the samples in each group.

2.1.3. Quantification of leaf damage levels

In this study, damage index (DI) was used to indicate the damage levels caused by different diseases/insects. For YR, PM and AH, the DI was determined by a visual estimation of the percent coverage of pustules/aphids on the leaf (Graeff et al., 2006; Zhang et al., 2012a; Luo et al., 2012). For this estimation, the DI value was recorded in intervals of 5% ranging from 5% to 100%. Leaves with a DI less than 5% were difficult to visually separate from normal ones; these were classified as normal leaves. All estimations were made according to leaf photos visualized by a trained technician to minimize subjective error.

2.1.4. Spectral features for stressor discrimination and detection

In addition to raw reflectance, various forms of spectral features were also included for discriminating and detecting the PM, YR and AH given their physical and biological significance. As a result, a total of 30 spectral features were chosen, including the first derivative transformed spectral features, continuous removal transformed spectral features and vegetation index. The first derivative transformed SFs and continuous removal transformed SFs were considered as they were efficient indicators of