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Detection and discrimination of pests and diseases in winter wheat based on spectral indices and kernel discriminant analysis

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ABSTRACT

Kernel discriminant analysis (KDA) can be used as a feasible strategy for identifying plant stresses, especially for detection of pests and diseases, considering the highly nonlinear distribution of hyperspectral absorption features that respond to biophysical variations in plants caused by foliar lesions. However, traditional computation of the kernel projection features produced by hyperspectral data is always affected by redundant information among the numerous wavelengths, subsequently leading to dimension disaster. In order to alleviate this problem, the aim of this study is to propose a spectral vegetation indices-based kernel discriminant approach (SVIKDA) for the detection and classification of yellow rust, aphid, and powdery mildew in winter wheat at the leaf and canopy level. Leaf and canopy level hyperspectral reflectance datasets were measured with a total of 314 and 187 samples, respectively. Fourteen Spectral Vegetation Indices (SVIs) related to foliar biophysical variations were employed as the input sample space; then, by using correlation analysis and independent *t*-tests, redundant information among SVIs was removed. Subsequently, a Gaussian kernel function was utilized to cast discriminant analysis into a nonlinear framework. Finally, using 5-fold cross validation, performance and transferability of this approach were evaluated. Our results revealed that the SVIKDA outperformed conventional linear discriminant approach on detection and classification among healthy wheat leaves and leaves infected with yellow rust, aphids, and powdery mildew. At the leaf level, the classification returned the overall accuracies (OA) of 82.9%, 89.2%, 87.9% for three occurrence levels, i.e. slight, moderate, and severe (Kappa > 0.85). Depending on the types and severities of infestations, the classification accuracy was between 76% and 95%; At the canopy level, the multiple classifications between healthy leaves and leaves with damages from the three different infestations still achieved an accuracy greater than 87% (Kappa = 0.84). In addition, this approach was also successfully applied in disease index (DI) estimation for a specific infestation at the leaf level, and optimal DI estimation returned high coefficients of determination ($R^2 > 0.7$). Furthermore, compared with the commonly used automatic classification algorithm, the SVIKDA achieved an accurate classification without losing the pathological basis of input variables. The results suggest that this method has reliable transferability and great robustness in detecting and discriminating pests and diseases for guiding precision plant protection.

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1. Introduction

Global change and natural disturbances have already caused a severe co-epidemic of pests and diseases in winter wheat (*Triticum aestivum L.*), such as aphids, fusarium, yellow rust, and powdery mildew. These threats may result in serious deterioration of grain yield and quality (Savary et al., 2012). Traditionally, manual scouting has been the only way to detect and discriminate these crop pests and diseases (Duveiller et al., 2007), but these investigations are expensive and time-consuming. Even after having identified the distribution of different infected wheat patches, precise use of bactericides and pesticides is hard to achieve in entire fields (Luck et al., 2011; Mahlein et al., 2012). To mitigate the problems of crop monitoring and pesticide overuse, real-time characterization, identification, and classification of different pests and

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diseases is a necessity. As a non-destructive way of collecting ground information, hyperspectral remotely sensed technologies have proven to be feasible in lesion detection and vitality monitoring (Buitrago et al., 2016; Jaillais et al., 2015; Lópezlópez et al., 2016; Yuan et al., 2013). Among different types of spectral features, spectral vegetation indices (SVIs) are efficient ways to capture the weak spectral signals that indicate certain foliar biophysical variations caused by pests and diseases, such as pigment degradation, reduction in canopy biomass, and a decrease in leaf water content. Huang et al. (2003) determined the sensitive bands of stripe rust at 350 nm, 780 nm, and 1250 nm, and based on these findings, they proposed to use the photochemical reflectance index (PRI) to quantify disease severity at the canopy level. Bravo et al. (2003) used wheat canopy spectral information at the ranges of 740–760 nm and 620–640 nm to calculate the Normalized Difference Vegetation Index (NDVI) and to successfully extract wheat patches with powdery mildew. Feng et al. (2016) measured canopy spectra of wheat at different levels of powdery mildew incidence, suggesting that the best two-band vegetation index ranges for powdery mildew detection were between 570–590 nm and 536–566 nm for the ratio vegetation index (RVI), and 568–592 nm and 528–570 nm for NDVI. These studies have demonstrated that a high spectral resolution, i.e. the use of narrow bands, is essential to discriminate biophysical variations in leaves caused by different infestations, since broadband indices are unable to exploit the subtle spectral features, meanwhile, the use of broadband information would limit the practical use of such approaches to the availability of hyperspectral data (Gamon et al., 1992). Therefore, in this study, only the hyper-spectral vegetation indices are employed.

Practical applications of remote techniques for crop control and management are lacking, and automatic or semi-automatic methods for detecting and monitoring various pests and diseases have been rarely considered, owing to the fact that 1) the pre-existing infestation sensitive indices are nonlinearly varying as the increase of pathogen attack (Bannari et al., 2007), 2) spectral feature diversities among the different pests and diseases are too weak to be discriminated (Guan et al., 2014; Huang et al., 2014). In order to alleviate these problems, nonlinear extensions of statistical learning methods through the "kernel trick" have been proposed to extract the principle components of input samples without losing the key pathogen attack information that allows for the separation of pests and diseases by species and severity (Mika et al., 1999), Then accurate and robust classification results could be achieved with hyperspectral data (Bengio et al., 2004). The main idea of kernel-based approaches is to map input data to a novel feature space through a nonlinear mapping, which produces a set of projective feature vectors by maximizing the between-class covariance and minimizing the within-class covariance (Baudat and Anouar, 2000). These methods integrate statistics and geometry in the so-called "kernel approaches" framework (Van et al., 2002). For instance, Cai et al. (2007) made use of spectral regression and kernel discriminant analysis (KDA) for facial recognition. Its computational costs was lower than the traditional linear discriminant analysis.

However, the computational progress of the projective feature vectors in the pre-existing KDA approaches involves eigen-decomposition of an input matrix, which is very expensive when a large number of hyperspectral bands are put into the model. For better achievement of KDA in quantitative remote sensing spectra processing, adopting sensitive SVIs instead of original hyperspectral reflectance as the initial input matrix may be a potential solution to this problem. In addition, given our literature review, the nonlinear discriminant technique has received little attention for detecting and classifying crop pests and diseases. In our review, using the combinations and transformations of SVIs as the original input sample space to develop a kernel function for KDA progress was still lacking in the field of agricultural quantitative remote sensing. Therefore, to facilitate both comprehensive combination of the sensitive SVIs and efficient computation in KDA, an SVI-based kernel discriminant analysis (SVIKDA) was proposed in this study to identify the healthy wheat and wheat infested with yellow rust, powdery mildew, and aphid by enhancing the between-classes covariance and narrowing the within-class covariance. Fourteen spectral vegetation indices (SVIs) were utilized for characterizing the foliar lesions caused by different pests and diseases. After filtering the redundant information among SVIs, our method effectively achieved the following objectives: 1) detect the spectral features of diseased and non-diseased wheat leaves, 2) differentiate infestations of yellow rust, aphids, and powdery mildew at both leaf and canopy levels, and 3) estimate the severity levels of each infestation. This study will also provide a theoretical basis for applying hyperspectral remote sensing to quantitatively classify and monitor different diseases and pests on wheat from a relatively early stage, and guide accurate field management.

2. Materials and methods

2.1. Experimental design and pathogen inoculation

The experiment was conducted at the Precision Agriculture Experimental Base in Xiaotangshan, Changping, Beijing (40°10.6′N, 116°26.3′E). The makeup of topsoil nutrients (0–30 cm depth) in the experimental area was as follows: soil organic matter 1.41–1.47%, nitrogen 0.07–0.11%, available phosphorus content 20.5–55.8 mg kg^{-1}, and rapidly available potassium 116.6–128.1 mg kg^{-1}.

Two cultivars of winter wheat '98-100' and 'Jingdong8' were selected due to their susceptibility to both yellow rust and powdery mildew. The cultivars '98-100' and 'Jingdong8' were inoculated with yellow rust and powdery mildew, respectively. In accordance with the National Plant Protection Standard (NPPS), yellow rust and powdery mildew were inoculated by spore inoculation in early April. The wheat cultivar 'Jingdong 8' was inoculated with aphids. During the growing season of winter wheat, wheat aphids occurred in the experimental field patches naturally.

2.2. Data acquisition

2.2.1. Spectral measurement of leaf and canopy samples

In this study, an ASD FieldSpec spectrometer (Analytical Spectral Devices, Inc., Boulder, CO, USA) was utilized to collect the leaf and canopy spectral information. The spectrometer was fitted with 25° field-of-view bare fiber-optic cable, and operated in the 350–2500 nm spectral region. The sampling interval was 1.4 nm between 350 and 1050 nm, and 2 nm between 1050 and 2500 nm. The spectral resolution was 3 nm for the region of 350–1000 nm and 10 nm for the region of 1000–2500 nm.

For leaf spectral measurement, the ASD spectrometer was equipped with a Li-Cor 1800-12 integration sphere (Li-Cor, Inc., Lincoln, NE, USA) used to collect the reflectance and transmittance of the upper surfaces of leaves. Considering the similar characters of near infrared bands between 800 and 1000 nm, only 400–800 nm spectral region was used in analysis. For each sampled leaf of wheat, five different zones were used to quantify the small but not negligible within-leaf variability. The scan time required for each sample was about two minutes. The sample was illuminated by a focused beam, and the radiation captured by the spectrometer was the average reflected radiation within the Li-Cor 1800-12 integration sphere. Data were collected around the middle of April, since the three diseases were in the incidence stage at that time. In the present study, spectra of 209 yellow rust-infested leaves, 140 aphid-infested leaves, and 133 powdery mildew-infested

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