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Research paper

Monitoring and evaluation in freeze stress of winter wheat (*Triticum aestivum* L.) through canopy hyperspectrum reflectance and multiple statistical analysis

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ABSTRACT

In order to evaluate the freeze stress of the winter wheat, field and pot experiments were conducted. The crop variables including plant height, above ground dry biomass (AGDB), chlorophyll content (CHLC), peroxidase (POD), superoxide dismutase (SOD), malondialdehyde (MDA), photosynthetic indexes, and canopy spectra were selected and assessed. Statistical methods of correlation analysis, principal component analysis (PCA), partial least squares (PLS), importance of variables analysis, and multiple linear regression (MLR) were implemented to establish freeze injury comprehensive evaluation index (FICEI), extract sensitive bands, and build the freeze injury predictive model. The results demonstrated that FICEI can be used to evaluate the damage degree. The major spectral regions were selected with the B-coefficient, variable importance in projection (VIP), and the frequencies of selection (FS) parameters derived from the PLS analysis. The combination of all three approaches can be utilized to reduce invalid spectral regions. According to the importance of variables analysis, the seven sensitive bands were extracted, which were 574 nm, 702 nm, 1093 nm, 1111 nm, 1210 nm, 1302 nm, and 1333 nm, respectively. The calibrated MLR model based on the selected bands demonstrated an excellent performance as the R^2 and RMSE were 0.924, 0.279 for FICEI. The model also illustrated an accurate and robust performance by using the pot validation data set since the higher value of coefficient of the determination and lower root mean squared error in validation model were confirmed. Our findings show that the estimation model for FICEI of winter wheat is reliable.

1. Introduction

Under the condition of global warming, the frequency and intensity of extreme weather events have been changed accordingly. Furthermore, the loss caused by disasters has been increasing. Freeze injury, occurring in one of the winter wheat growth periods, often happens as a natural disaster. Freeze injury has become one of the main factors influencing winter wheat growth (Sofalian et al., 2007). The freeze injury occurred frequently. However, the occurrence of the time was varied in different regions. It mainly occurred at the jointing stage in North China. It was documented at the heading stage in the Mediterranean coast, North and South America (Marcellos and Single, 1984). Compared to the stems and leaves of winter wheat, the spike is more sensitive to the low temperature, and its sensitivity enhances as the developmental process proceeded (Whaley et al., 2004). Due to the power of anti-cold disappeared at low temperature sensitive period especially following the winter wheat panicle being developed, freeze injury makes the wheat seed setting rate to be reduced, even no seed, and finally leads to a considerable reduction in production (Mahfoozi et al., 2006). Therefore, timely and accurately monitoring the winter wheat growth statue is essential. In addition, providing quantitative damage evaluation and strategic decision can effectively alleviate the problem caused by freeze injury.

Remote sensing technique can quickly monitor the occurrence and range of disasters. It can also provide timely agricultural information for the agriculture department decision makers and farmers. Through the application of remote sensing technique, it is easy to take all kinds of the promoting, regulating, and controlling measures and achieve the purpose of reducing disaster and increasing income and efficiency.

Previous scholars conducted a lot of researches on monitoring crop freeze injury by using large scale remote sensing. For example, Coll et al. (1994) proposed a split window algorithm that could achieve the

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Fig 1. Field and pot experiments.

objective of the inversion of surface temperature by using NOAA/AVHRR data. Lou et al. (2013) used the NOAA-AVHRR data and split window algorithm to retrieve the minimum ground temperature and monitor tea garden freeze injury. They further evaluated the losses of freeze injury in their study. Kerdiles et al. (1996) studied the spatial distribution of winter wheat frost damage of Argentina according to the linear relationship between the minimum temperature data and NOAA-AVHRR brightness temperature data. Generally, the occurrence and severity of freeze injury are not only related to the temperature, but also affected by other factors, such as varieties, irrigation, and cultivation conditions etc. If the crop suffers from the freeze injury, its leaf cell structure damage that results in the difference of near infrared, mid-infrared reflectance, and vegetation index based on this feature can effectively monitor the freeze injury situation of crop (Jurgens, 1997). Wang et al. (2016a) specified the frost damage levels by using the normalized difference vegetation index (NDVI), yield data, and implemented monitoring and forecasting of winter wheat freeze injury. Feng et al. (2009) monitored the freeze injury of winter wheat by using NDVI changes before and after the freeze injury. They further used the growth recovery rate to reveal the effect of freeze injury on yield.

Although the previous researches have established the solid technological foundation for crop freeze injury by using the remote sensing, however, it is critically challenging to meet the current demand for the monitoring effect based on the low resolution of remote sensing images and the hysteresis of the vegetation index changes. Obviously, hyperspectral remote sensing technique is an important development direction in ground object monitoring.

A large number of studies showed that it was feasible to monitor crop stress and growth in a real time by using hyperspectral remote sensing (Thenkabail and Smith, 2000; Glenn et al., 2004). Ren et al. (2014) studied hyperspectral performance characteristics and the change of the red edge after freezing injury at the jointing stage, and achieved the timely monitoring of winter wheat freeze injury. It was also feasible to monitor winter wheat seedling freeze injury by using hyperspectral imaging technique as it could accurately reflect the frozen parts (Wu et al., 2012). Wang et al. (2014), through counting on stem survival rate, established a freeze injury inversion model based on principal components analysis (PCA). They proved that the canopy hyperspectrum and PCA technology were promising in effectively detecting the winter wheat freeze injury.

Although natural disaster monitoring has achieved a major development using remote sensing technology (Kaufman et al., 1998; Majumdar and Massonnet, 2002; Pantaleoni et al., 2007; Jin and Yan, 2003; Pu et al., 2007), it is still a lack of research in terms of crop freeze injury hyperspectral monitoring and comprehensive agronomic parameters related to the freezing injury. Therefore, it is crucial and practical significance to actively carry out the research of crop freeze injury and provide the new method and approach for monitoring the crop freeze injury. In addition, there is a close relationship between the strength, duration length of low temperature, and freeze injury severity of winter wheat. Obviously, the aims of this study were to: (1) construct the FICEI evaluation method by using PCA and cluster analysis, evaluate, and validate the performance of FICEI in monitoring winter wheat freeze injury according to the characteristics of frost damage; and (2) identify effective band regions for FICEI, extract the effective wavelengths via PLS regression, and construct the monitoring model of winter wheat freeze injury by combining MLR method. The results will help to develop a comprehensive evaluation approach for rapid and non-destructive detection of winter wheat freeze injury by using hyperspectral technology. The findings of this research will also provide theoretical basis and technical support for monitoring freeze injury for winter wheat growth.

2. Materials and methods

2.1. Experimental design

The study was carried out as two categories: *i.e.,* pot and field experiments. Both pot and field trials were conducted in Shanxi Agricultural University (N 37°25′, E 112°33′) in 2014–2015. Calcareous cinnamon soil developed from loess parent material was selected as the test soil. Soil fertility was medium with an organic matter content of 22.01 g kg^{-1}, effective phosphorus content of 18.43 mg kg^{-1}, rapidly available potassium content of 236.9 mg kg^{-1}, and alkali solution nitrogen content of 53.8 mg kg^{-1}.

Field experiment: The cultivar Jintai 182, which is strong winteriness cultivar, was used as the planting material. It was sowed on October 2, 2014. The experimental plot area was 4 × 5 m^2, with a line spacing of 20 cm. Field management was conducted with a general high-yield field. The low temperature stress was conducted by using freezing test box (self-made device) from April 15th, 2015 (Fig. 1). Detailed treatments and representations are shown in Table 1. The triplicate treatments were implemented in the experiment. The field experiment data were used for model establishment.

Pot experiment, each pot contained 4 kg of soil from the site where the field trial was finally conducted. There were 20 plants per pot. Cultivar, sowing time, stress time, and treatments settings were the same as the field experiment. The low temperature stress was conducted by using plant growth chamber (Model: 3760; Thermo Fisher Scientific Inc. Marietta, USA). These data were collected to test the

Table 1
Treatment settings of low temperature stress.

Representations	Treatments	
	Time (hours)	Temperature (°C)
CCK	–	–
C1	4	−2
C2		−4
C3		−6
C4	12	−2
C5		−4
C6		−6