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Full Length Article

Identification and Characterization of Spectral Response Properties of Rice Canopy Infested by Leaf Folder

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Abstract

As one of the most fatal insect pests, rice leaf folder [*Cnaphalocrocis medinalis* Guenee] reduces grain yield by folding the leaves and scraping the leaves′ green tissues. This study aimed to identify and characterize such an insect using the ground-based hyperspectral data taken with a portable ASD (Analytical Spectral Devices, Inc.) spectrometer. After performing reflectance conversion and spectral-curve smoothing, the spectral response properties were firstly analyzed and compared concerning different infestation levels. Afterwards, the correlation analysis was conducted to optimally select characteristic bands sensitive to infestation severities according to the correlation coefficients (*r*), and three bands located at 424 nm (*r*=-0.802), 758 nm (*r*=-0.916), and 1141 nm (*r*=-0.895) were specifically chosen. Finally, a hyperspectral insect index of rice leaf folder (HIIRLF) was constructed using the reflectance values and corresponding weight coefficients in accordance with the contribution in spectral change rates of three bands. The results showed that there was a significant negative correlation between infestation levels and reflectance values. The HIIRLF was effective to identify the rice leaf folder, with a coefficient of determination (R^2) of 0.827 (n=18). Specifically, near-infrared spectra (692-1349 nm) were the best selection to differentiate infestation levels and the *in situ* hyperspectral data provided a better solution for non-destructively estimating the relative infestation levels of rice canopies caused by leaf folder.

Keywords: Field hyperspectral data; Hyperspectral insect index; Infestation levels; Rice leaf folder

Introduction

Rice (*Oryza sativa* L.) is one of the most important grain crops in China and its yield and quality determine the food security to a great degree. Nevertheless, various kinds of stress factors have exerted a negative impact on the sustainable farming of rice, such as insect pests and diseases, nutrient deficiencies, drought *etc*., and have also reduced resource-use efficiency (Qin *et al.*, 2005; Motlagh and Kaviani, 2008; Luo *et al*., 2010). In recent years, more diseases and insect pests are frequently threatening rice plants in yield and quality, especially with the fluctuant climate change. Rice leaf folder [*Cnaphalocrosis medinalis* Guenee (*Lep., Pyralidae*)] has been considered as one of the serious insect pests. Consequently, it is very necessary to monitor and obtain timely and effective crop protection strategies to prevent those damages or losses, which can make a substantial contribution to rice production (Elibuyuk and Bostan, 2010; Lucas, 2011). Unfortunately, traditional field survey methods to assess insect damage typically depend on field scouting, which have been proven to be expensive, time-consuming, and especially difficult for large farms (Lucas, 1998). With the appearance of remote sensing technology, it has been widely applied in the diagnosis studies of various stressed agricultural crops (Hatfield and Pinter, 1993). Depending on specific sensitive spectral bands and ranges, hyperspectral data have been used in detection of insect and disease infestations *etc*., (Nilsson, 1995).

More specifically, remote sensing provides an effective and economical solution for monitoring and identifying the disease- and insect-infested plants in a noninvasive and nondestructive way (Zhang *et al*., 2002). Furthermore, this approach could also be very useful for determining the chemical pesticides control strategies by deriving more accurate and quantitative insect assessment (Jones, 2010). In comparison with broadband data from multispectral remote sensing, as a more advanced detection technology, hyperspectral remote sensing is being utilized more in the analysis of diagnosing insects or diseases stressed plants. However, in previous studies, remote-sensing-based rice diseases were primarily explored. Kobayashi *et al.* (2001) evaluated the rice panicle blast using ratios of reflectance from airborne multispectral radiometer. Larsolle (2007) evaluated that how different parts of the rice reflectance spectra were affected by disease severities using a multivariate method. Yang (2010) analyzed the canopy hyperspectral reflectance spectra of two rice cultivars infected with leaf blight and established spectral models to identify disease severities. Liu *et al.*

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(2010) utilized principal components analysis (PCA) and neural network (NN) techniques to identify and classify fungal infestation severity in rice panicles. Conversely, fewer researches on rice insect pests were carried out using remote sensing techniques. Leaf folder is one of major insect pests in rice, which distributes across the rice planting regions in China (Rao *et al*., 2010). When rice is infested with this insect, it will cause foliar damage to badly influence the growth and nutrient apportion. Due to internal damage in chlorophyll pigments and tissue structure, insect-infested rice will be greatly influenced in photosynthesis and metabolism. Their growth will be stressed and morphologically display on the canopy (Qin *et al.*, 2005). Consequently, the insect-infested rice canopies will have different spectral properties and physical and biological parameters compared with healthy plants (Carter, 1993; Baret *et al*., 1994).

Leaf folder causes many changes of rice canopy and those differences can be just used to distinguish the rice canopies infested by leaf folder, which is also the theoretical foundation to identify insect infestation levels using hyperspectral remote sensing dataset. Based on the collected *in situ* hyperspectral data of eighteen sampling spots using a portable field spectrometer, the primary objectives of this study were to characterize the spectral responses of rice canopies infested with leaf folder at different infestation levels and furthermore construct an insect spectral index for estimating infestation severity degree from field hyperspectral measurement.

Materials and Methods

Experimental Site

An experiment was conducted in the rice fields of farming villages in Yuanjiang City, which is a county-level city of Yiyang City, Hunan Province, China. It is located between 112°14'37″-112°56'20″ E and 28°42'26″-29°11'17″ N, with an average altitude of 30 m above sea level in the flat alluvial plains of the northern part (Yuanjiang Statistical Information Network, http://tj.yuanjiang.gov.cn/index.asp). There are totally 77,660 ha agricultural land for planting grain crops, among which paddy rice fields account for 74,600 ha (2009). Due to the subtropical humid monsoon climate, its mean annual temperature is 16.7°C and the mean annual rainfall is around 1,322 mm which mainly concentrates in the months from April to June. Depending on fertile soil, rich water resource and meteorological conditions, rice is primarily planted in this city as the pillar agricultural industry.

Experimental Design

A field survey was carried out during 13-16 September, 2010, when it was just the booting or heading period of dual-season late rice. This stage was also the key period to form yield, so the incidence of rice leaf folder can reduce the crop yield and quality. Firstly, 25 rice plots was predefined on the high-resolution image of Google Earth and their coordinates were also recorded and input into a handheld Global Positioning System (GPS, Trimble® GeoXH) receiver with less than 1 m positioning accuracy. Subsequently, *in situ* investigation was made by taking a car with a GPS antenna integrated with Arcmap GPS module. According to the real-time navigation trail, the target positions can be found. When rice leaf folder was found in the paddy rice field, insect severity was estimated under the help of experienced agriculturist. At the same time, the canopy spectra and chlorophyll contents (SPAD values) were respectively collected with a portable ASD (Analytical Spectral Devices, Boulder, CO, USA) Filed Spec Pro spectrometer (with a 350-2500 nm spectral range and a 25° field of view) and Konica Minolta SPAD-502.

Estimating Insect Severity

To investigate the insect severity of leaf folder-affected rice canopy, a 1×1 m area was selected for each survey plot. According to the classification criteria (Table 1) of monitoring and forecasting the rice leaf-roller (GB/T 15793—200X), there were totally five levels from health to severe damage, and the specific levels were determined with the help of experienced pathologist. To effectively adapt to remote sensing-based data analysis, those five severities were merged to three levels. Specifically, a total of four levels were specified: healthy, light, moderate and severe in our study.

Hyperspectral Data Collection and Preprocessing

When collecting canopy-reflected spectra, the probe was placed at a height of 0.8 m above the ground to obtain more insect information. For each sampling spot, a total of 10 replicate measurements were taken. After original hyperspectral values were measured, further processing procedures must be required to covert the DN (Digital Number) values to reflectance using the calibrated reference panel. Here, ASD-viewspec Pro Version 6.0 was used to export original DN to Microsoft Excel and Eq. 1 was used to derive the converted reflectance.

$$R_t = \frac{\mathrm{DN}_t}{\mathrm{DN}_r} \times R_r \times 100\% \qquad (1)$$

Where, R_t is the target's calibrated reflectance using the reference panel, DN_t is the target's DN value acquired by ASD spectrometer, DN_r is the measured DN value of reference panel, and R_r is the known reflectance of the reference panel.

To suppress the environmental noise and exclude abnormal values, some data preprocessing must be performed. Firstly, to demonstrate more clearly the reflectance responses to the changes of insect occurrence with different damage levels, normalized reflectance is computed by a ratio (Eq. 2) (Pu, 2009; Rao *et al*., 2010).

This ratio can suppress the illumination differences and improve the mutual comparative effect among different damage levels (Yu *et al.*, 1999). Secondly, an adjacent-averaging smoothing method was used to smooth the reflectance curves for excluding abnormal values and improve curve characteristics. Ten processed spectral curves were generated for each spot and the average was used as the final reflectance. Afterwards, an average was taken using the adjacent 10 bands to reduce the hyperspectral data redundancy, and finally the original 2151 bands came down to 215 bands (Wang and Sousa, 2009). Additionally, rice always grows in the water-contained paddy field, so water vapor exerts greatly a negative impact on reflectance curves, especially for the absorption spectra of water vapor such as 1350-1450 nm, 1780-2000 nm and 2350-2500 nm. Before analyzing the spectral characteristics, they must be firstly excluded.

$$f_{ni} = f_i \Big/ \overline{\sum_{i=1}^{n} f_i} \quad (2)$$

Where, f_{ni} is the normalized reflectance value at the wavelength of i, f_i is the reflectance value at the wavelength of i, n is the total bands of each spectral curve, and $\overline{\sum_{i=1}^{n} f_i}$ is the mean reflectance of that curve.

Results

General Comparison of Infested Rice Canopies

As shown in Fig. 1a, it could be found that the chlorophyll content gradually decreased with the increasing insect damage levels. Specifically, for the spectral response properties (Fig. 1b), it could be obviously seen that the curve characteristics were very similar for different levels. All of them showed the typical spectral properties of green vegetation: green peak, red valley and high near-infrared (NIR) reflectance. However, different damage levels could still be obviously differentiated in the NIR spectrum, while they failed to be distinguished in the visible and short-wave infrared (SWIR) spectral regions. In the NIR spectrum, the reflectance gradually decreased with the increasing damage levels, and their change trends were the same for four levels. Conversely, the curve fluctuations were more severe in the SWIR spectrum due to the impact of water vapor absorption, so they must be smoothed to reflect the real damage conditions.

Spectral Response Properties of Different Insect Damage Levels

In comparison with Fig. 1b and Fig. 2b, the curves were apparently smoothed, especially in the SWIR spectrum (2000-2350 nm). Fig. 2a was the normalized spectral curves and had some differences than Fig. 2b. It was obvious that the overall trends of spectral curves were flattened, especially in the visible and NIR spectra (350-1350 nm). Specifically, the curves of healthy rice canopy were obviously separated from other levels, especially in the NIR and SWIR spectral ranges. Fig. 2c and 2d were respectively the comparison of spectral properties of different insect damage levels in the visible and NIR spectra. It could be found that they generally showed reverse spectral response characteristics. In Fig. 2c, the reflectance gradually decreased with the increasing damage levels in the same wavelength range, while it gradually increased in Fig. 2d.

The Insect Index for Estimating Damage Levels

To demonstrate the specific comparison between seriously leaf folder-infested and healthy rice canopies, the spectral differences and change rates were illustrated in Fig. 3a. Considering the spectral difference curve, it was obvious that the values were negative in the visible spectrum (350-691 nm), which indicated that the reflectance values of healthy rice canopies were less than that of the insect-infested. Conversely, the spectral difference values were positive and the maximum value was 8.56 (at 1104 nm) in the NIR spectrum (692-1349 nm), which showed that the reflectance values of healthy rice plants were greater than the insect-infected. In the SWIR spectrum (1451-1779 nm and 2001-2349 nm), it showed the similar change with the NIR spectrum. On the change rate curve, it reached the highest point in the NIR spectrum and the maximum value reached 18.2% (at 1341 nm), then it ranked the second and the maximum value was 14.34% (at 2333 nm) in the SWIR spectrum, and it owned the smallest change and the maximum value was -0.37% (at 558 nm) in the visible spectrum.

To quickly estimate the damage level for a certain sampling spot, it is necessary to construct a hyperspectral index using the collected *in situ* hyperspectral reflectance. A total of eighteen sampling spots were used to investigate the correlation between the insect levels and reflectance values. They specifically included three normal spots, six light spots, six moderate spots and three serious spots. The analysis result showed that there was a significant negative correlation between spectral reflectance and disease severity in the wavelength range of 400-1300 nm (Fig. 3b). Specifically, three intervals were divided by three spectral wavelength ranges: 400-720, 720-1115 and 1115-1300 nm. For those three intervals, three bands with the maximum correlation coefficients (r) were identified: 424 nm (r=-0.802), 758 nm (r=-0.916), and 1141 nm (r=-0.895). Then, a hyperspectral insect index for rice leaf folder (HIIRLF) was built with three characteristic bands (Eq. 3). In addition, corresponding weight coefficients were also determined in accordance with the change rates of three bands in Fig. 3a.

Table 1: Classification criteria for estimating the insect severity of rice canopy infested by leaf folder

Incidence	Insect level	Leaf rolling ratio per unit area (rolling leaves/total leaves) (%)
Slight	1	<5.0
Slight to moderate	2	5.0-20.0
Moderate	3	20.1-35.0
Moderate to severe	4	35.1-50.0
Severe	5	>50.0

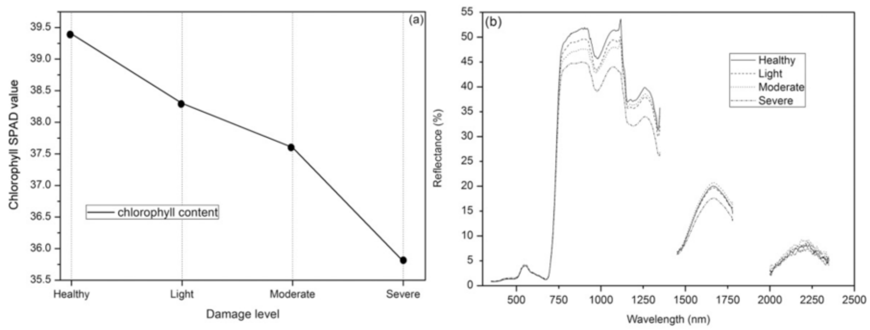

Fig. 1: Response differences of four insect levels in chlorophyll SPAD value (a) and spectral reflectance (b)

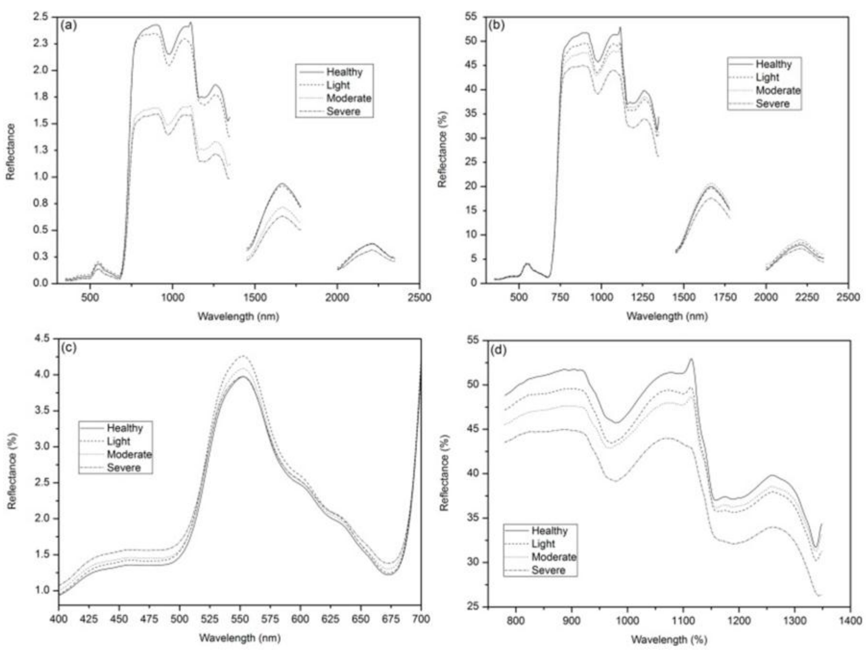

Fig. 2: Comparison among spectral reflectance for different insect damage levels: (a) is the normalized reflectance curves; (b) is the smoothed reflectance curves; (c) is the spectral characteristics in the visible spectrum; and (d) is the spectral characteristics in the NIR spectrum

To validate the index, the acquired eighteen sampling spots with different insect levels were used and their fitting linear models and coefficients of determination (R^2) were obtained using the chlorophyll SPAD values (a) and HIIRLF (b), respectively (Fig. 4). It can be found that the R^2 of (a) was higher than that of (b).

$$HIIRLF = -0.40 \times \frac{R424_{\text{normal}} - R424_{\text{insect-infested}}}{R424_{\text{normal}}} + 0.25 \times \frac{R758_{\text{normal}} - R758_{\text{insect-infested}}}{R758_{\text{normal}}} + 0.35 \times \frac{R1141_{\text{normal}} - R1141_{\text{insect-infested}}}{R1141_{\text{normal}}} \quad (3)$$

Where, $R424_{\text{normal}}$, $R758_{\text{normal}}$, $R1141_{\text{normal}}$ represent the mean reflectance values of healthy rice canopies at 424, 758, 1141 nm, respectively; $R424_{\text{insect-infested}}$, $R758_{\text{insect-infested}}$, $R1141_{\text{insect-infested}}$ represent the reflectance values of rice canopies seriously infested with leaf folder at 424, 758, 1141 nm, respectively.

Discussion

Rice is the most important cereal grain to provide human

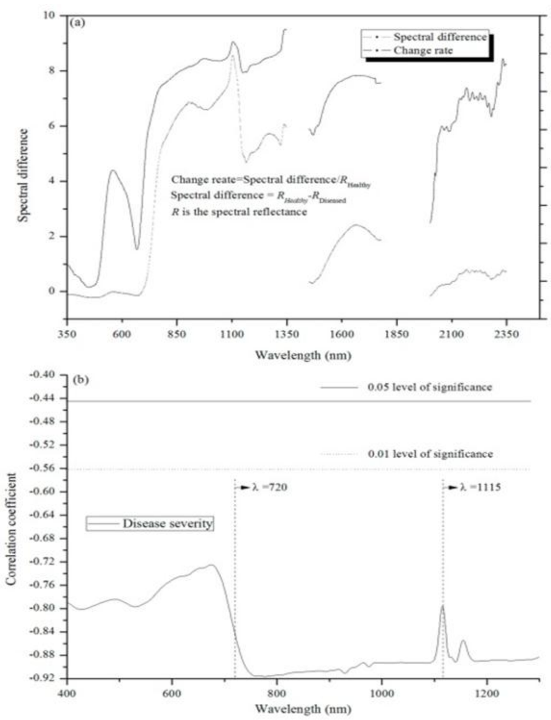

Fig. 3: The spectral difference and change rate between normal and leaf folder-infested rice canopies (a) and the correlation coefficients between insect severity levels and reflectance (b)

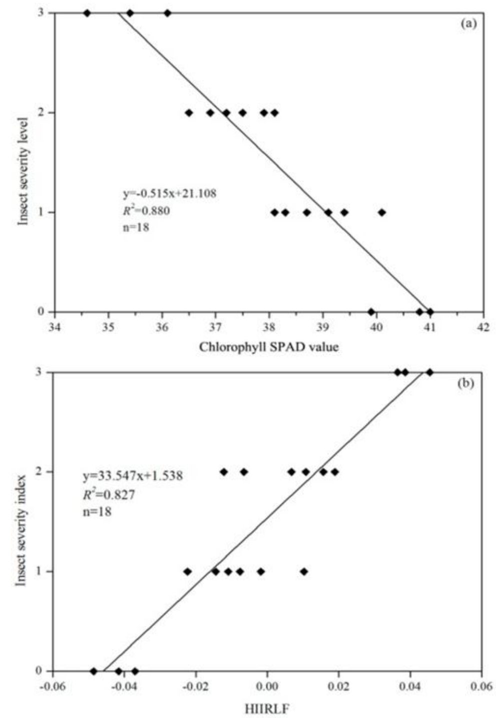

Fig. 4: Comparison of fitting linear relationships of insect damage levels between chlorophyll SPAD values and HIIRLF

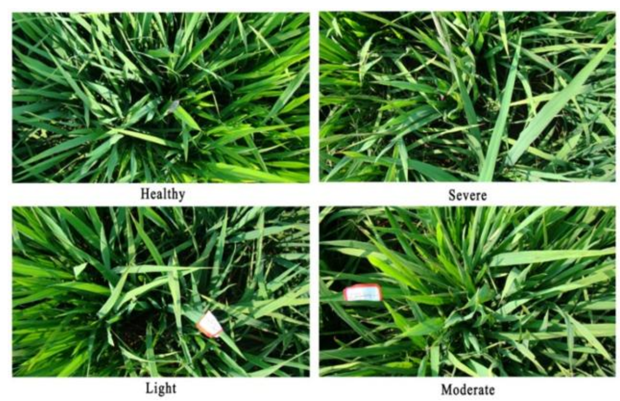

Fig. 5: Visual comparisons of rice canopies infested by leaf folder with four damage levels

nutrition and caloric intake. However, increasing natural stress factors are threatening to affect its yield and quality, especially with the wider climate fluctuations in recent years (Rosenzweig and Parry, 1994; Matthews *et al*., 1997; Aggarwal and Mall, 2002). As an essential hindering factor, the incidence and prevalence of insect pests have often negatively affected the growth and yields of rice plants. Consequently, how to effectively monitor and diagnose the insect infestations has been paid special attention, especially for rice farmers and agricultural decision-making departments. The emergence of remote sensing techniques, especially the ground-based hyperspectral remote sensing, has provided a suite of tools to characterize and identify rice insect pests in the field. When rice is infested by leaf folder, the rice leaves will be folded and lead to a reduction in yield in the end. Although some changes can be visually observed by farmers, the specific damage severities cannot be determined. Furthermore, at the initial stage of insect infestation, the incidence cannot usually be observed directly from rice canopies, but they have been damaged in actual cases. As a result, early detection of insect infestation is the most important issue in making urgent decisions and protecting further infestations from occurring (Venette *et al*., 2000).

In past agricultural practices, farmers mainly depend on the visual sensing of optical changes in rice canopies in the assessment of insect risk. Unfortunately, such a traditional method has always been a time-consuming process with a low monitoring accuracy (Parker *et al*., 1995; Huang *et al*., 2007). Recently, the developments in optical sensor technology have facilitated the direct detection of foliar insect pests under field conditions (West *et al*., 2003). The optical sensors can collect the interaction between electromagnetic radiation and rice plants, and the interaction varies in different wavelength bands. In general, healthy rice plants always have typical vegetation characteristics: low reflectance at visible wavelengths (400–700 nm); high reflectance in the NIR (700–1,200 nm); and low reflectance in wide wavebands in the SWIR (1,200–2,400 nm).

However, they will exhibit significant differences depending on the level of health and or vigor (Wooley, 1971). The differences provide a theoretical foundation for detecting rice insect pests infested with various damage levels and make the monitoring result more reliable based on remote sensing technology.

A common-used near-ground hyperspectral spectrometer (ASD) was used in our study to collect the *in situ* hyperspectral remote sensing dataset in the field. This device has been widely used previously and approved to be effective in the identification and characterization of different plants affected by various kinds of diseases and insect pests (Abdel-Rahman *et al*., 2010; Prabhakar *et al*., 2011; Zhao *et al*., 2012). In general, remote sensing of crop plant vigour has concentrated on the link between plant pigments, especially chlorophylls and biomass, whose combination is collectively referred to as photosynthetically active biomass (Hall *et al*., 2002). It can be obviously found that leaves are more seriously folded and the canopy cover also increasingly decreases when damage severity increases (Fig. 5). This phenomenon changes the bidirectional reflectance distribution function (BRDF) of rice canopy, so the insect severity can be monitored according to the reflectance differences concerning different damage levels. As shown in Fig. 1a, those leaves with more serious damage have lower chlorophyll content. The reason for this phenomenon can be interpreted in the following aspects: (1) the larvae of rice leaf folder can destroy the inner green tissues of leaves, so they inevitably cause scorching and leaf drying (Kandibane *et al*., 2010); (2) with the increase of larvae, more rice leaves are folded and those larvae feed on nutrient supplies; (3) the capability of chlorophyllinite to load chlorophyll is damaged by larvae.

When referring to the spectral reflectance, they show different change features at different wavelengths. The reason for this change can be interpreted as that the spectral reflectance of green vegetation is determined by different factors over different spectral ranges: (1) it is mainly controlled by various kinds of pigments such as chlorophyll in the visible spectrum; (2) it is mainly controlled by leaf cell structure in the NIR spectrum; and (3) it is mainly determined by water content in the SWIR spectrum. When rice plants are infested by rice leaf folder, their larvae destroy the rice leaves and cause scorching and leaf drying, so the chlorophyll inevitably decreases (Fig. 1a) and the reflectance increases unsteadily for the infested rice canopy in the visible spectrum. In addition, the larvae also fold the leaves and ruin the cell structure, and the reflectance accordingly decreases in the NIR spectrum. Comparing the spectral responses of rice canopies with different insect damage levels, it can be found that the separation in the NIR spectrum is generally better than that in the visible and SWIR spectra.

In comparison with in-field investigation of insect severity index, it is more convenient to non-destructively collect the spectral reflectance of rice canopies. Consequently, it is quite necessary to construct a rational model for obtaining the severity index using just the acquired *in situ* spectral values. In our study, three bands with the maximum correlation coefficients were simultaneously used to construct a hyperspectral index (HIIRLF). To validate the effect, chlorophyll SPAD values and HIIRLF were compared and the result showed that R^2 of linear fitting model from SPAD values was a little higher than HIIRLF. However, the model from measured point SPAD values cannot truly reflect the chlorophyll status of the whole rice canopy. The reason for such a phenomenon is that the measured SPAD values are just the relative chlorophyll content by averaging several sampling points for each rice canopy, while HIIRLF considers the mean spectra of the whole canopy and it is a more comprehensive index, which integrates three characteristic bands in the visible and NIR spectral ranges. Therefore, the monitoring result from HIIRLF can be also more reliable. To estimate the damage level for a certain sampling spot, two steps will be required: one is to collect the spectral reflectance and pick up the reflectance values of three characteristic bands, and the other is to calculate the HIIRLF and the insect damage level can be quickly determined using the fitting linear model (Fig. 4b).

In conclusion, this study identified and characterized the spectral response properties of rice canopies infested by leaf folder. In general, the rice plants with different insect damage levels could show the typical spectral properties of green vegetation: green peak, red valley and high near-infrared reflectance. Specifically, different damage levels can still be obviously differentiated in the NIR spectrum (692-1349 nm). Concerning the change features of different infestation levels, the chlorophyll content gradually decreased with the increasing insect damage levels. Conversely, the spectral reflectance showed different changes: it increased with the increasing damage in the visible spectrum, but it decreased in the NIR spectrum. Furthermore, a hyperspectral insect index (HIIRLF) was constructed and its effect was also validated by comparing the fitting linear modes using chlorophyll SPAD values and HIIRLF, respectively. The monitoring result was also more reliable, because this index considered comprehensively the spectral properties of three characteristic bands in visible and NIR spectral regions. This study indicated the model from HIIRLF was considered as a better solution for non-destructively identifying the damage levels of rice canopies infested by leaf folder from *in situ* hyperspectral data.

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