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Characterization of brown planthopper damage on rice crops through hyperspectral remote sensing under field conditions

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Abstract Field experiments were conducted to characterize the brown planthopper (BPH) (*Nilaparvata lugens* (Stål.) damage stress on rice crops through hyperspectral remote sensing. The BPH-damaged rice crop had higher reflectance in visible (VIS) and lower reflectance in near-infrared regions (NIR) of the electromagnetic spectrum compared with uninfested plants. Mean reflectance of the rice crop varied among different BPH damage levels in various wavebands, with the greatest variation in NIR (740–925 nm). Correlations between plant reflectance and BPH damage depicted four sensitive wavelengths, at 764, 961, 1201 and 1664 nm in relation to BPH stress on the rice crop. Three new brown planthopper spectral indices (BPHI) were formulated by combining two or more of these sensitive wavelengths. Some of the hyperspectral indices reported in the literature were also tested for their suitability to detect BPH stress on rice crops. Based on crop reflectance corresponding to the sensitive wavelengths, a multiple-linear regression model was developed ($R^2=0.71$, RMSE=1.74, $P<0.0001$) and validated ($R^2=0.73$, RMSE=0.71, $P<0.0001$) that would help to monitor BPH stress on a rice crop and to issue forewarnings to growers.

Keywords *Nilaparvata lugens* (Stål.) · Spectral reflectances · Wavebands

Introduction

Rice is the primary food crop for more than three billion people in the world (Khush 2005) and is also an important staple crop of many countries in Asia (Yang *et al.* 2008). Among rice pests, brown planthopper (BPH), (*Nilaparvata lugens* (Stål.) Hemiptera: Delphacidae), is one of the notorious pests responsible for large-scale devastation that results in important crop losses amounting to as high as 60 % (Srivastava *et al.* 2009). The BPH is a difficult pest to monitor, because by the time plant damage becomes evident, significant yield loss has already been inflicted. It is a sort of 'hidden' factor to the farmer and its timely detection through regular monitoring is the key to effective management of the pest.

Growth characteristics of crop plants at different stages could be distinguished by measuring the spectral reflectances from visible (VIS) and near infrared (NIR) regions of the spectrum (Inoue *et al.* 1998, 2008; Yang and Chen 2004). The reflectance pattern from plant

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foliage is determined by chemical composition and physical properties of the plant tissues, and the spectral properties of the remote sensing equipment (Bauer 1985; Myneni and Ross 1991). The high spectral resolution provided by the hyperspectral remote sensing in the VIS and the NIR regions provided a promising method to detect the severity of pest damage (Shibayama *et al*. 1993; Zhang *et al*. 2006).

Yang *et al.* (2007) and Prasannakumar *et al.* (2013) differentiated among the BPH damage levels based on spectral characteristics at the VIS and the NIR regions under controlled conditions. Similarly, Prabhakar *et al.* (2011) assessed the different levels of cotton leaf hopper damage under field conditions. Spectral reflectance of a crop thus offers the promise of monitoring pest activity and provides an opportunity to survey large areas quickly with an appreciable reduction in manpower and expenditure, thereby facilitating timely forewarning to the growers. However, in India little information is available on application of this technology to detect plant stress, particularly that of rice BPH under field conditions. It was thus deemed necessary to develop spectral signatures for BPH damage on rice and explore the possibility of assessing the extent of the pest damage based on rice crop reflectance.

Materials and methods

Field experiment

Research was conducted in an experimental rice field during the rainy seasons of 2010 and 2011 at the Indian Agricultural Research Institute in New Delhi (28°36′36″ N, 77°13′48″E). Twenty-two-day-old seedlings of rice variety ‘Pusa Basmati 1’ (PB-1) were transplanted on 20 July during both 2010 and 2011 in 24 plots, each measuring 3.5 m x 2.5 m, to allocate six treatments with four replications. The plants were maintained with the recommended fertilizer amounts: nitrogen (N), phosphorus (P_2O_5), potash (K_2O) and zinc (Zn) at 120, 60, 40 and 25 kg ha^{-1}, respectively. The N was applied as diammonium phosphate (DAP) and urea, P_2O_5 as DAP, K_2O as muriate of potash and Zn as zinc sulfate. The N was applied three times, at transplanting, peak tillering and anthesis, while P_2O_5 and K_2O were applied as basal applications. The crop was irrigated regularly in order to avoid water stress.

The entire field was enclosed in nylon mesh to avoid pest migration. Variable numbers of BPH brachypterous females and winged males were released in different plots to create differential BPH damage levels. The rice crop was assessed regularly for BPH damage and was scored from undamaged (level 0) to complete hopper burn (level 9) based on INGER scale (INGER 1996) (Table 1).

Spectral measurements

Spectral reflectance of the rice crop, having differential BPH damage, was measured at 1-nm intervals over wavelengths ranging from 350 to 2500nm with a FieldSpec3 portable spectroradiometer (Analytical Spectral Devices (ASD), Boulder, CO, USA). The instrument was able to communicate through wireless access with a laptop computer that could be used to record and process data using ASD software. Before collecting reflectance, the instrument was calibrated with respect to solar radiation using a reference panel, Spectralon (Labsphere, Inc., North Sutton, NH, USA). Reflectance spectrum was obtained through comparison of the radiance of the target plants with that of Spectralon. The instrument was set to yield reflectance spectra averaging 50 spectra of a target per sec in order to increase accuracy of the data. With a 25° field of view, the sensor was kept at a height of 80cm above the plant canopy in order to cover the entire rice canopy (17.6cm). Observations for all plots were recorded from the fixed positions under cloudless sunlight conditions between 1100 and 1300h local standard time. The BPH damage on a rice crop usually appears during the 70–80 days after transplanting (DAT) under local conditions. Therefore, spectral reflectance of rice crop recorded between 70 and 80 DAT for respective wavebands during the 2 years were pooled and analyzed.

Spectral reflectance values were averaged for each of 10-nm intervals along the 350–2500nm range and jumps at 1000nm and 1800nm were smoothed using software Hyper Agri (Version 4.2; developed by IARI). Spectral noises at 1355–1424, 1805–1964 and 2445–2500nm were removed to obtain clear curves.

Data analysis

Spectral reflectance of the rice crop under differential BPH damage within each of the wavebands, *viz.,* UV (Ultra-violet), V (Violet), B (Blue), G (Green), Y (Yellow), O (Orange), R (Red), NIR (Near infrared)

Table 1 Differential brown planthopper damage (BPH) levels on the rice crop for measuring spectral reflectance under field conditions

Scale*	BPH damage Symptoms
Level 0	No damage
Level 1	Slight yellowing of a few plants
Level 3	Leaves partially yellow but with no hopperburn
Level 5	Leaves with pronounced yellowing and some stunting or wilting, 10–25 % of plants with hopperburn
Level 7	More than half the plants wilting or with hopperburn, remaining plants severely stunted
Level 9	All plants dead

*INGER (1996)

and MIR (Mid infrared), were analyzed using one-way analysis of variance (ANOVA), the BPH damage levels being treatments with four replicates each. Likewise, spectral reflectance at different wavebands within each of the damage levels was also analyzed using one-way ANOVA, wavebands being considered as treatments with four replicates each. Rice crop reflectance with regard to BPH damage levels as well as wavebands was compared separately based on least significant difference (LSD). Variability in spectral reflectance owing to differential BPH damage was evaluated using linear correlation. The BPH damage levels and corresponding reflectance at each of 1nm intervals over the 350–2500nm range were correlated. Correlation coefficients (r) obtained were plotted against wavelengths to create a correlation–wavelength curve. Wavelengths corresponding to peaks in the correlation–wavelength curve were identified as sensitive wavelengths (Jones *et al.* 2010; Prabhakar *et al.* 2011; Yang *et al.* 2007). Three new brown planthopper spectral indices (BPHI) were formulated by combining two or more of these sensitive wavelengths. These as well as 11 other hyperspectral indices reported in the literature (Table 2) were subjected to linear regression to quantify their relation with BPH damage.

A multilinear regression model was developed using the SAS statistical package version 9.2 to enable assessment of crop damage based on reflectance of a BPH-damaged rice crop. The BPH damage levels were regressed against spectral reflectances at each of the sensitive wavelengths identified using the correlation–wavelength curve, such that:

$$Y = a + b_1 * R_{\lambda 1} + b_2 * R_{\lambda 2} + b_3 * R_{\lambda 3} + \ldots\ldots b_n * R_{\lambda n},$$

where: a is the intercept, and b_1, b_2, . . . bn are the regression coefficients for reflectances (R) at sensitive wavelengths (λ1, λ2, . . . λn), respectively.

The developed model was validated using independent data on rice crop reflectance and corresponding BPH damage levels (0–9) that were recorded in a separate experiment.

Results

Spectral reflectance

Spectral reflectance of the rice crop as influenced by differential BPH damage under field conditions varied along the wavelength domain of 350–2500nm. Spectral reflectance of uninfested plants was lower than that of infested crops in the VIS region (400–700nm). Reflectance of infested plants in the VIS was found to be directly related to BPH damage wherein reflectance increased with an increase in damage from around 400nm to the red edge shoulder around 668nm. However, peak of spectral reflectance in the VIS around 550–560nm was higher for an uninfested crop than for an infested crop. In the NIR (740–925nm), an uninfested crop had a higher reflectance than an infested crop, reflectance having decreased with an increase in BPH damage. Rice crop reflectance thus exhibited a negative relationship with BPH damage in the NIR. In the MIR, two water absorption bands were characterized around 1450 and 1975nm, owing to a sharp decline in spectral reflectance of both uninfested and infested rice crops. Water absorption bands were evident immediately following the discontinuities in reflectance curve that resulted due to removal of noises in spectral data from 1355 to 1424nm and from 1805 to 1964nm (Fig. 1).

Mean rice crop reflectance had wide intra-band variability among different BPH damage levels in each of nine wave bands, *viz.,* UV, V, B, G, Y, O, R, NIR and MIR. The BPH damage caused less variability in crop

Table 2 Spectral vegetation indices calculated based on spectral reflectance of the rice crop damaged by the brown planthopper

Vegetation indices	Formula	References
Simple ratio (SR)	R695/R420	Carter (1994)
Photochemical Reflectance Index (PRI)	(R531−R570)/(R531+R570)	Gamon *et al.* (1992)
Normalized Pigment Chlorophyll Index (NPCI)	(R685−R445)/(R685+R445)	Penuelas *et al.* (1993)
Water Band Index (WBI)	(R970)/(R900)	Penuelas *et al.* (1993)
Transformed Chlorophyll Absorption Index (TCARI)	3*((R700−R670)−0.2*(R700−R550) (R700/R670))	Haboudane *et al.*(2002)
Red Edge Position (REP)	700+40(R_{re}−R700)/(R740−R700) where, R_{re}=(R670+R780)/2	Guyot and Baret (1988)
Moisture Stress Index (MSI)	(R1600)/(R820)	Hunt *et al.* (1989)
Normalized Difference Vegetation Index (NDVI)	$(R_{NIR}-R_{RED})/(R_{NIR}+R_{RED})$	Rouse *et al.* (1974)
Green Normalized Difference Vegetation Index (GNDVI)	(R750−R550)/(R750+R550)	Gitelson and Merzlyak (1996)
Soil Adjusted Vegetation Index (SAVI)	$(R_{NIR}-R_{RED})(1+L)/(R_{NIR}+R_{RED}+L)$	Huete (1988)
Optimized Soil Adjusted Vegetation Index (OSAVI)	(1+0.16) (R800−R670)/(R800+R670+0.16)	Rondeaux *et al.* (1996)
Brown planthopper Index-1 (BPHI-1)	R_{1201}/R_{961}	this study
Brown planthopper Index-2 (BPH-2)	$(R_{764}-R_{1164})/(R_{764})$	this study
Brown planthopper Index-3 (BPH-3)	$(R_{1664}-R_{1201}/R_{1664}+R_{1201})$	this study

reflectance at shorter wavelengths (350–730nm), but it accounted for greater variability in crop reflectance at longer wavelengths, *viz.,* NIR (740–925nm) followed by MIR (926–1800nm) (Fig. 2). The greatest difference in rice crop reflectance was found between BPH damage level 9 and level 0 in the NIR (740–925nm); crop reflectance being 19.7±0.1% and 61.93±0.26%, respectively. Besides, rice crop reflectance showed significant inter wave-band differences within each of the BPH damage levels (Table 3). Significantly higher rice crop reflectance in the NIR under each of the BPH damage levels indicated that perhaps this wave-band could be a sensitive region in the electromagnetic spectrum for the detection of BPH stress under field conditions (Table 3).

Identification of sensitive bands and band ratios

Values of correlation coefficients that were obtained by relating rice crop reflectance to different BPH damage levels at 1-nm intervals, when plotted against wavelengths, revealed peaks and troughs in the curve so obtained (Fig. 3). Based on these peaks and troughs,

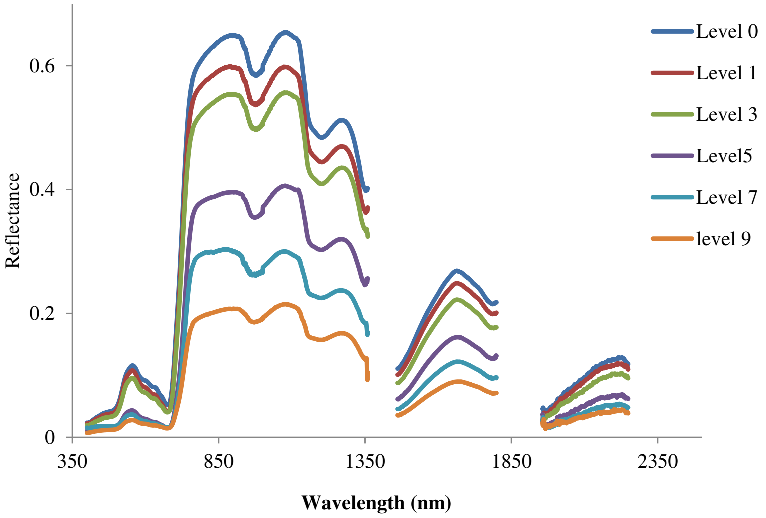

Fig. 1 Reflectance spectra of rice plants at different wave bands in relation to differential brown planthopper infestation levels

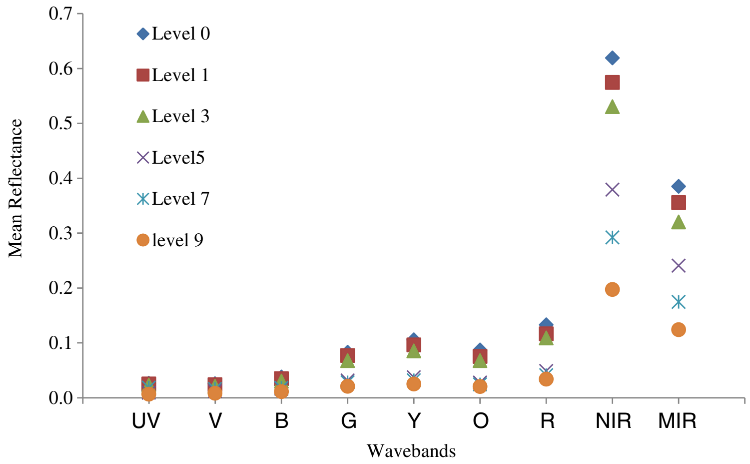

Fig. 2 Variation in mean reflectance (based on different spectral ranges within a band) in relation to variable brown planthopper infestation levels

four sensitive wave-bands were identified: 764nm (r=–0.674), 961nm (r=–0.70), 1201nm (r=–0.70) and 1664nm (r=–0.60). Using two or more of these bands in different combinations, the following three new BPH indices were formulated:

$$\text{Brown planthopper Index-2(BPHI-1)} = R_{1201}/R_{961}\left(R^2 = 0.71; P < 0.001; \text{RMSE} = 0.029\right) \quad (1)$$

$$\text{Brown planthopper Index-2(BPHI-2)} = \left(R_{764}\text{–}R_{1164}\right)/\left(R_{764}\right)\left(R^2 = 0.74; P < 0.001; \text{RMSE} = 0.047\right) \quad (2)$$

$$\text{Brown planthopper Index-3(BPHI-3)} = \left(R_{1664}\text{–}R_{1201}/R_{1664} + R_{1201}\right)\left(R^2 = 0.76; P < 0.0001; \text{RMSE} = 0.053\right) \quad (3)$$

In addition, other indices that were collected from the literature and tested during the present study also showed a good relationship with BPH infestation levels. These included: Photochemical Reflectance Index (PRI) (R^2=0.61, P<0.0001, RMSE=0.010); Normalized Pigment Chlorophyll Index (NPCI) (R^2=0.68, P<0.0001, RMSE=0.038); Water Band Index (WBI) (R^2=0.69, P<0.0001, RMSE=0.112); Transformed Chlorophyll Absorption in Reflectance Index (TCARI) (R^2=0.924, P=0.002, RMSE=0.0235); Moisture Stress Index (MSI) (R^2=0.65, P<0.0001, RMSE=0.279); Normalized Difference Vegetation Index (NDVI) (R^2=0.755, P<0.0001, RMSE=0.0961); Soil Adjusted Vegetation Index (SAVI) (R^2=0.724, P<0.0001, RMSE=0.256); Optimized Soil Adjusted Vegetation Index (OSAVI) (R^2=0.79, P=0.016, RMSE=0.043) (Table 4). However, new indices (BPHI) that were developed during the present study exhibited a better relationship with BPH damage (higher R^2) than the tested traditional indices except TCARI and OSAVI. Among the new indices, Brown planthopper Index-3(BPHI-3)=$(R_{1664}-R_{1201}/R_{1664}+R_{1201})(R^2=0.76; P<0.0001; \text{RMSE}=0.053)$ proved to be superior to BPHI-1 and BPHI-2 and this could be used to predict the BPH damage under field conditions.

BPH damage-reflectance model

A multilinear regression model was developed between damage levels and plant reflectances R^2=0.71) as:$Y=16.768998+60.10784*\lambda_{961\text{nm}}-130.93968*\lambda_{1201\text{nm}}-23.73013*\lambda_{764\text{nm}}+79.40564*\lambda_{1664\text{nm}}$(RMSE=1.74; P<0.0001). The developed model was validated satisfactorily (R^2=0.73; RMSE=0.71; P<0.0001) to detect the BPH damage from the reflectance spectra of a rice crop under field conditions (Fig. 4). The identified sensitive bands together accounted for 73 % variability in BPH damage.. The model would thus be useful to predict BPH damage based on rice crop reflectance rather than field counting, that is generally avoided by growers, and would facilitate issuing of timely forewarnings.

Table 3 Mean spectral reflectance of the rice crop in different wavebands measured under field conditions in relation to differential brown planthopper (BPH) damage

Waveband (nm)	Mean reflectance (%) ^{z,y}						LSD P=0.05
	Level 0	Level 1	Level 3	Level 5	Level 7	Level 9	
UV (350-399)	$0.0261 \pm 0.04^{a,5}$	$0.0252 \pm 0.04^{b,5}$	$0.0229 \pm 0.04^{c,5}$	$0.0091 \pm 0.01^{d,4}$	$0.0184 \pm 0.03^{e,3,4}$	$0.0064 \pm 0.00^{f,4}$	0.0008
V (400-424)	$0.0253 \pm 0.04^{a,4,5}$	$0.0239 \pm 0.04^{b,4,5}$	$0.0209 \pm 0.03^{c,4,5}$	$0.0118 \pm 0.02^{d,3,4}$	$0.0156 \pm 0.01^{e,3,4}$	$0.0082 \pm 0.01^{f,4}$	0.0008
B (425-489)	$0.0378 \pm 0.05^{a,4,5}$	$0.0347 \pm 0.04^{b,4,5}$	$0.0302 \pm 0.04^{c,4,5}$	$0.0160 \pm 0.01^{d,4}$	$0.0178 \pm 0.00^{e,4}$	$0.0113 \pm 0.01^{f,4}$	0.0009
G (490-559)	$0.0828 \pm 0.32^{a,4}$	$0.0768 \pm 0.31^{a,3,4}$	$0.0676 \pm 0.28^{b,4,5}$	$0.0312 \pm 0.12^{c,3,4}$	$0.0282 \pm 0.09^{c,3,4}$	$0.0208 \pm 0.07^{d,3,4}$	0.0062
Y (560-584)	$0.1054 \pm 0.13^{a,3,4}$	$0.0961 \pm 0.14^{b,3,4}$	$0.0853 \pm 0.12^{c,3,4}$	$0.0372 \pm 0.07^{d,3,4}$	$0.0319 \pm 0.05^{e,3,4}$	$0.0251 \pm 0.03^{f,3,4}$	0.0028
O (585-639)	$0.0868 \pm 0.07^{a,3,4}$	$0.0753 \pm 0.08^{b,3,4,5}$	$0.0677 \pm 0.06^{c,3,4,5}$	$0.0276 \pm 0.03^{d,3,4}$	$0.0242 \pm 0.03^{e,3,4}$	$0.0206 \pm 0.02^{f,3,4}$	0.0015
R (640-730)	$0.1329 \pm 1.06^{a,3}$	$0.1165 \pm 0.99^{a,b,3}$	$0.1088 \pm 0.39^{b,3}$	$0.0488 \pm 0.49^{c,3}$	$0.0409 \pm 0.38^{c,3}$	$0.0337 \pm 0.27^{c,3}$	0.021
NIR (740-925)	$0.6193 \pm 0.26^{a,1}$	$0.5745 \pm 0.22^{b,1}$	$0.5303 \pm 0.21^{c,1}$	$0.3791 \pm 0.19^{d,1}$	$0.2920 \pm 0.14^{e,1}$	$0.1970 \pm 0.10^{f,1}$	0.0054
MIR (926-1800)	$0.3851 \pm 0.18^{a,2}$	$0.3554 \pm 0.17^{b,2}$	$0.3204 \pm 0.16^{c,2}$	$0.2408 \pm 0.11^{d,2}$	$0.1745 \pm 0.09^{e,2}$	$0.1240 \pm 0.06^{f,2}$	0.0129
^{x}LSD (P=0.05)	0.165	0.151	0.144	0.105	0.076	0.054	-

Abbreviations: UV = ultraviolet, V = violet, B = blue, G = green, Y = yellow, O = orange, R = red, NIR = near infrared, MIR = mid infrared

^{z} Within the same row, values with a common superscript letter do not differ significantly (P = 0.05)

^{y} Within the same column, values with a common superscript number do not differ significantly (P = 0.05)

^{x} LSD = least significant difference

Discussion

Higher reflectance of a rice crop in the VIS with an increase in BPH damage suggested a reduction in chlorophyll content of leaves due to the pest feeding. Chlorophyll reduction was perceptible through visual observations since a BPH-damaged crop exhibited hopper burn symptoms in the form of yellowing, curling and wilting of leaves. An uninfested crop was greener and that might absorb a higher amount of radiation than an infested crop in the blue (450nm) and red (680nm) bands. Higher plant reflectance in the VIS region owing to pest-induced biochemical changes in photosynthetic pigments has been reported previously (Gausman 1982; Mass and Dunlap 1989; Salisbury and Ross 1969). Other studies that have found plant reflectance patterns in the VIS region similar to our study included BPH damage in rice (Yang and Cheng 2001), and greenbug (Mirik *et al.* 2006) and Russian wheat aphid (Mirik *et al.* 2007) damage in wheat. However, higher peak

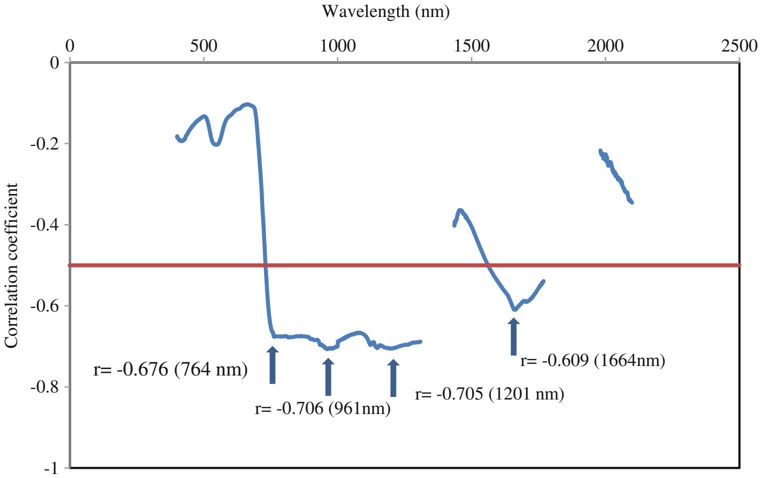

Fig. 3 Correlation coefficient (r) between reflectance spectra of rice plants at wave bands and different brown planthopper infestation levels

Table 4 Co-efficient of determination (R^2) and probability (P) of different vegetation indices calculated based on spectral reflectance of the rice crop damaged by the brown planthopper

Vegetation indices	F value	R^2	*P*	RMSE
Simple ratio (SR)	4.47	0.52	0.102	0.606
Photochemical Reflectance Index (PRI)	78.24	0.61	<0.0001	0.010
Normalized Pigment Chlorophyll Index (NPCI)	134.83	0.68	<0.0001	0.0389
Water Band Index (WBI)	142.69	0.69	<0.0001	0.112
Transformed Chlorophyll Absorption Index (TCARI)	49.00	0.92	0.002	0.023
Red Edge Position (REP)	6.43	0.61	0.064	2.16
Moisture Stress Index (MSI)	115.98	0.65	<0.0001	0.207
Normalized Difference Vegetation Index (NDVI)	191.67	0.75	<0.0001	0.096
Green Normalized Difference Vegetation Index (GNDVI)	5.38	0.57	0.081	0.035
Soil Adjusted Vegetation Index (SAVI)	163.40	0.72	<0.0001	0.256
Optimized Soil Adjusted Vegetation Index (OSAVI)	15.69	0.79	0.0167	0.043
Brown planthopper Index-1 (BPHI-1)	149.63	0.71	<0.0001	0.029
Brown planthopper Index-2 (BPH-2)	172.02	0.74	<0.0001	0.047
Brown planthopper Index-3 (BPH-3)	203.05	0.76	<0.0001	0.053

reflectance of an uninfested crop in comparison with an infested crop at 550–560 nm might be ascribed to higher reflectance of green light (500 to 600 nm) by more concentrated green leaf pigments in an uninfested crop, which has also been reported earlier (Mirik *et al.* 2006, 2007; Riedell and Blackmer 1999).

Lower reflectance of an infested crop in the NIR region (675–1125nm) as compared with an uninfested crop could be attributed to BPH-inflicted leaf curling, shrinking and wilting that might scatter incident radiation rather than reflecting it from the leaf surface. A decrease in plant reflectance because of leaf color fading, cell structure damage and alteration in air-cell spongy mesophyll, responsible for photon scattering in the NIR region, was earlier reported in studies on BPH (Prasannakumar *et al.* 2013; Yang *et al.* 2007), mustard aphid (Kumar *et al.* 2010) and cotton leaf hoppers (Prabhakar *et al.* 2011). Asner (1998) also reported the

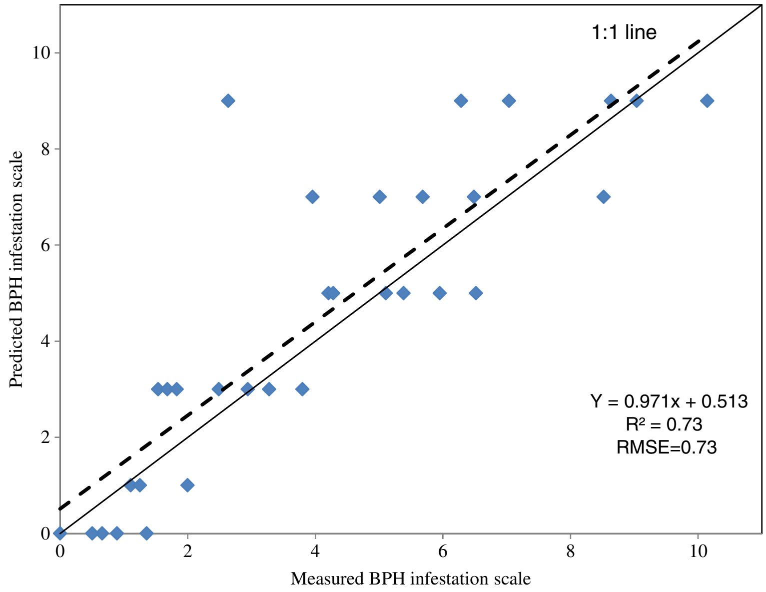

Fig. 4 Relationship between brown planthopper infestation levels predicted through regression model and observed infestation levels in experiment

maximum reflectance from uninfested plants (level 0) due to the strongest multiple scattering and transmittance in the NIR region.

Lower reflectance of a BPH-damaged crop compared with an uninfested crop in the MIR was not indicative of any BPH-induced water stress on the crop, in contrast to the general perception that it might cause water stress. Curran (1985) found that reflectance in the MIR region was greatly influenced by green-leaf moisture content with strong absorption bands and the size of reflectance peaks following these bands decreased with an increase in leaf moisture content. However, in our study, lower spectral reflectance of an infested crop compared with an uninfested crop at water absorption bands, and at peaks following them, could probably be attributed to increased water uptake by an infested crop under unlimited water availability to replenish cell sap removal by the BPH, as reported earlier (Prasannakumar *et al.* 2013). However, the MIR region has generally not been discussed in relation to the effect of biotic stresses on plant reflectance in most previous studies (Kumar *et al.* 2010; Mirik *et al.* 2007; Prabhakar *et al.* 2011).

The correlation–wavelength curve depicted peaks and troughs throughout the wavelength range of 350–2500 nm indicated that not only the spectral characteristics but optical properties and reflectance too were waveband dependent. Similar results were also obtained in previous studies (Asner 1998; Yang and Chen 2004).

Single band reflectance from the plant canopy is likely to be affected by factors such as solar angle, soil background, crop growth and other unknown factors. Instead of its use as such, simple/normalized ratios of inter-band crop reflectance help to minimize the influence of aforesaid externalities (Lillesand *et al.* 2004). New BPH indices (BPHI) were thus developed to be able to predict the BPH damage under field conditions using plant reflectance. Although traditional indices such as TCARI and OSAVI showed somewhat better predictability of the BPH damage than new BPH indices, the traditional ones are general purpose indices used to predict the effect of abiotic factors on plant pigments, whereas BPH-indices are specific for the pest, which is a biotic stress factor (Haboudane *et al.* 2002). Such pest-specific indices were developed earlier for rice BPH (Yang *et al.* 2007), tomato bacterial leaf spot disease (Jones *et al.* 2010) and cotton leaf hopper (Prabhakar *et al.* 2011).

The BPH damage-reflectance model developed and validated in this study indicated that BPH damage could be monitored using spectral reflectance of the crop. Spectral reflectance of rice plants corresponding to sensitive wavelengths, *viz.,*764, 961, 1201 and 1664nm, individually showed a moderate correlation (r=–0.60 to –0.70) with BPH damage; however, these together accounted for 73% variability in BPH damage (R^2=0.73), as evidenced by a multiple linear regression model (Fig. 4). Recently, Prasannakumar *et al.* (2013) identified four sensitive wavelengths (1986nm, r=0.63; 665nm, r=0.58; 1792nm, r=0.53; 500nm, r=0.52) for BPH-damaged rice plants under controlled conditions. Variation in sensitive wavelengths for the same pest on the rice crop might be due to the environmental heterogeneity under field conditions. Furthermore, spectral reflectances are subject to change by plant growth rate and photosynthetic capacity of chloroplasts, solar angle, shadowing, illumination canopy coverage, soil background, atmospheric conditions and the viewing angle of the recording device (Riedell and Blackmer 1999; Yang *et al.* 2005).

Conclusions

This study revealed that BPH damage on a rice crop could be differentiated under field conditions based on the reflectance pattern of infested and uninfested crops in the NIR and VIS regions of the electro-magnetic spectrum. Reflectance at wavelengths identified to be sensitive to the BPH damage can be employed to assess BPH damage in the field, which would prove easier than population counts of the pest. Application of hyper-spectral remote sensing would pave the way for timely forewarning to growers and action against BPH.

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