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Assessment of Brown Planthopper, (*Nilaparvata lugens*) [Stål], damage in rice using hyperspectral remote sensing

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Hyperspectral remote sensing was used to detect stress on potted rice plants caused by the Brown Planthopper (BPH), *Nilaparvata lugens* (Stål). BPH damage influenced reflectance of rice plants compared to uninfested plants in the visible and near-infrared regions of the electromagnetic spectrum. Correlations between plant reflectance and BPH damage, when plotted against wavelengths, enabled us to identify four sensitive wavelengths, at 1986, 665, 1792 and 500 nm, in relation to BPH stress on rice plants. Based on rice plant reflectance corresponding to the sensitive wavelengths, three hyperspectral indices were developed. The BPH damage showed a positive association with normalized pigment chlorophyll index, and a negative relationship with normalized difference vegetation index and soil adjusted vegetation index. Using rice plant reflectance corresponding to the sensitive wavelengths, a multiple-linear regression model was developed and validated, which would facilitate assessment of BPH damage based on rice plant reflectance, thereby ensuring prompt forewarning to stakeholders.

Keywords: *Oryza sativa*; pest stress; reflectance; spectral indices; spectral signature; wavebands

1. Introduction

Rice is the most important staple food crop for more than half of the world's population (Maclean et al. 2002), which certainly holds true for India. In 2011, an area of approximately 41.85 million hectares was under rice cultivation in India, with a production that year of 102 million tonnes (Anonymous 2012). In India, the yield loss inflicted on rice due to insect pests has been estimated to be between 21 and 51 per cent (Prakash et al. 2007), which is one of the major reasons for poorer crop productivity in India compared with China and Sri Lanka (Krishnaiah et al. 2008). In view of land area constraints, an increase in crop productivity has to be achieved through improved crop production and protection technologies. The Brown Planthopper (BPH), *Nilaparvata lugens* (Stål) (Homoptera: Delphacidae), is one of the pests responsible for large-scale devastation to the rice crop, causing yield losses amounting to as high as 60% (Srivastava et al. 2009; Kumar et al. 2012). BPH is a difficult pest to monitor, consequently, by the time plant damage becomes evident, significant loss in yield is inevitable. Timely detection of BPH's incidence in the crop, through regular monitoring, is the key to effective pest management.

Plants or other objects can be distinguished through remote sensing based on reflectance – "spectral signatures" – from their surfaces produced over different wavebands of the electromagnetic spectrum (Lewis 2003). The reflectance pattern from plant foliage is determined by the chemical composition and physical properties of the plant's tissues, and the spectral properties of the remote sensing equipment (Bauer 1985; Myneni and Ross 1991). Crops may be affected by both biotic and abiotic stresses in the field. However, it is difficult to determine the cause of plant stress through remote sensing without standardizing spectral signatures for different types of stress (Arya 2011). Biotic stresses, such as diseases and damage inflicted by insects, alter the chlorophyll characteristics, chemical concentrations, cell structure, nutrient and water uptake, and gas exchange of the plant, leading to differences in reflectance from the foliage (Raikes and Burpee 1998). The use of reflectance spectra for monitoring vegetation condition has gained popularity owing to the intensive development of hyperspectral remote sensing equipment, which provides additional bands within the visible, near-infrared (NIR) and shortwave-infrared (SWIR) regions. Most hyperspectral sensors acquire radiance information in less than 10-nm bandwidths from the visible to the SWIR region (400–2500 nm) (Asner 1998). It is possible to collect several hundred spectral bands in a single acquisition, thus producing many more detailed spectral data through hyperspectral remote sensing than broad band technique (Govender et al. 2007).

Yang and Cheng (2001) and Yang et al. (2007) found the severity of damage inflicted by leaf-folder moth and BPH in rice to be measurable through differences in reflectance from the visible and NIR regions on the spectral domain. Because work on spectral signatures of crop pests in India remains very scanty, we therefore aimed to evaluate the hyperspectral remote sensing technique to assess the damage due to BPH, currently the most important pest of rice.

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Table 1. Differential brown planthopper (BPH) damage levels generated for measuring spectral reflectance of rice plants.

Treatments[a] (BPH damage)	No. of BPH male and female pairs released	Damage symptom due to BPH infestation
Level 0	Uninfested	No damage
Level 1	4	Slight yellowing of few leaves
Level 3	8	Leaves partially yellowing but with no hopper burn
Level 5	12	Leaves with pronounced yellowing and some wilting
Level 7	16	Most of the leaves wilting with hopper burn
Level 9	20	All plants dead

[a] Source: INGER (1996).

2. Materials and methods

2.1. *Generation of differential brown planthopper damage*

Experiments for creating differential BPH damage levels were undertaken during the rainy season of 2010 and 2011 at the Indian Agricultural Research Institute, New Delhi (28°36′36″N, 77°13′48″E). Seeds of Pusa Basamti 1 rice were sown in a nursery and 22-d old seedlings were transplanted in black opaque plastic pots (0.3 m diameter, 0.2 m height) in a glasshouse, at densities of three seedlings per pot. The plants were maintained following recommended fertilizer dosage: nitrogen (N), phosphorous (P_2O_5), potash (K_2O) and zinc (Zn) at 120, 60, 40 and 25 kg/ha, respectively. The N was applied through diammonium phosphate (DAP) and urea, P_2O_5 through DAP, K_2O through muriate of potash and Zn through zinc sulphate. The N was used in three equal splits at transplanting, peak tillering and anthesis, while P_2O_5 and K_2O were used as basal applications. Plants were irrigated when needed to avoid causing water stress to them. The experiments involved six treatments (Table 1) in completely randomized design (CRD) with four replications. Treatments comprised differential BPH damage, ranging from uninfested plants (level 0) to complete hopperburn (orange colouration caused by phloem-feeding; level 9) in accordance with INGER (1996). To obtain different BPH damage levels, 45-d old rice seedlings were infested with differential numbers of brachypterous females and winged males. Requisite numbers of adults for release (Table 1) were obtained from a four-years old BPH culture maintained in wire mesh cages on potted plants of Taichung Native -1 (TN-1) and other susceptible rice cultivars in one of our glasshouses. (A field-collected sample of the BPH population is mixed with this culture every year to ensure genetic heterogeneity.) To prevent escape of released insects, potted plants were individually enclosed in mylar (polyester film) cages that had an open-top covered with nylon mesh together with several side-holes for ventilation.

2.2. *Spectral measurements*

Spectral reflectance from rice plants infested with different BPH densities (and thus potential damage levels) was measured at 1-nm intervals with a field-portable spectroradiometer (FieldSpec3, Analytical Spectral Devices® [ASD]). The instrument had a facility to communicate through wireless access with a laptop computer that could be used to record and process data through ASD software. Prior to observation, the instrument was calibrated with respect to solar radiation using a reference panel, Spectralon®. Reflectance spectra were obtained by comparing the radiance of the target plants with that of the Spectralon. The instrument was set to yield an average of 50 spectra for a target at any one time. To represent the field situation, all pots were placed out under sunlit conditions at field spacing for rice (0.2 m row × 0.15 m plant) before observation. With a 25° field of view, the sensor was kept at 80 cm height above the plant to ensure complete plant foliage coverage. Reflectance from rice was recorded from the fixed positions under cloudless sunlight conditions between 1100 h and 1300 h Indian standard time. Rice plant reflectances at 75 d after transplanting (DAT) during the two years were pooled for analysis. Pooling was done because reflectances were similar for respective BPH damage levels at the same wavelengths during the two years. Plant reflectance values were averaged at 10-nm intervals and "jumps" (large increments) at 1000 nm and 1800 nm were smoothened using Hyper Agri® software developed at our institute). "Noise" at 1355–1424, 1805–1964 and 2445–2500 nm was removed. Mean spectral reflectance for different wavebands were also determined: ultraviolet (UV) (350–399 nm), violet (V) (400–424 nm), blue (B) (425–489 nm), green (G) (490–559 nm), yellow (Y) (560–584 nm), orange (O) (585–639 nm), red (R) (640–730 nm) and NIR (740–925 nm) and mid infra-red (MIR) (926–2500 nm).

2.3. *Data analysis*

Spectral reflectances from rice plants at different BPH damage levels within each of the wavebands – UV, V, B, G, Y, O, R, NIR and MIR – were analysed using one-way analysis of variance (ANOVA). Damage levels were taken to be treatments, and the mean reflectance from four rice plants in a waveband was taken as a replicate. Likewise, reflectances at different wavebands within each of damage levels – that is, levels 0, 1, 3, 5, 7 and 9 – were also analysed through one-way ANOVA, taking wavebands as treatments and reflectance from four rice plants at a damage level as replicates. Rice plant reflectance with regard to BPH damage levels as well as wavebands was compared separately based on least significant difference (LSD).

Changes in spectral reflectance with varying BPH damage were evaluated using linear correlation. Spectral reflectances from rice foliage corresponding to different BPH damage levels between 350 nm and 2500 nm were correlated with the pest damage at each of the1-nm intervals. Correlation coefficients (*r*) thus obtained were

Table 2. Spectral vegetation indices computed/developed based on reflectance from rice canopy as affected by brown planthopper infestation.

Vegetation Index	Formula	Reference
Normalized Pigment Chlorophyll Index (NPCI)	[a]$(R_{685} - R_{445})/(R_{685} + R_{445})$	Penuelas et al. (1993)
Normalized Difference Vegetation Index (NDVI)	$(R_{NIR} - R_{RED})/(R_{NIR} + R_{RED})$	Rouse et al. (1973)
Soil Adjusted Vegetation Index (SAVI)	$(R_{NIR}\text{-}R_{RED})(1 + L)/(R_{NIR} + R_{RED} + L)$[b]	Huete (1988)
Brown planthopper Index-1 (BPHI-1)	R_{665}/R_{1782}	Present study
Brown planthopper Index-2 (BPHI-2)	$(R_{1792} - R_{665})/(R_{1792} + R_{665})$	Present study
Brown planthopper Index-3 (BPHI-3)	$(R_{1792} - R_{1986}/R_{1792} + R_{1986})$	Present study

[a] R_{445}, R_{665}, R_{685}, R_{1782}, R_{1792}, R_{1986}, R_{NIR} and R_{RED} refer to spectral reflectance at 445, 665, 685, 1782, 1986, near infrared (NIR) and red wavelengths in nanometres, respectively.

[b] $L = 0.5$.

plotted against wavelengths to obtain a correlation–wavelength curve. Wavelengths that corresponded to peaks in the correlation–wavelength curve were identified as sensitive wavelengths (Yang et al. 2007; Jones et al. 2010; Prabhakar et al. 2011).

Based on sensitive wavelengths identified, new spectral indices, namely BPHI-1, BPHI-2 and BPHI-3, were developed (Table 2). To develop these indices, simple ratios of reflectances, corresponding to any two sensitive wavelengths at a time, were determined in different combinations. Likewise, ratios of difference and sum of reflectances, corresponding to any two of sensitive wavelengths at a time, were computed in different combinations. Twenty-eight of such ratios were calculated for each BPH damage level. The BPH damage levels were regressed against corresponding values of each of the ratios; then, based on the coefficient of determination (R^2) value, the first three were taken as BPHI-1, BPHI-2 and BPHI-3. In addition, the hyperspectral vegetation indices – normalized pigment chlorophyll index (NPCI), normalized difference vegetation index (NDVI) and soil adjusted vegetation index (SAVI) – were computed according to the formulae given in Table 2. The BPH damage levels were regressed against the corresponding values of each of the NPCI, NDVI and SAVI to evaluate them for damage quantification based on spectral reflectances from rice plants.

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

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

where a is the intercept, and $b_1, b_2, \ldots b_n$ are the regression coefficients for reflectances (R) at sensitive wavelengths ($\lambda_1, \lambda_2, \ldots \lambda_n$), respectively.

Our model was validated by means of an independent data set for reflectances of rice plants corresponding to BPH damage levels (0–9) at different wavelengths. These data were generated by releasing BPH adults on rice plants and reflectances were measured when requisite damage levels were detected.

3. Results and discussion

3.1. Spectral reflectance in relation to brown planthopper infestation

Spectral reflectance of rice plants under different BPH damage levels was significantly lower than the reflectance of uninfested plants at green, yellow, orange and red wavelengths in the visible region and in the near infrared region (Table 3). However, reflectance of uninfested and infested plants did not differ significantly in ultraviolet, violet and blue wavelengths with respect to damage level 3. A significant difference in reflectance of uninfested and infested plants in most of the wavebands indicated detectability, by remote sensing, of even low intensity damage. At a given damage level, spectral reflectance showed significant inter-band differences particularly between visible and NIR bands. Reflectance of uninfested as well as infested plants increased with increasing wavelength up to the yellow band, then decreased at orange and again increased at red, thereby creating peaks and troughs in the reflectance curve at around 560 nm and 700 nm, respectively. Reflectance at green, yellow, orange and red wavelengths (490–730 nm) in the visible region did not decrease consistently with an increase in BPH damage level. However, in the NIR region (740–925 nm) reflectance decreased consistently with an increase in the BPH damage. On the other hand, in the MIR region (926–2500 nm) two water absorption bands were witnessed around 1450 nm and 1975 nm, which were characterized by a sharp decline in spectral reflectance of both uninfested and infested rice plants. 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 1424 nm and from 1805 to 1964 nm (Figure 1). Mean spectral reflectance of rice plants for different wavebands as affected by differential BPH damage varied across the nine bands – UV, V, B, G, Y, O, R, NIR and MIR (Table 3). Variation in plant reflectance due to BPH damage was smaller at shorter wavelengths (350–730 nm) and larger at longer wavelengths, namely NIR (740–925 nm). The greatest difference in plant reflectance occurred between BPH damage level 9 and damage level 0 in the NIR region (Table 3).

In previous studies, a mixed pattern of spectral reflectance was recorded from pest-infested crops in the visible

Table 3. Mean reflectance of rice plants at different spectral wave bands in relation to differential brown planthopper (BPH) infestation

Wave bands (nm) per damage level	$^{@}$Mean reflectance ± standard error					LSD
	Level 0	Level 1	Level 3	Level 5	Level 7	Level 9	(P <0.05)
UV (350–399)	$^{\$}0.0303 \pm 0.09^{a;1}$	$^{\$}0.0318 \pm 0.09^{b;1}$	$0.0297 \pm 0.03^{a;1}$	$0.0267 \pm 0.03^{c;1}$	$0.0271 \pm 0.02^{c;1}$	$0.0345 \pm 0.03^{d;1}$	0.0008
V (400–424)	$^{\&}0.0375 \pm 0.04^{a;1,2}$	$0.0408 \pm 0.05^{b;1}$	$0.0365 \pm 0.04^{a;1,2}$	$0.0338 \pm 0.04^{c;1,2}$	$0.0325 \pm 0.03^{d;1}$	$0.0409 \pm 0.03^{b;1,2}$	0.0011
B (425–489)	$^{\&}0.0473 \pm 0.04^{a;1,2}$	$0.0504 \pm 0.03^{b;1,2}$	$0.0463 \pm 0.04^{a;1,2}$	$0.0443 \pm 0.05^{d;1,2,3}$	$0.0400 \pm 0.03^{e;1,2}$	$0.0502 \pm 0.04^{b;1,2,3}$	0.0011
G (490–559)	$0.0870 \pm 0.28^{a;1,2,3}$	$0.0779 \pm 0.19^{b;1,2}$	$0.0709 \pm 0.16^{c;1,2}$	$0.0714 \pm 0.17^{c;1,2,3,4}$	$0.0621 \pm 0.15^{d;1,2}$	$0.0697 \pm 0.11^{c;2,3,4}$	0.0051
Y (560–584)	$0.1052 \pm 0.11^{a;2.3}$	$0.0884 \pm 0.09^{b;1,2}$	$0.0829 \pm 0.05^{c;2}$	$0.0867 \pm 0.04^{b;3,4}$	$0.0734 \pm 0.05^{e;1,2}$	$0.0808 \pm 0.02^{d;3,4}$	0.0019
O (585–639)	$0.0900 \pm 0.06^{a;1,2,3}$	$0.0768 \pm 0.04^{b;1,2}$	$0.0772 \pm 0.02^{b;1,2,3}$	$0.0833 \pm 0.01^{c;2,3,4}$	$0.0664 \pm 0.02^{d;1,2}$	$0.0806 \pm 0.01^{e;3,4}$	0.0009
R (640–730)	$0.1295 \pm 0.79^{a;3}$	$0.1074 \pm 0.58^{b;2}$	$0.1059 \pm 0.48^{b;3}$	$0.1115 \pm 0.45^{b;4}$	$0.0892 \pm 0.43^{c;2}$	$0.1002 \pm 0.28^{b;4}$	0.0147
NIR (740–925)	$0.3782 \pm 0.09^{a;4}$	$0.3153 \pm 0.08^{b;3}$	$0.2943 \pm 0.09^{c;4}$	$0.2727 \pm 0.10^{d;5}$	$0.2342 \pm 0.06^{e;3}$	$0.1989 \pm 0.05^{f;5}$	0.0022
MIR (926–2500)	$0.3198 \pm 0.26^{a;4}$	$0.2649 \pm 0.22^{b;3}$	$0.2567 \pm 0.19^{c;4}$	$0.2430 \pm 0.19^{d;5}$	$0.1992 \pm 0.17^{e;3}$	$0.1949 \pm 0.10^{e;5}$	0.0054
LSD (*P* <0.05)	0.071	0.061	0.050	0.050	0.050	0.035	

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

$^{@}$Mean based on four replications during each of two years and data pooled for two years.

$^{\$}$Values with same superscript (alphabets) within same row do not differ significantly.

$^{\&}$Values with same superscript (numerical) within same column do not differ significantly.

region. While reflectance from infested plants in this spectral region was higher than uninfested crops in the case of BPH damage in rice (Yang and Cheng 2001), and Green Bug, *Schizaphis graminum* (Rondani) (Mirik et al. 2006) and Russian Wheat Aphid *Diuraphis noxia* Kurdjumov (Mirik et al. 2007) damage in wheat; it was found to be lower in infested crops than in uninfested crops in the case of Mustard Aphid, *Lipaphis erysimi* Kaltenbach (Kumar et al. 2010) and Rice Leaf-folder, *Cnaphalocrocis medinalis* (Guenee) (Yang and Cheng 2001), as was the case in the present study. It was suggested that pests might induce production of higher amounts of anthocyanins, which could cause a difference in reflectance between damaged and undamaged leaves (Stone et al. 2001). 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). In our study, BPH-infested plants had lower reflectance than uninfested plants in the visible region, which suggests that pest-feeding did not cause any reduction in chlorophyll concentration within the leaves. In the event of a reduction in leaf chlorophyll content, reflectance of infested plants would have been greater than that of uninfested plants (Boyer et al. 1988). Nonetheless, BPH-infested plants in experiments, especially those under higher damage levels, were observed to have turned yellowish and to have curled and shrunk leaves, perhaps indicating loss of leaf pigments. Despite BPH damage having reduced the concentration of leaf pigments, reflectance of damaged plants was lower than that of uninfested plants, which was against the trend. This is likely to have been due to a proportional increase in reflectance of uninfested plants caused by internal or external factors that made the reflectance of infested plants seem lower. The anomaly between the visible reflectance pattern recorded in the present study and that recorded by Yang and Cheng (2001) could thus possibly be due to an increase in reflectance of uninfested plants in the visible region resulting from changes in concentrations of leaf pigments, plant condition or factors related to radiation and the measuring device. Kumar et al. (2010) observed that aphid-infested mustard foliage had lower reflectance despite having 50% lower chlorophyll concentration than uninfested plants.

While there is variability with respect to reflectance pattern of infested plants in the visible region, reflectance of infested plants in the NIR was previously observed to be, without exception, uniformly lower than uninfested plants (Yang et al. 2001, 2007; Kumar et al. 2010; Prabhakar et al. 2011). Lower reflectance of infested plants in the NIR region (740–925 nm) compared with uninfested plants can be ascribed to curling, shrinking and wilting of leaves due to BPH damage that might have led to scattering instead of reflectance of incident radiation, thereby resulting in decreased reflectance from infested plants. In previous studies, damage due to rice BPH (Yang et al. 2007), Mustard aphid (Kumar et al. 2010)

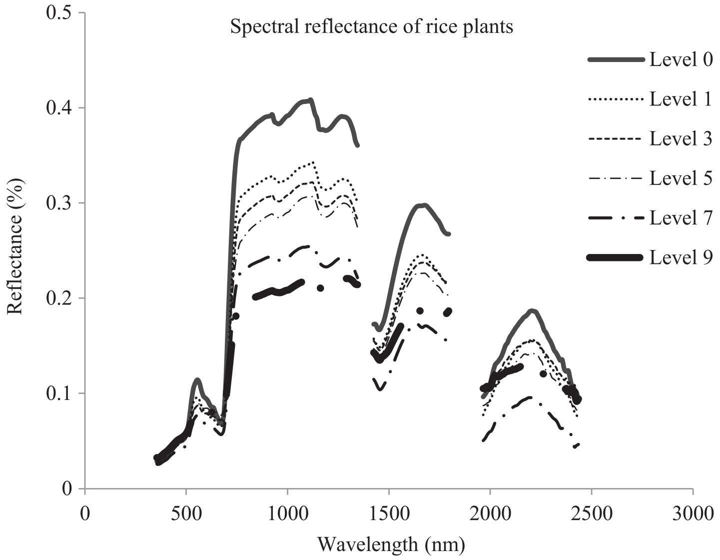

Figure 1. Spectral reflectance of rice plants at different wavebands in relation to differential infestation levels of brown planthopper.

and Cotton leafhopper, *Amrasca biguttula bigutulla* (Ishida) (Prabhakar et al. 2011) was found to reduce plant reflectance in the NIR due to photon scattering that occurred owing to leaf colour fading, cell structure damage and alteration in air-cell spongy mesophyll. Asner (1998) also reported the maximum reflectance from uninfested plants (level 0) due to the strongest multiple scattering and transmittance in the NIR region.

In this study, the MIR region had two water absorption bands at around 1450 nm and 1975 nm (Figure 1) in uninfested as well as in infested plants. As both types of plant showed absorption of radiation by moisture content in leaves, we infer that BPH-feeding did not result in water stress to infested plants. This made sense, as both uninfested and infested plants were regularly watered, so minimizing the risk of increasing water stress. Previously, Curran (1985) found the MIR region to be greatly influenced by moisture content of green leaves with strong absorption bands, and they also noticed that the size of reflectance peaks following these bands decreased with an increase in leaf moisture content. However, in our study, lower spectral reflectance of infested plants compared with uninfested plants at water absorption bands, and at peaks following them, could probably be due to increased water uptake by infested plants under conditions of unlimited water availability to replenish cell sap removal by the BPH. In previous studies, the MIR region has generally not been discussed in relation to effect of biotic stresses on plant reflectance (Mirik et al. 2007; Kumar et al. 2010; Prabhakar et al. 2011).

In our study the NIR band was found to be most important one for distinguishing between BPH-infested and uninfested plants using remote sensing. Pusa Basmati 1, a scented rice variety, is highly susceptible to BPH, and other scented cultivars have also been found to be equally susceptible to that particular pest. Cultivars with tolerance to BPH might exhibit low or moderate damage under similar pest pressure at which Pusa Basmati 1 shows high damage. However, significant differences in spectral reflectance of uninfested and BPH infested rice plants in the majority of wavebands, as recorded in the present study, indicates that remote sensing is capable of detecting low levels of BPH damage. As the reflectance pattern on Pusa Basmati 1 encompassed low to high BPH damage levels, remote sensing could be employed in the detection of BPH damage in the field on cultivars having differential susceptibility to that pest.

3.2. *Identification of sensitive bands through correlation*

Correlation coefficients (r) for the relationship between plant reflectance at each of 1-nm intervals from 350 nm to 2500 nm and corresponding BPH damage levels, when plotted against wavelengths, enabled us to identify four sensitive bands: 1986 nm ($r = 0.63$), 665 nm ($r = 0.58$), 1792 nm ($r = 0.53$) and 500 nm ($r = 0.52$) (Figure 2). The correlation–wavelength curve showed peaks and troughs throughout the spectral domain of 350–2500 nm, which indicates that not only the spectral characteristics but also the optical properties and reflectance were waveband-dependent; this also has been observed in previous studies (Asner 1998; Yang and Chen 2004). Zhou et al. (2010) were able to detect BPH stress in rice under greenhouse conditions through ground-based hyperspectral radiometry, and they identified several bands from the visible to MIR wavelengths that proved sensitive to BPH damage.

3.3. *Spectral indices*

Three new BPH severity indices were developed as:

$$\text{BPH Index-1 } (R_{665}/R_{1792}), \tag{1}$$

$$\text{BPH Index-2} = (R_{1792} - R_{665}/R_{1792}+R_{665}), \tag{2}$$

$$\text{BPH Index-3} = (R_{1792} - R_{1986}/R_{1792}+R_{1986}), \tag{3}$$

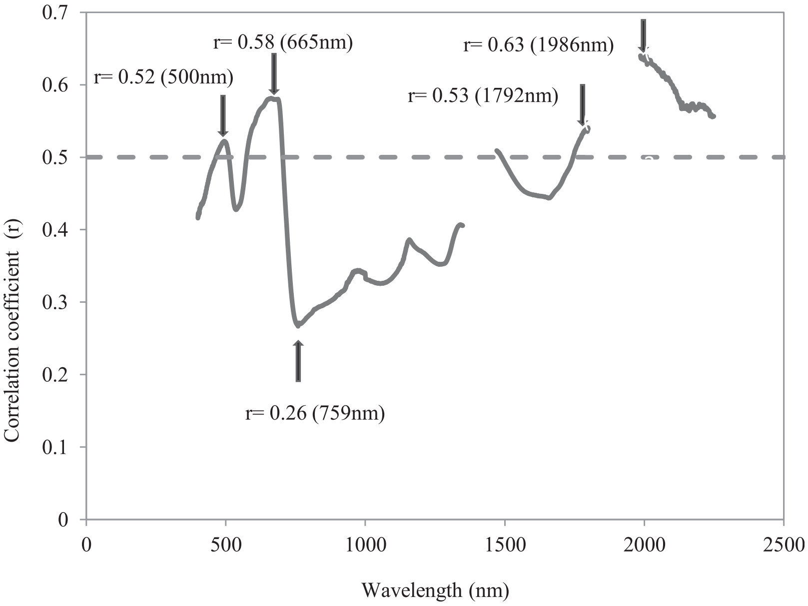

Figure 2. Correlation coefficients (*r*) between spectral reflectance of rice plants at different wavebands and brown planthopper infestation levels.

where R_{665}, R_{1792} and R_{1986} are the reflectances at wavelengths 665, 1792 and 1986 nm, respectively.

Regression analysis revealed a positive relationship between BPH damage level and BPH Index-1 ($R^2 = 0.65$, $P < 0.0001$, Figure 3A), and a negative relationship for both BPH Index-2 ($R^2 = 0.67$, $P < 0.0001$, Figure 3B) and BPH Index-3 ($R^2 = 0.78$, $P < 0.0001$, Figure 3C). Furthermore, BPH damage was also positively correlated with index NPCI ($R^2 = 0.57$, $P < 0.0001$, Figure 3D), but negatively correlated with NDVI ($R^2 = 0.82$, $P < 0.0001$, Figure 3E), and SAVI ($R^2 = 0.70$, $P < 0.0001$, Figure 3F). As spectral vegetation indices are based on reflectance in the visible, NIR and MIR bands that are subject to influence by leaf pigments, cell structure and leaf water content, respectively, their relationship with BPH damage, as observed here, indicates that the pest probably affected cell structure, leaf area and leaf pigment concentration. Spectral vegetation indices are mathematical transformations that help to normalize the plant reflectance measured in heterogeneous environments (Riedell and Blackmer 1999; Yang et al. 2005). Generally, they act as indicators of plant health and can be used to detect and quantify photosynthetic pigments, nutrient deficiencies and stresses (Penuelas et al. 1994; Pinter et al. 2003). However, the NDVI and SAVI, being based on broad wavebands, lack the diagnostic capability of identifying a particular type of stress (Pinter et al. 2003). On the other hand, the NPCI was found to be useful for detecting water and nutrient stress, as it correlated strongly with certain plant physiological responses (Gamon et al. 1997). It could thus be said that the NPCI, NDVI and SAVI are general purpose indices, and although they could be related to BPH damage on rice plants, they might be applicable to detection of both abiotic and biotic stresses on crop plants in certain situations and not in others. However, the new indices, BPHIs 1, 2, 3, are specific to BPH damage as these are based on reflectances that were found to be sensitive to damage due to the pest. The new indices also showed better predictability than the NPCI and can thus provide a better means of detecting BPH stress to rice plants. Previously, based on non-specificity of generic vegetation indices, Lillesand et al. (2004) suggested that reflectance variation due to different factors such as solar angle, background scattering and other unknown factors could be minimized by developing new indices. Prabhakar et al. (2011) developed new indices that showed potential for detecting leaf hopper damage in cotton.

3.4. *Brown planthopper damage–reflectance model*

A multilinear regression model between BPH damage levels and plant reflectance($R^2 = 0.99$) was developed as:

$$Y = -26.206 - 65.08^{*}R_{\lambda 500\mathrm{nm}} + 59.993^{*}R_{\lambda 665\mathrm{nm}} + 3.629^{*}R_{\lambda 1792\mathrm{nm}} + 8.753^{*}R_{\lambda 1986\mathrm{nm}}. \tag{4}$$

The model was satisfactorily validated using a different data set for plant reflectance and BPH damage ($R^2 = 0.94$; RMSE $= 0.79$, Figure 4). The model can be used to predict BPH damage level based on plant reflectances at sensitive wavelengths (500, 665, 1792 and 1986 nm), which can be measured for an infested crop either at the field level or obtained through satellite imagery. The model would be useful for forewarning rice growers against the threat of BPH simultaneously in extensive areas with use of satellite imagery that provides data on plant reflectance encompassing entire regions. Huang et al. (2008) established the airborne multi-spectral imaging system to be of great importance in area-wide pest management systems. By the same token, owing to the BPH's migratory behaviour, timely information on its

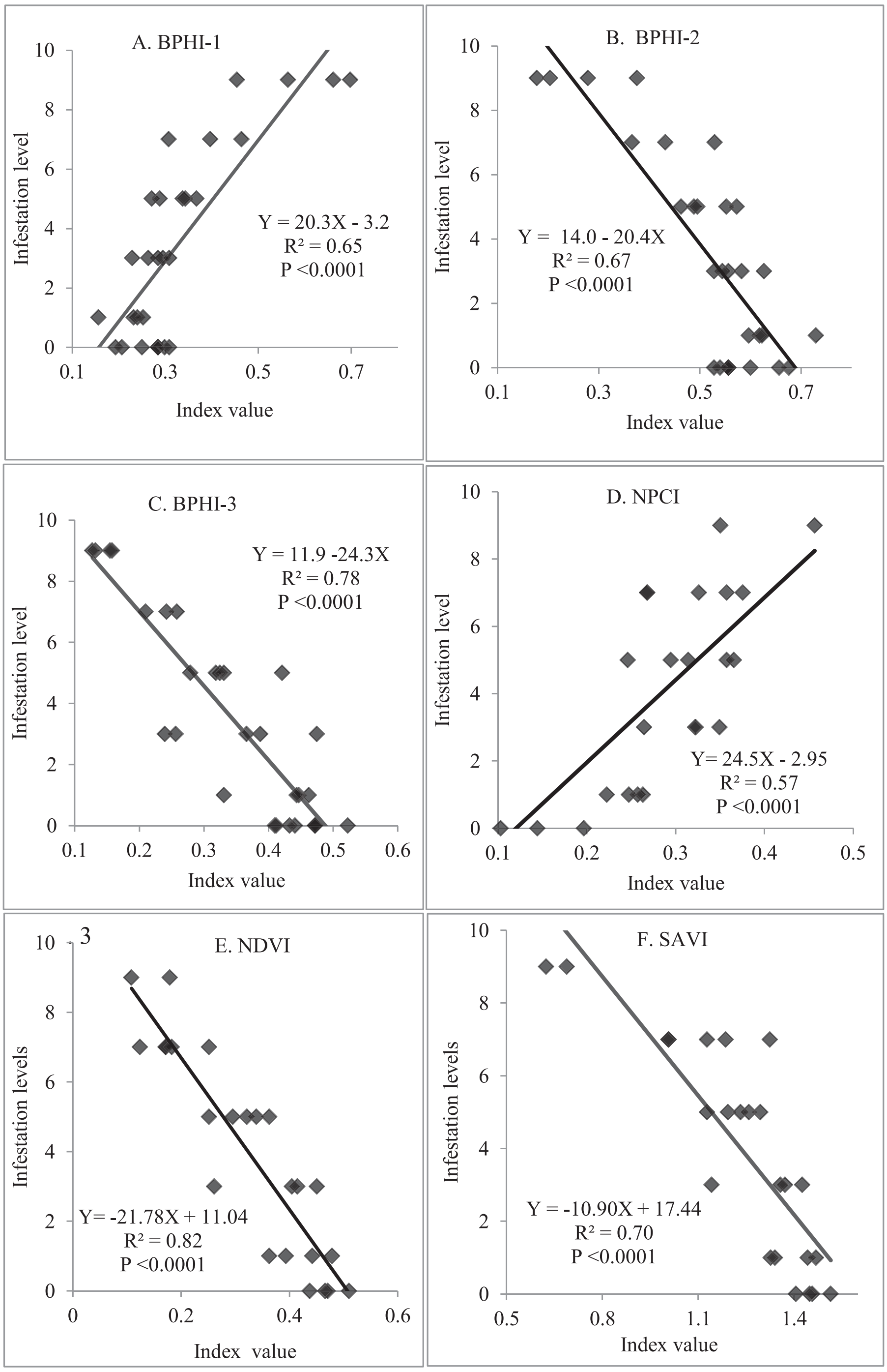

Figure 3. Relationship between different spectral vegetation indices and brown planthopper infestation levels (BPHI-, Brown Planthopper Index; NPCI-, Normalized Pigment Chlorophyll Index; NDVI-, Normalized Difference Vegetation Index; SAVI-, Soil adjusted Vegetation Index).

population build-up in certain areas might also help to forewarn growers in adjacent areas.

Spectral reflectances of rice plants corresponding to sensitive wavelengths individually showed moderate correlation ($r = 0.63$–0.52) with BPH damage levels (Figure 2); however, these together could account for 94% variability in BPH damage ($R^2 = 0.94$) as evidenced by validation of our multilinear regression model (Figure 4). Such spectral models have previously been developed for detecting stress due to leaf-folder (Yang et al. 2007; Haung et al. 2012) and bacterial leaf blight of rice (Yang 2010).

To ensure reliable assessment of BPH damage through remote sensing, sensitive wavelengths for BPH need to be distinguished from those of other pests of rice such as leaf folder and leaf blast that might occur simultaneously in the field and show overlapping effects on plants. Note that the occurrence of these pests on the crop in north India is temporally separated – that is, while leaf folder and leaf blast are important during the pre-flowering crop phase,

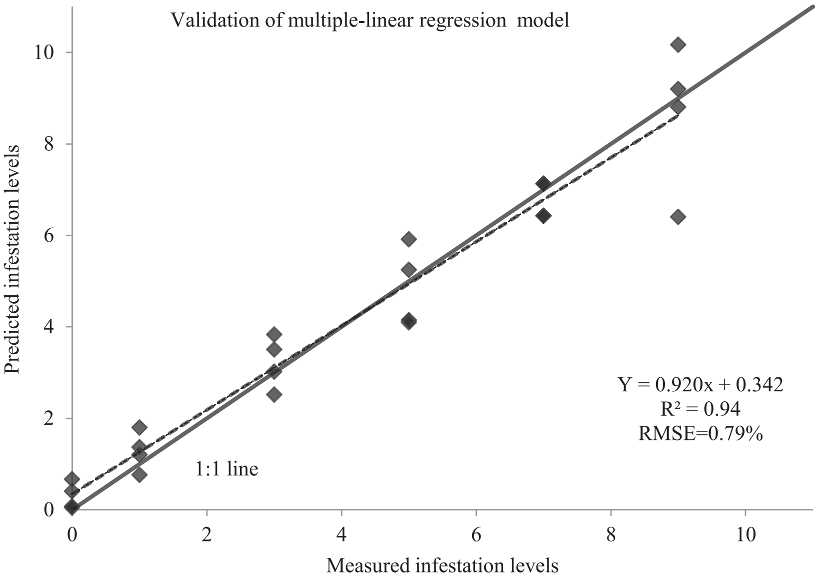

Figure 4. Relationship between brown planthopper infestation levels predicted through multiple-linear regression model and those observed in experiments.

BPH occurs during the post-flowering phase. Nonetheless, information on spectral signatures of important pests of rice is required for meaningful application of remote sensing techniques in pest management.

4. Conclusion

Based on differences in reflectance of uninfested and infested plants mainly in the NIR region and to certain extent in the visible region of the electromagnetic spectrum, hyperspectral remote sensing could be used to measure BPH damage to rice plants. The BPH spectral signatures could facilitate detection of pest damage to the crop, thereby helping forecasters to issue timely warnings to stakeholders.

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