HYPERSPECTRAL FIELD SPECTROMETRY FOR ESTIMATING GREENBUG (HOMOPTERA: APHIDIDAE) DAMAGE IN WHEAT

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ABSTRACT

Remote sensing techniques have the potential to provide information about vegetation characteristics. Therefore, this study was designed to determine the ability of a hyperspectral field spectrometer along with a digital camera to estimate greenbug (*Schizaphis graminum* Rondani) damage to wheat (*Triticum aestivum* L.) in field condition. Percentage reflectance data and digital images were collected over 1 m^2 wheat plots in four fields in mid-May of 2005. Percentage reflectance data were transformed into spectral vegetation indices and a damage quantification software package was used to determine percentage damage in each of the digital images. The percentage damage was also visually assessed on the ground. A simple linear regression procedure was conducted to investigate the relationships between spectral vegetation indices and percentage damage obtained from the ground and digital images. The results show that there were strong relationships between percentage damage and a newly developed Damage Sensitive Spectral Index ($DSSI_{1-3}$). The coefficients of determination (R^2) were 0.77, 0.86, 0.92, and 0.95 for the percentage damage determined using the digital images and $DSSI_{1-3}$ for fields 1-4, respectively. The relationships between the percentage damage collected on the ground and $DSSI_{1-3}$ were 69%, 81%, 89%, and 92% for the fields 1-4, respectively. These results strongly suggest that percentage reflectance and digital image data can be used to estimate greenbug damage in wheat under field conditions with a high degree of accuracy and precision.
Keywords: Remote sensing, vegetation indices, spectrometer, greenbug, wheat.

INTRODUCTION

Wheat is planted to the largest agricultural area worldwide each year because it is well adapted for mild to harsh growth conditions (Western Organization of Resource Councils, 2002). Planted hectares, thus, constitute the main nutritional source for people in most of the world, as well as food for livestock and poultry (Western Organization of Resource Councils, 2002). Higher global wheat production is projected for the future due to increasing demands for food needed to support a growing human population. The United States of America (USA) ranks third among all countries in wheat production (Western Organization of Resource Councils, 2002) indicating that wheat is one of the most important field crops in the country. However, wheat production is not constant from year to year in the USA, or worldwide, due to extremes in weather and pest outbreaks. Greenbug (*Schizaphis graninum* Rondani), Russian wheat aphid (*Diuraphis noxia* Mordvilko), and bird cherry-oat aphid (*Rhopalosiphim padi* Linnaeus) are three common aphids that attack wheat and other small grains. Greenbug is the single most important insect pest in winter wheat in the southwestern USA. Greenbug injects toxic salivary secretions into plant cells, which break down cell walls to facilitate feeding as they extract plant nutrients. Damage symptoms of greenbug initially appear as groups of small, reddish, pinpoint spots or patches on the upper side of host leaves. If greenbug feeding continues, injury appears as chlorotic and necrotic lesions and eventually infested leaves and then the whole plant dies (Riedell and Blackmer, 1999). The presence of this aphid on plants directly and indirectly causes significant reduction in wheat yield in the USA. Roughly, densities of 25-30 greenbugs per stem over seven days caused a 50% decrease in some components (numbers of heads and kernels and total kernel weight) of winter wheat yield at the 2-3 leaf vegetative growth stage, and the same reduction was observed when the densities of greenbug were between 30 and 40 at the boot stage (Kieckhefer and Kantack, 1988). Wheat production losses due to greenbug infestation on wheat for the US economy were estimated to be between $60M to over $100M annually (Webster et al., 2000). Greenbug infestations do not occur in any predictable pattern in space and time (Yang et al., 2005).

There is a large volume of published literature related to the interaction between aphids and their host plants, including greenbug (Kieckhefer and Kantack, 1988; Burd and Elliott, 1996; Riedell and Blackmer, 1999 among many others). However, widespread occurrence of aphid infestation and damage on field crops all over the world has not been well documented using a quick, repeatable, and cost-effective technique. One technique that has been proven to have ability for observing aphid infestation and the plant response to aphid stress is remote sensing (Yang et al., 2005; Michels et al., 1999; Riedell and Blackmer, 1999). Unfortunately, limited number of investigations dealing with remote measurements of crop stress caused by aphid infestation addressed aphid-induced stress in wheat growing in controlled environments at the leaf or plant levels. It has not been confirmed whether the findings of these investigations in greenhouses at the leaf or plant scale can be practical in field situations at the canopy level. In a review of a large body of published information, Pinter et al. (2003) concluded that the spectral properties of the crop canopies growing in the fields are more complex and not similar to single leaves studied under carefully controlled illumination. It is crucial to conduct research to fill this gap in our knowledge. This research is needed not only for adequate pest management practices but also for understanding the natural interactions of aphids and their host plants using an unbiased, reliable, and efficient method.

Another alternative method that is consistent, unbiased, and precise, is computer automated digital image analysis (Steddom et al., 2004; Turner et al., 2004). Computerized digital image analysis is also a nondestructive and noninvasive method that can capture, process, and analyze information from images (Richardson et al., 2001; Díaz-Lago et al., 2003; Karcher and Richardson, 2003). Current image collection equipment and image analysis programs offer the possibility to acquire hundreds of high quality images per hour, which can be analyzed later with a high degree of automation at the observer's convenience (Díaz-Lago et al., 2003). Additionally, digital images can be stored and used as historical archives of vegetation status for a possible future need. Readily-available, low-cost computers, cameras, scanners, and software packages make this method attractive at the present time (Steddom et al., 2004). Furthermore, Steddom et al. (2005) defined the importance of image analysis for plant pathology as "A picture is worth a thousand words."

With the ability to detect stress, estimated damage severity through digital image analysis and spectral vegetation indices can be combined to quantify greenbug damage in wheat. This combination presents an unbiased, nondestructive, and rapid damage quantification method needed to monitor the health condition of the wheat crop at a single or at multiple times during the course of a growing season. This combination also has the benefit of excluding the experimental and evaluator errors, leaving only instrumental errors inherent in instrumental design. The objective of the present study was to quantify the relationship between spectral vegetation indices and visually- and digitally-estimated greenbug damage in winter wheat.

MATERIALS AND METHODS

Field Locations and Sampling Procedure

Greenbug infestations in four winter wheat fields were identified around Chillicothe and Odell, TX, on 18 May 2005 (Figure 1). Two fields were in Hardeman County near Chillicothe, TX, (34˚25'N latitude, 99˚48'W longitude, and altitude 410 m; Field 1 hereafter) and (34˚24'N latitude, 99˚49'W longitude, and altitude 408 m; Field 2 hereafter). The remaining two fields were located in Wilbarger County near Odell, TX, (34˚35'N latitude, 99˚40'W longitude, and altitude 388 m; Field 3 hereafter) and (34˚34'N latitude, 99˚39'W longitude, and altitude 495 m; Field 4 hereafter). In all fields, 2, 200 m transects (one from north to south and the other west to east directions) were set up. A total of 18 and 20 1 m^2 greenbug-damaged wheat samples in each of Fields 1-2, and 3-4 were established at 20 m intervals on 18 and 19 March 2005, respectively. The wheat crop was at Zadoks' stage 32 (Zadoks et al., 1974).

Remote Sensing Measurement

Spectral measurements were made with an Ocean Optics S2000 hyperspectral hand-held spectrometer (Ocean Optics Inc. Dunedin, Florida). Dark current and white reference readings were taken at the beginning of every 8-10 samples (approximately every 15 minutes). The spectrometer is a linear, charge-coupled device (CCD)-array detector that collects reflectance data from 339.71 nm to 1,015.52 nm with a continuous spectral resolution ≈ 0.33 nm. The field of view of the spectrometer is 25˚. To reduce the sheer volume of data recorded for each plot by the spectrometer, adjacent wavelengths were initially averaged to 1 nm intervals. To determine optimal band centers and spectral resolutions in relation with greenbug damage, these band centers were then increased 20 times by averaging every 2, 3,…, 20 neighboring bands. The hyperspectral spectrometer was mounted to a pole and elevated about 220 cm above the flat surface to collect reflected light from the wheat canopy over 1 m^2 sample areas. Subsequent to the spectral measurements, 1 m^2 frame was placed over each of the scanned samples and high quality (Tagged Image File Format: TIFF) digital images were taken by a Nikon coolpix5000 digital camera that was mounted on a pole and kept 200 cm over and perpendicular to the sample plots to cover areas slightly larger than the 1 m^2. Both image and reflectance data acquisition was performed between 11:00 and 14:30 to keep the effect of the sun angle the same for all samples.

Percentage Greenbug Damage Estimation through ASSESS

All images from Fields 1-4 were cropped by digitizing the area inside of the 1 m^2 frames through ASSESS: Image Analysis Software for Plant Disease Quantification (Lamari, 2002). Cropped images were used to determine the percentage greenbug damage on leaves. The percentage greenbug damage was estimated following the methods in the ASSESS user's manual. Masking and thresholding were performed on leaves (green coverage) using hue saturation intensity (HSI) color space and saturation values. The percentage greenbug damage was then calculated as lesion pixels/leaf pixels x 100%. Color space settings were determined for several images from each field. The macro facilities of ASSESS were used, as detailed in the tutorial of the user's manual, to process all images from the same field with the same settings, thereby keeping the user's bias to a minimum. Four different macro settings, one for each field, were used to reduce the field variability because soil background varied across the fields. In order to compare visual rating and digital image analysis, the percentage greenbug damage was also visually assessed in all fields.

Spectral Index Formulation

Various vegetation indices were computed in order to investigate their relationships with percentage greenbug damage. Throughout this research, the band centers used to calculate spectral vegetation indices drawn from the literature were sometimes replaced with new wavebands from hyperspectral data. Among the vegetation indices tested, the Visible Atmospherically Resistant Index [VARI = $(R_{green} - R_{red})/(R_{green} + R_{red} - R_{blue})$] developed by Gitelson et al. (2002) was examined in detail and then modified by adding NIR and green wavebands with the following equation:

$$VARI = (R_i - R_j - R_k - R_l)/((R_i - R_j) + (R_k - R_l))$$

where R_i is the reflectance values or band centers in the ranges between 700 and 900 nm, R_j between 750 and 950 but greater than R_i, R_k between 500 and 700 nm, and R_l between 500 and 750 nm but greater than R_k. In the present study, three versions of this index were used. These were designated, Damage Sensitive Spectral Index$_1$, $_2$, and $_3$ ($DSSI_1$, $DSSI_2$, and $DSSI_3$).

$$DSSI_1 = (R_{719} - R_{875} - R_{511} - R_{537})/((R_{719} - R_{875}) + (R_{511} - R_{537}))$$
$$DSSI_2 = (R_{823} - R_{862} - R_{636} - R_{654})/((R_{823} - R_{862}) + (R_{636} - R_{654}))$$
$$DSSI_3 = (R_{836} - R_{875} - R_{654} - R_{680})/((R_{836} + R_{875}) + (R_{654} - R_{680}))$$

where R_{719}, R_{873}, R_{509}, R_{537} are the reflectance values of wavebands centered at 719 nm, 875 nm, 511 nm, and 537 nm, respectively.

In addition, Green Normalized Difference Vegetation index (GNDVI) (Gitelson and Merzlyak, 1997) was modified with the following equation:

$$GNDVI = (R_{800\text{-}950} - R_{500\text{-}600})/(R_{800\text{-}950} + R_{500\text{-}600})$$

where $R_{800\text{-}950}$ are the reflectance values in the ranges between 800 and 900 nm and $B_{500\text{-}600}$ between 500 and 600 nm. The original formulation of GNDVI is:

$$NDVIgreen = (R_{690\text{-}710} – R_{540\text{-}570})/(R_{690\text{-}710} – R_{540\text{-}570})$$

Simple linear regression analyses were conducted to quantify the relationships between spectral vegetation indices and greenbug damage using S-PLUS 6.2 Professional for Windows (Insightful Inc. Seattle, WA).

RESULTS

Summary statistics of visually- and digitally-estimated percentage greenbug damage to wheat were given in Table 1. The minimum visually-estimated mean percentage greenbug damage (52 ± 6%/1 m^2) to wheat was found in Field 4, whereas Field 3 had the maximum visually-estimated average percentage greenbug damage (70 ± 6%/1 m^2).

Table 1: Summary statistics of digitally- and visually-estimated percentage greenbug damage to winter wheat for four fields

	Field 1		Field 2		Field 3		Field 4	
Statistics	VEPGD	DEPGD	VEPGD	DEPGD	VEPGD	DEPGD	VEPGD	DEPGD
Minimum	38	40	42	42	15	47	10	26
Mean	65	65	66	67	70	77	52	69
Maximum	96	95	95	95	100	96	100	99
SE	4	4	4	4	6	3	6	4
LCI (0.95)	56	57	58	59	59	70	38	60
UCI (0.95)	74	74	74	75	82	84	66	78

Fields 1-2: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18; Fields 3-4: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2, n = 20;
VEPGD: Visually-estimated percentage greenbug damage; DEPGD: Digitally- estimated percentage greenbug damage; *SE:* Standard Error of the mean; *LCI:* Lower Confidence Interval; *UCI:* Upper Confidence Interval.

Field 1 had visually-estimated average greenbug damage of 65 ± %/1 m^2 while Field 2 had visually-estimated mean greenbug damage of 66 ± 4%/1 m^2. The digitally-estimated minimum percentage greenbug damage (65 ± 4%/1 m^2) was found in Field 1 followed by Field 2 (67 ± 4%/1 m^2), Field 3 (69 ± 4%/1 m^2), and Field 4 (77 ± 3%/1 m^2) in ascending order. Simple linear regression analyses revealed strong relationships between visually- and digitally-estimated greenbug damage in wheat. The R^2 values were 0.94, 0.96, 0.87, and 0.90 for Fields 1-4, respectively.

Remotely sensed data transformed into vegetation indices highly related with greenbug damage in wheat across the fields (Tables 2-3). In Tables 2-3, three vegetation indices; $DSSI_{1\text{-}3}$, GNDVI, and Pigment Specific Normalized Difference (Blackburn, 1998); that had the highest relationships with greenbug damage are given for each of the four study fields. The scatter plot, regression line, and R^2 between $DSSI_{1\text{-}3}$, and visually- and digitally- estimated greenbug damage are shown in Figures 2-3 for four fields because they produced consistently strong relationships with greenbug damage in wheat across the fields. The highest relationship (R^2 = 0.97) was found between digitally-estimated greenbug damage and GNDVI and PSND. The relationship between $DSSI_3$ and digitally-estimated greenbug damage was slightly lower (R^2 = 0.95) when compared with GNDVI or PSND (Table 2). The lowest but strong relationship (R^2 = 0.77) in this study was between $DSSI_2$ and digitally-estimated greenbug damage for Field 1 (Figure 2). The PSND did not have significant relationship (R^2 = 0.16) at α = 0.10 with digitally-estimated greenbug damage, whereas GNDVI had significant but weak relationship (R^2 = 0.38) with greenbug damage for Field 2. The R^2 values were 0.86, 0.67, and 0.63 between digitally-estimated greenbug damage and $DSSI_1$, PSND, and GNDVI, respectively, for Field 2. The $DSSI_3$ and GNDVI were equally related with digitally-estimated greenbug damage collected in Field 3 (R^2 = 0.92), whereas PSND had slightly better relationship (R^2 = 0.92) with greenbug damage collected in the same field.

Table 2: Coefficient of determination (R^2) with the associated statistics for three spectral vegetation indices, digitally-estimated percentage greenbug damage to wheat, and four fields

Field	Index	Formula	Reference	R^2	*Model p*	*β p*
Field 1	$DSSI_2$	$(R_{823}-R_{862}-R_{636}-R_{654})/((R_{823}-R_{862})+(R_{636}-R_{654}))$	This Paper	0.77	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.38	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.16	0.10	0.10
Field 2	$DSSI_1$	$(R_{719}-R_{875}-R_{511}-R_{537})/((R_{719}-R_{875})+(R_{511}-R_{537}))$	This Paper	0.86	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.63	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.67	< 0.00	< 0.00
Field 3	$DSSI_3$	$(R_{836}-R_{875}-R_{654}-R_{680})/((R_{836}+R_{875})+(R_{654}-R_{680}))$	This Paper	0.92	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.92	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.94	< 0.00	< 0.00
Field 4	$DSSI_3$	$(R_{836}-R_{875}-R_{654}-R_{680})/((R_{836}+R_{875})+(R_{654}-R_{680}))$	This Paper	0.95	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.97	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.97	< 0.00	< 0.00

Fields 1-2: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18; Fields 3-4: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2, n = 20; DSSI: Damage Sensitive Spectral Index; GNDVI: Green Normalized Difference Vegetation Index; *Modified from Gitelson and Merzlyak (1997); PSND: Pigment Specific Normalized Difference; $R_{823,}$ $R_{862,}$ $R_{636,}$ R_{654}: Reflectance values from wavebands centered at 823, 862, 636, 654 nm with a spectral resolution of 13 nm, respectively.

The relationships generated between three vegetation indices and visually-estimated greenbug damage were poorer when compared with digitally-estimated greenbug damage (Table 3). The strongest relationship (R^2 = 0.92) was found between visually-estimated greenbug damage and PSND and $DSSI_3$ for Field 4 (Table 3 and Figure 3). The relationship between GNDVI and visually-estimated greenbug damage was slightly lower (R^2 = 0.90) when compared with PSND and $DSSI_3$. The poorest but good relationship (R^2 = 0.69) in this study was between $DSSI_3$ and visually-estimated greenbug damage for Field 1. The PSND had weak relationship (R^2 = 0.22) with visually-estimated greenbug damage, whereas GNDVI had moderate relationship (R^2 = 0.43) with greenbug damage for Field 2. The R^2 values were 0.81, 0.65, and 0.60 between visually-estimated greenbug damage and $DSSI_1$, PSND, and GNDVI, respectively, for Field 1. The $DSSI_3$ and PSND were equally related with visually-estimated greenbug damage collected in Field 3 (R^2 = 0.89), whereas GNDVI had slightly lower relationship (R^2 = 0.83) with greenbug damage collected in the same field.

Table 3: Coefficient of determination (R^2) with the associated statistics for three spectral vegetation indices, visually-estimated percentage greenbug damage to wheat, and four fields

Field	Index	Formula	Reference	R2	Model p	β p
Field 1	$DSSI_2$	$(R_{823}-R_{862}-R_{636}-R_{654})/((R_{823}-R_{862})+(R_{636}-R_{654}))$	This Paper	0.69	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.43	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.22	0.05	0.05
Field 2	$DSSI_1$	$(R_{719}-R_{875}-R_{511}-R_{537})/((R_{719}-R_{875})+(R_{511}-R_{537}))$	This Paper	0.81	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.60	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.65	< 0.00	< 0.00
Field 3	$DSSI_3$	$(R_{836}-R_{875}-R_{654}-R_{680})/((R_{836}+R_{875})+(R_{654}-R_{680}))$	This Paper	0.89	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.83	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.89	< 0.00	< 0.00
Field 4	$DSSI_3$	$(R_{836}-R_{875}-R_{654}-R_{680})/((R_{836}+R_{875})+(R_{654}-R_{680}))$	This Paper	0.92	< 0.00	< 0.00
	GNDVI*	$(R_{849}-R_{550})/(R_{849}+R_{550})$	This Paper	0.90	< 0.00	< 0.00
	PSND	$(R_{797}-R_{498})/(R_{797}+R_{498})$	Blackburn (1998)	0.92	< 0.00	< 0.00

Fields 1-2: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18; Fields 3-4: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2, n = 20; DSSI: Damage Sensitive Spectral Index; GNDVI: Green Normalized Difference Vegetation Index; *Modified from Gitelson and Merzlyak (1997); PSND: Pigment Specific Normalized Difference. $R_{823,}$ $R_{862,}$ $R_{636,}$ R_{654}: Reflectance values from wavebands centered at 823, 862, 636, 654 nm with a spectral resolution of 13 nm, respectively.

DISCUSSION

The authors are unaware of any studies attempted to quantify the relationship between spectral vegetation indices and greenbug damage or any other damage types estimated through digital image analysis. However, correlating the estimates of leaf area index, a central biophysical variable influencing the land surface processes (Wang et al., 2005), through various leaf area index meters to spectral vegetation indices has been a well established practice in remote sensing studies (Schlerf et al., 2005; Walthall et al., 2004; Anderson et al., 2004; Hu et al., 2004 among many others). Another comparison that has long been used is the relationship between vegetation indices and plant chlorophyll concentration measured by spectrophotometers after chemical extraction or chlorophyll meters (Rosemary et al., 1999; Broge and Mortensen, 2002). Another example is that evaluating the relationship between green vegetation cover estimated using digital images and spectral vegetation indices (Purevdorj et al., 1998; Gitelson et al., 2002).

The results of this study indicate that remotely sensed data recorded by a hyperspectral spectrometer and a digital camera have the potential to aid in monitoring greenbug damage in wheat growing under field conditions. However, although the spectral vegetation indices tested gave strong relationships, there was no single best index for greenbug damage in all situations. It appears that the sensitivity of an index differs due to environmental and ecological variability from one place to another. Therefore, no single index with the same spectral bands was found to have high correlation with greenbug damage in this research. It is also appears that there is no single spectral index applicable for all surface characteristics including stress quantification in plants. This implies that a few spectral vegetation indices can be calculated and associated with greenbug damage in fields where the variability in soil, vegetation, and weather differs from place to place. In this study, $DSSI_{1-3}$, GNDVI, and PSND were highly related to greenbug damage, thus, they are recommended for studies of aphid damage in wheat.

CONCLUSIONS

Digitally-estimated, as well as visually-assessed greenbug damage had robust relationships with vegetation indices. Digital image analysis may be an alternative to visual techniques, even though there were no substantial differences in coefficients of determination between visually assessed versus digitally-estimated greenbug damage. However, digital data hold an advantage because they can be reproduced, stored, and used as historical documents of vegetation status for a later time. Strong relationships between spectral indices and greenbug damage suggest that both hyperspectral and multispectral imaging sensors can be used as a quick, nondestructive, repeatable, and cost-effective technique to detect aphid and other types of damage in wheat. Future research using image data taken from aircraft or satellite platforms are also needed to expand the study area to whole field or landscape level.

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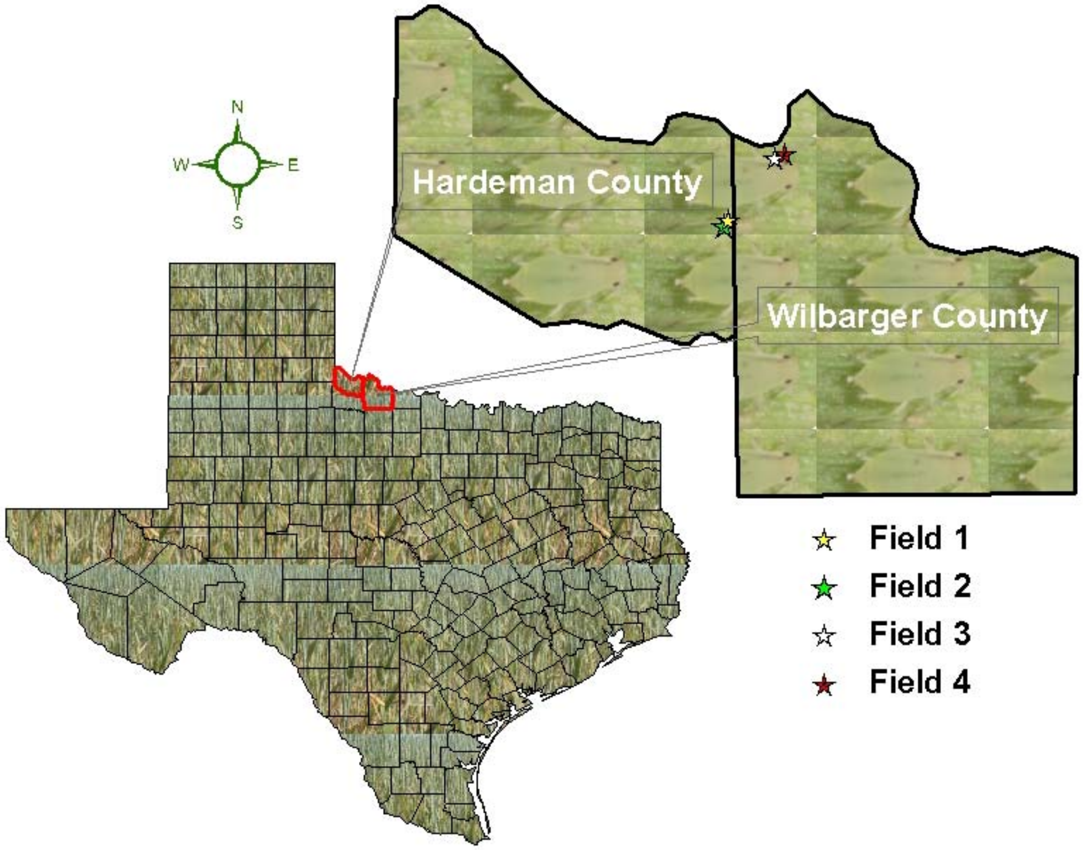

Figure 1: Location of greenbug infestation in four fields on 18-19 May 2005. Fields 1-2: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18. Fields 3-4: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2, n = 20.

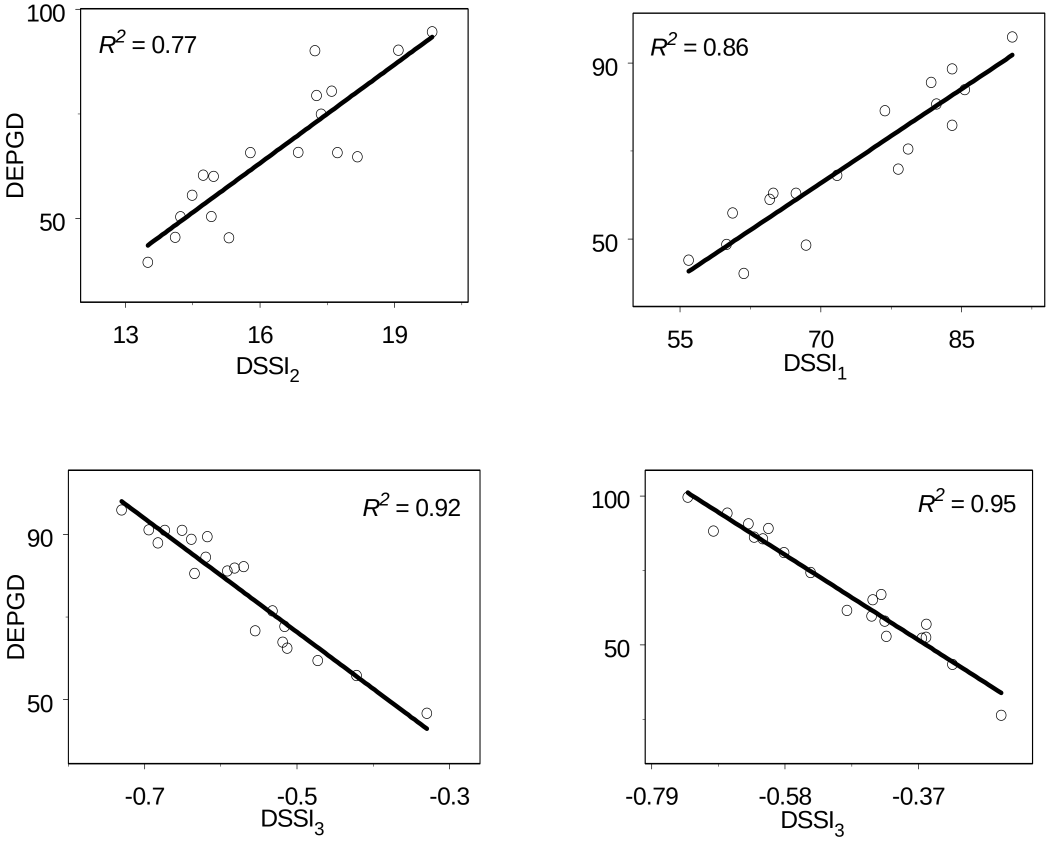

Figure 2: Scatter plot, regression line and the R^2 obtained by regressing the $DSSI_{1-3}$ against greenbug damage for Fields 1-4.
DEPGD: Digitally-estimated percentage greenbug damage. Fields 1: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18 (upper left). Fields 2: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18 (upper right). Fields 3: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2, n = 20 (lower left).
Fields 4: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2,
$DSSI_1$: Damage Sensitive Spectral Index = $(B_{719}-B_{875}-B_{511}-B_{537})/((B_{719}-B_{875})+(B_{511}-B_{537}))$.
$DSSI_2$: Damage Sensitive Spectral Index = $(B_{823}-B_{862}-B_{636}-B_{654})/((B_{823}-B_{862})+(B_{636}-B_{654}))$.
$DSSI_3$: Damage Sensitive Spectral Index = $(B_{836}-B_{875}-B_{654}-B_{680})/((B_{836}+B_{875})+(B_{654}-B_{680}))$.
$B_{719}, B_{875}, B_{511}, B_{537}$: Reflectance values from wavebands centered at 719, 875, 511, 537 nm with a spectral resolution of 13 nm, respectively.

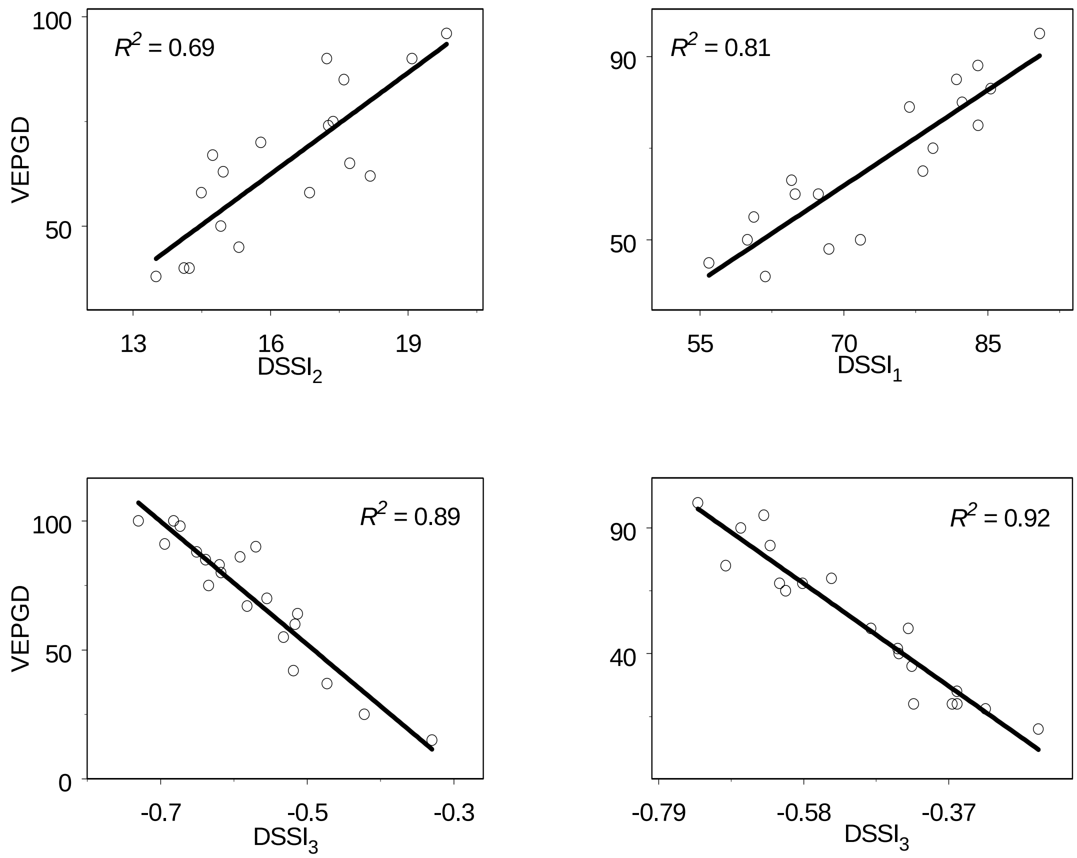

Figure 3: Scatter plot, regression line and the R^2 obtained by regressing the $DSSI_{1\text{-}3}$ against greenbug damage for Fields 1-4.
VEPGD: Visually-estimated percentage greenbug damage. Fields 1: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18 (upper left). Fields 2: Hardeman County near Chillicothe, TX, sampled on 18 May 2005, sample size = 1 m^2, n = 18 (upper right). Fields 3: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2, n = 20 (lower left).
Fields 4: Wilbarger County near Chillicothe, TX, sampled on 19 May 2005, sample size = 1 m^2,
$DSSI_1$: Damage Sensitive Spectral Index = $(B_{719}-B_{875}-B_{511}-B_{537})/((B_{719}-B_{875})+(B_{511}-B_{537}))$.
$DSSI_2$: Damage Sensitive Spectral Index = $(B_{823}-B_{862}-B_{636}-B_{654})/((B_{823}-B_{862})+(B_{636}-B_{654}))$.
$DSSI_3$: Damage Sensitive Spectral Index = $(B_{836}-B_{875}-B_{654}-B_{680})/((B_{836}+B_{875})+(B_{654}-B_{680}))$.
B_{719}, B_{875}, B_{511}, B_{537}: Reflectance values from wavebands centered at 719, 875, 511, 537 nm with a spectral resolution of 13 nm, respectively.