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Reflectance characteristics of Russian wheat aphid (Hemiptera: Aphididae) stress and abundance in winter wheat

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Received 16 October 2006; received in revised form 24 January 2007; accepted 1 March 2007

Abstract

The Russian wheat aphid (*Diuraphis noxia* (Mordvilko)) infests wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and other small grains and grasses. Russian wheat aphid infestations are unpredictable in time and space. In favorable conditions, Russian wheat aphid feeding can result in heavy damage to wheat and barley in a short period of time. A repetitive monitoring strategy that allows for rapid assessment of aphid infestation and damage over the growing season is critically needed. Tracking the irregular infestation patterns of Russian wheat aphid in order to optimize control efforts is central to the successful management of this aphid. One method that has been shown over a number of years to be useful for monitoring some insect outbreaks is to measure the light reflected by the infested canopy, plant, or leaf. Hence, this research was designed to investigate: (1) the potential use of remotely sensed data to discern and identify differences in spectral reflection patterns (spectral signatures) of winter wheat canopies with and without Russian wheat aphid infestation, and (2) the relationship between spectral indices and Russian wheat aphid abundance in wheat canopies growing in field conditions. Russian wheat aphid-infested wheat canopies had significantly lower reflectance in the near infrared region and higher in the visible range of the spectrum when compared with noninfested canopies. Linear regression analyses showed that there were varying relationships between Russian wheat aphid density and spectral vegetation indices, with coefficients of determination (r^2) ranging from 0.91 to 0.01. These results indicate that remote sensing data have the potential to distinguish damage by Russian wheat aphid and quantify its abundance in wheat. However, success for Russian wheat aphid density estimation depends on the selection of spectral vegetation indices.

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Keywords: Aphid infestations; Remote sensing; Russian wheat aphid; Spectral signatures; Spectral indices; Wheat

1. Introduction

One of the major insect pests of wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and other small grains and grasses worldwide is the Russian wheat aphid, *Diuraphis noxia* (Mordvilko) (Vandenberg et al., 2001). Plant stress from the Russian wheat aphid is a combination of developmental, biochemical, physiological, and morphological responses. Plant growth stages, time and duration of the feeding, nutritional status of the host plants, aphid abundance,

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and environmental factors affect plant responses to aphid infestation (Macedo et al., 2003). While feeding, Russian wheat aphid injects a toxin into the plants. This toxin is responsible for many of the stress symptoms, the most characteristic of which are white or reddish-purple longitudinal streaks on the leaves and sometimes the stem (Kazemi et al., 2001; Unger and Quisenberry, 1997; Burd and Burton, 1992). Heavily infested plants are stunted leading to reductions in dry weight, leaf area, and chlorophyll concentration (Riedell and Blackmer, 1999; Gilchrist et al., 1984; Burd et al., 1994; Miller et al., 1994).

Although the Russian wheat aphid is widely distributed, the economic impact to small grains mostly and frequently occurs in South Africa, the US, and Canada (Lage et al., 2004; Archer and Bynum, 1992). Since its discovery in Texas, it has rapidly spread across the US and infested wheat and barley fields of 17 western states and three Canadian provinces (Legg et al., 1994; Kindler et al., 1992; Jones et al., 1989). Studies indicated that economic injury levels due to Russian wheat aphid feeding in small grains can vary within a given region (Randolph et al., 2003; Archer and Bynum, 1992; Archer et al., 1998; Gray et al., 1990). Therefore, the economic injury levels were calculated for areas in which Russian wheat aphid frequently and significantly damages to wheat and barley. Archer and Bynum (1992) reported that there were 0.46 and 0.48% yield losses for each 1% increase in damaged and infested tillers, respectively, at the pre-heading growth stage in TX. The economic injury level for the spring infestations was 0.9 aphid per seven plants at seven tiller growth stage in Kansas (Girma et al., 1993). Archer et al. (1998) reported that the yield losses were $\approx 1\%$ and 0.67% per percentage infested or damaged tiller at two tiller growth stage in Montana and Washington, respectively. Archer et al. (1998) reported that the yield losses were 0.5% per percentage infested or damaged winter wheat tillers at the growth stages 31 in Colorado. Winter wheat yield loss due to Russian wheat aphid infestation was 37% in the Canadian Prairies (Butts et al., 1997).

Cumulative economic losses from Russian wheat aphid infestation in wheat and barley in the US have been estimated at nearly \$1 billion since 1987 (Webster et al., 2000). Of this damage, nearly 60% has occurred in the Texas and Oklahoma Panhandles, northeastern Colorado, western Kansas, and southwestern Nebraska (Smith et al., 2004). The Russian wheat aphid infestations are unpredictable in time and space (Elliott et al., 2005). In favorable conditions, Russian wheat aphid feeding can result in heavy damage to wheat and barley in a short period of time.

A repetitive monitoring strategy that allows for the rapid assessment of aphid infestation and damage over the growing season is critically needed. Tracking the irregular infestation patterns of Russian wheat aphid in order to optimize control efforts is central to the successful management of this aphid. One method that has been shown over a number of years to be useful for monitoring some insect outbreaks is to measure the light reflected by the infested canopy, plant, or leaf. The health of a plant can be readily determined by measuring the relative intensity of visible and near infrared (NIR) light reflected from its leaves and studying changes in plant growth. Optical properties of mature and healthy green leaves or vegetation are characterized by high absorption in the blue (400–500 nm), increased reflection in the green (500–600 nm), high absorption in the red (600–700 nm), and very high reflectance and transmittance in the NIR (700–1500 nm) (Gates, 1970). Spectral responses of vegetation in the visible (400–700 nm) region are primarily governed by the abundance of chlorophylls, carotenoids, and anthocyanins (Broge and Mortensen, 2002; Sims and Gamon, 2002; Gamon and Surfus, 1999; Peñuelas and Filella, 1998). The optical properties of vegetation in the NIR are due to the discontinuities between cell walls and intercellular air spaces in internal leaf structure (Peñuelas and Filella, 1998). Changes in pigment concentrations as well as internal leaf structure are strongly related to the physiological status (Blackburn, 1998a,b), and, consequently, spectral features of vegetation. During the interaction between stressors and their host plants, the physiological state of the invaded tissue is altered, which reflects the changes in photosynthesis, transpiration, metabolism, and temperature (Peñuelas and Filella, 1998). Ultimately, stressors lead to poor growth, loss of vigor, and eventually death of plants or vegetation (Richardson et al., 2004). Therefore, within a given growth condition, reflectance measurement, namely remote sensing, seems to be very effective to differentiate stressed and unstressed plants or vegetation.

Spectral indices combine spectral information contained in two wavebands or more, usually in the visible and NIR or both. Spectral indices aim to increase the extraction of optimal spectral information from the objects of interest. A few spectral indices among many were created to retrieve spectral information on vegetation stress caused by biotic stressors. Peñuelas et al. (1995a) designed the normalized phaeophytinization index (NPQI) to estimate cumulative mite (*Panonychus ulmi* Koch) days on apple trees (*Malus domestica*). Apan et al. (2004) created the Disease-Water Stress Indices (DWSI₁₋₅) to evaluate orange rust disease on sugarcane (*Saccharum* spp.). However, these indices have not been largely used or tested for different stressors.

From ground to satellite based remote sensing has been effectively used to monitor insect infestations in forest trees, orchard species, and agricultural crops. Luther et al. (1997), Carter et al. (1998), Radeloff et al. (1999), and Leckie et al. (2005) used remote sensing imagery to detect insect defoliations in forest stands. Insect outbreaks in citrus (*Citrus* spp.) groves (Hart and Myers, 1968; Hart et al., 1973; Everitt et al., 1994), cotton [*Gossypium hirsutum* L. (Heald et al., 1972; Everitt et al., 1996)], and alfalfa [*Medicago sativa* L. (Everitt et al., 1991)] were distinguished using remotely sensed data. Bird and bee densities were estimated using satellite imagery and lidar data (Prins et al., 2005; Shaw et al., 2005), respectively. Strong relationships were found between greenbug, *Schizaphis graminum* (Rondani), abundance in greenhouse grown wheat and spectral indices derived from field radiometers (Niño, 2002; Yang et al., 2005). Riedell and Blackmer (1999) conducted a greenhouse study to characterize leaf reflectance spectra of wheat stressed by Russian wheat aphid. In that study, it was concluded that leaf reflectance in the 625–635 nm and 680–695 nm as well as the normalized total pigment to chlorophyll a ratio index (NPCl) were good indicators of chlorophyll loss and leaf senescence caused by aphid feeding.

Reflectance changes in response to biotic and abiotic stressors have been largely documented, however, natural Russian wheat aphid infestations and damage to field crops in real-time field situations have not been studied. What is well understood, however, is that most stressors increase reflectance in the visible and decrease reflectance in the NIR regions (Peñuelas et al., 1995a; Raikes and Burpee, 1998). Remote sensing research for natural Russian wheat aphid infestations in near real-time field use is preferred because it could provide spatial and temporal information. Satellite remote sensing provides sufficient data for large scale (regional) studies but it has known to have limitations such as temporal and spatial resolution, and cloud cover for unpredictable patterns of Russian wheat aphid infestations in time and space, whereas air-borne systems have a higher resolution and time flexibility. However, aircraft remote sensing may suffer due to mismatching the image pixels with Russian wheat aphid spots on the ground for providing fundamental baseline data. Another possible drawback of airborne systems is the problem of spectral pixel mixing, which is the mixture of the signals from different objects such as soil, healthy and infested plants or vegetation, different species, and varying cover levels (Mirik et al., 2005). Hand-held remote sensing instruments are useful for small-scale operational field monitoring of biotic and abiotic stress agents and novel research purposes (Jackson, 1986). Evidently, a limiting factor is their applicability for only small areas when compared with aircraft and satellite sensors. However, using hand-held spectrometers to quantify the unknown spectral characteristics of noninfested and infested plant canopies due to insect feeding at a small-scale is needed because hand-held remote sensing devices have better temporal, spectral, and spatial resolutions, as well as the accuracy of collecting reflectance data over per unit area. Reflectance data obtained by hand-held instruments over small-areas provides information to understand spectral interactions between insect pests and their host plants, as well as fundamental ground-truth for interpretation of remote sensing data measured from satellite and aircraft.

Therefore, a logical initial step is to use a field spectrometer for understanding the spectral response of Russian wheat aphid-infested wheat canopies and developing spectral signatures since ground-based sensors have better temporal, spatial, and spectral resolutions to differentiate Russian wheat aphid-stress than image-based remote sensing. In addition, spectral measurement of Russian wheat aphid-infested wheat canopy made with a field spectrometer can be used as a fundamental ground-truth for satellite and aerial images. No information is available in the literature as to whether remote measurements of reflected spectra from Russian wheat aphid-infested wheat can be correlated with Russian wheat aphid abundance.

The objective of the present study was two-fold: (1) to examine the spectral properties of wheat stressed by Russian wheat aphid feeding and nonstressed canopies throughout the visible and NIR regions of the spectrum and (2) investigate the relationships between spectral indices and Russian wheat aphid abundance in wheat growing in field conditions using a hand-held hyperspectral remote sensing instrument.

2. Materials and methods

2.1. Field locations

The study was conducted in three winter wheat fields in 2004 and one field in 2005. One field (referred to as Field 1 through the rest of this work) was located near Amarillo, Deaf Smith County, Texas (35°09'N latitude, 102°27'W longitude, and altitude approximately 1160 m) (Table 1). Two winter wheat fields were located on southeastern Colorado: one (referred to as Field 2 through the rest of this work) near Springfield, Baca County (37°53'N latitude, 102°78'W

Table 1

Location, sampling date, sampling time, wheat growth stage, sample size, sample number, spectrometer height for four fields where Russian wheat aphid and reflectance data were collected

	Field 1 ^a			Field 2	Field 3	Field 4
Latitude	35°09'N	35°09'N	35°09'N	37°53'N	38°01'N	36°68'N
Longitude	102°27'W	102°27'W	102°27'W	102°78'W	102°62'W	102°42'W
Altitude (m)	1160	1160	1160	1296	1235	1218
Sampling date	21 April 2004	05 May 2004	17 May 2003	19 May 2004	20 May 2004	18 May 2005
Sampling time	12:45–2:00	12:30–2:15	12:30–1:45	12:15–2:00	12:15–2:30	12:30–1:30
Growth Stages (Zadok's scale)	45	69	75	65	65	60
Sample size (m ²)	0.25	0.25	0.25	0.25	0.25	1
Sample number	15	20	20	20	25	20
Spectrometer height (m)	0.65	0.65	0.65	0.65	0.65	2.2
State	Texas	Texas	Texas	Colorado	Colorado	Oklahoma
County	Deaf Smith	Deaf Smith	Deaf Smith	Baca	Prowers	Cimarron

^a Sampled three times in 2004.

longitude, and altitude approximately 1396 m) and the other (referred to as Field 3 through the rest of this work) near Lamar, Prowers County (38°01'N latitude, 102°62'W longitude, and altitude approximately 1135 m) (Table 1). The remaining field (referred to as Field 4 through the rest of this work) was situated near Boise City, Cimarron County, Oklahoma (36°68' latitude, 102°42'W longitude, and altitude approximately 1218 m) (Table 1).

2.2. Sampling procedures

On the first data collection date in Field 1 a ground survey was conducted to establish sample plots. A total of 15 small plots of Russian wheat aphid-infested wheat were established. Another 15 plots of noninfested wheat (neither Russian wheat aphid nor visual evidence of its stress were found) were established as near as possible to the infested samples through a ground survey on 21 April 2004. A total of 15, 0.25-m² were taken from each of the Russian wheat aphid-infested and noninfested wheat plots. The wheat crop was at Zadoks' stage 45 (Zadoks et al., 1974). During the second and third data collections on 5 and 17 May 2004 20, 0.25 m² samples were established in Russian wheat aphid-infested plots along with the same number of noninfested plots in Field 1 at each sample date. The wheat crop was at Zadoks' stages 69 and 75 on 5 and 17 May 2004, respectively. In Fields 2–3, 20 and 25, 0.25 m² samples were taken in Russian wheat aphid-infested and noninfested plots, respectively. While 25 control samples were established in Field 3, noninfested samples were not taken in Field 2 due to the presence of Russian wheat aphids in the entire field. Wheat was at Zadoks' stage 65 in Fields 2–3. Twenty, 1 m² samples for each of the infested and noninfested wheat canopies were selected in Field 4. The wheat crop was at Zadoks' stages 60. The sample locations were selected to represent the range of aphid abundance and stress severity, thus were not random because the objective of the study was to examine the differences in reflection patterns of infested and noninfested wheat canopies and to relate aphid abundance to hyperspectral data. To randomly sample the study fields and still have the same range of abundance and stress levels would have required many more plots than the logistics of the study could accommodate. Another reason for systematic sample rather than on a random basis is that the Russian wheat aphid infestation in wheat and barley fields usually does not occur uniformly but rather in clusters referred to as "Russian wheat aphid hot spots."

2.3. Remote sensing measurements

Spectral measurements were made with an Ocean Optics S2000 hyperspectral hand-held spectrometer (Ocean Optics Inc., Dunedin, FL). The dark current and spectralon readings were taken at the beginning of every 8–10 samples (approximately every 15 min). The spectrometer is a linear, charge-coupled device (CCD)-array detector that collects reflectance data from 339.71 to 1015.52 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 the best band centers and spectral resolutions in relation to the Russian wheat aphid abundance, these band centers were then increased nine times by averaging every 2, 3, ..., 10 neighboring bands. The hyperspectral spectrometer was mounted on a pole and elevated about 0.65- and

2.20-m above plot surface to collect reflected light from the wheat canopy over 0.25- and 1-m² samples in Fields 1–3 and Field 4, respectively. Reflectance data acquisition was started at 12:15 and ended before 2:30 to keep the effect of sun angle similar for all samples from all fields. No disturbing cloud was observed during the spectral measurements for all fields. Data collection was made three times; 21 April 2004, 5 and 17 May 2004 in Field 1, once on 19–20 May 2004 in Fields 2–3, respectively, and on 18 May 2005 in Field 4.

2.4. Aphid data collection

Shortly after spectral measurements, a 0.25- and 1-m² frame was placed over each sample and 30 tillers were randomly collected inside of each frame in Fields 1–3 and Field 4, respectively. Russian wheat aphids were counted on each of 30 tillers per plot. Subsequent to counting Russian wheat aphids on 30 tillers, the numbers of wheat tillers including randomly collected 30 tillers within each frame were tallied, randomly collected 30 tillers were added, and Russian wheat aphid densities were estimated as follow: Total aphids per plot = total tillers × total aphid on 30 tillers/30.

2.5. Data analysis

Twenty vegetation indices compiled from the literature were initially computed in order to quantify their relationships with Russian wheat aphid abundance (Table 2). Throughout this research, the band centers used to calculate spectral vegetation indices were slightly decreased or increased by replacement of hyperspectral wavebands that had a spectral resolution of 8 nm. S-PLUS 7.0 for Windows (Insightful Inc. Seattle, WA) was used to quantify the relationships between spectral vegetation indices and Russian wheat aphid abundance. Russian wheat aphid abundance was set as the independent variable and spectral indices were set as the dependent variables. Russian wheat aphid abundance in regression analysis was weighted for Fields 1–2. The weighting procedure in least-square regression corrects the problem of heteroskedasticity by log-likelihood estimation of a weight that adjusts the errors of prediction. Accordingly, this method can sometimes improve the fit of regression model with repeated values in the predictor. Therefore, weighted regression is a proper method for those situations in which not all observations contribute equally to the fit (S-PLUS, 2001). A paired *t*-test procedure for comparing the reflectance from undamaged and damaged-wheat by Russian wheat aphid for fields was conducted using S-PLUS 7.0 for Windows. Statistical significance of regression models and paired *t*-test was evaluated at $\alpha = 0.05$ for all data sets.

Table 2
Twenty spectral vegetation indices initially used in this study

Index	Abbreviation	Reference
Anthocyanin Reflectance Index	ARI	Gitelson et al. (2001)
Aphid Index	AI	Mirik et al. (2006b)
Damage Sensitive Spectral Index ₂	DSSI ₂	Mirik et al. (2006a)
Disease-Water Stress Index 4	DWSI-4	Apan et al. (2004)
Green Normalized Difference Vegetation Index	GNDVI	Daughtry et al. (2000)
Modified Chlorophyll Absorption in Reflectance Index	MCARI	Daughtry et al. (2000)
Modified Normalized Difference Vegetation Index	MNDVI	Sims and Gamon (2002)
Modified Simple Ratio	MSR	Sims and Gamon (2002)
Normalized Difference Vegetation index _{750–705}	NDVI _{750–705}	Gitelson and Merzlyak (1994)
Normalized Difference Vegetation Index _{801–670}	NDVI _{801–670}	Daughtry et al. (2000)
Normalized Phaeophytinization Index	NPQI	Peñuelas et al. (1995a)
Normalized Total Pigment to Chlorophyll a Ratio Index	NPCI	Peñuelas et al. (1993)
Physiological Reflectance Index	PRI	Gamon et al. (1992)
Pigment Specific Normalized Difference	PSND	Blackburn (1998a,b)
Pigment Specific Simple Ratio	PSSR	Blackburn and Steele (1999)
Plant Senescence Reflectance Index	PSRI	Merzlyak et al. (1999)
Ratio Analysis of Reflectance Spectra	RARS	Chappelle et al. (1992)
Simple Ratio	SR	Jordan (1969)
Structure Insensitive Pigment Index	SIPi	Peñuelas et al. (1995b)
Visible Atmospherically Resistant Index	VARI	Gitelson et al. (2002)

Table 3

Descriptive statistics of Russian wheat aphid abundance on winter wheat in four fields

Field	Minimum	Mean	Maximum	S.E.	LCI (0.95)	UCL (0.95)
1-DS1	1839	5977	12,132	657	4488	7,465
1-DS2	5617	9716	26,342	1106	7401	12,032
1-DS3	832	9590	46,592	2253	4874	14,306
2	1023	3883	8,083	469	2901	4,865
3	0	5691	14,823	841	3956	7,426
4	0	4582	15,652	916	2664	6,500

S.E.: standard error of the mean; LCI: lower confidence interval; UCI: upper confidence interval. Field 1*: Deaf Smith County near Amarillo, TX. DS1–DS3: Data sets 1–3 because this field sampled three times on 21 April, 5 and 17 May 2004; $n = 15, 20,$ and $20,$ respectively, Field 2: Baca County near Springfield, CO, sampled on 19 May 2004; $n = 20,$ Field 3: Prowers County near Lamar, CO, sampled on 20 May, 2004; $n = 25,$ Field 4: Cimarron County near Boise City, OK, sampled on 18 May 2005; $n = 20,$ sample size = 0.25 m^2 for all fields except Field 4 that was $1 \text{ m}^2.$

3. Results

Descriptive statistics for Russian wheat aphid abundance are presented in Table 3. Russian wheat aphid abundance in wheat varied widely within each field, permitting a wide range of aphid abundance in regression analyses. The highest ($9716 \pm 1106/0.25 \text{ m}^2$) and lowest ($3883 \pm 469/0.25 \text{ m}^2$) mean Russian wheat aphid densities were found in Field 1 on 5 May 2004 and Field 2, respectively. Field 4 had the second lowest average Russian wheat aphid abundance ($4582 \pm 916/1 \text{ m}^2$) followed by Field 3 ($5691 \pm 841/0.25 \text{ m}^2$), Field 1 on 21 April 2004 ($1646 \pm 248/0.25 \text{ m}^2$), and on 17 May 2004 ($9590 \pm 2253/0.25 \text{ m}^2$) in ascending order.

Paired t -test comparisons of Russian wheat aphid-infested and noninfested wheat plots yielded significant differences ($\alpha = 0.05$) in all areas of the spectrum (Table 4). Representative average reflectance measured from the Russian wheat aphid-infested and noninfested wheat canopies are shown in Fig. 1. It is evident that the spectral response of the wheat canopies was significantly affected by Russian wheat aphid feeding (Fig. 1). The reflectance of wheat canopies in the NIR region was significantly lower in contrast to a significant increase in the visible spectrum due to Russian wheat aphid feeding (Fig. 1 and Table 4). The Russian wheat aphid-infested wheat canopies always captured less or reflected more light than the noninfested wheat canopies in the range from 400 nm to the red edge shoulder at 750 nm for Field 1 on 21 April 2004, 740 nm for Field 1 on 17 May 2004, 740 nm for Field 3, and 730 nm for Field 4.

In Table 5, of the five spectral indices out of 20 in Table 2, the one that had the highest relationship with Russian wheat aphid abundance for each of the six data sets was chosen and compared across the fields studied and with the traditional normalized difference vegetation index (NDVI) calculated using the band centers at 805.5 and 668.5 nm. The predictive powers of spectral indices were improved by weighting the Russian wheat aphid abundance for Fields 1–2. In general, there were poorer relationships between spectral indices and Russian wheat aphid abundance collected

Table 4

Paired t -test comparison of percentage reflectance between Russian wheat aphid-infested and noninfested winter wheat for three fields at five wavelength intervals

Field		Wavelength (nm)				
		400–499	500–599	600–739	740–900	400–739
1-DS1	t	17	20	21	–13	15
	p	<0.00	<0.00	<0.00	<0.00	<0.00
1-DS3	t	14	18	28	–15	14
	p	<0.00	<0.00	<0.00	<0.00	<0.00
3	t	23	18	19	–5	13
	p	<0.00	<0.00	<0.00	<0.00	<0.00
4	t	13	12	14	–14	11
	p	<0.00	<0.00	<0.00	<0.00	<0.00

t : paired t -test statistic; p : probability; Field 1*: Deaf Smith County near Amarillo, TX. DS1 and DS3: Data set 1 and 3 because this field sampled three times on 21 April, 5 and 17 May 2004; $n = 15, 20,$ and $20,$ respectively, and date sets 1 and 3 used. Sampled twice on 21 April and 17 May 2004; $n = 15$ and $n = 20,$ respectively, Field 3: Prowers County near Lamar, CO, sampled on 20 May, 2004; $n = 25,$ Field 4: Cimarron County near Boise City, OK, sampled on 18 May 2005; $n = 20.$

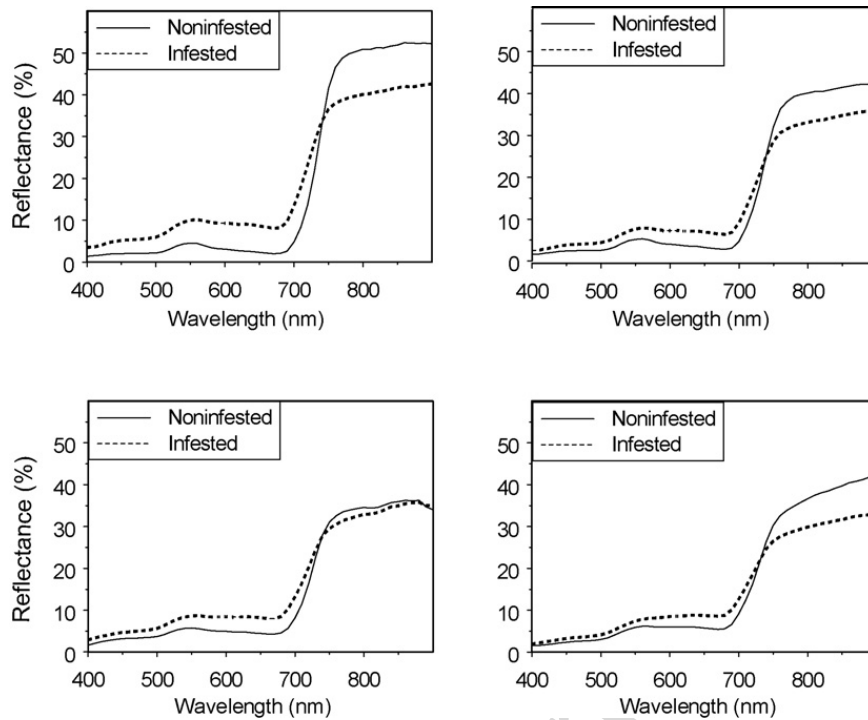


Fig. 1. Percentage spectral reflectance (400–900 nm range) of Russian wheat aphid-infested and noninfested winter wheat canopies associated with three fields. Field 1: Deaf Smith County near Amarillo, TX, sampled on 21 April (upper left); $n = 15$ and sampled on 17 May 2004 (upper right), $n = 20$. Field 3: Prowers County near Lamar, CO, sampled on 20 May, 2004 (bottom left); $n = 25$. Field 4: Cimarron County near Boise City, OK, sampled on 18 May 2005 (bottom right); $n = 20$.

in Field 1 on 21 April 2004 and in Field 2 when compared with densities obtained in remaining dates and fields. The strongest ($r^2 = 0.91$) linear relationship was found between structure insensitive pigment index (SIPI) computed as $(R_{804.5} - R_{508.5}) / (R_{804.5} - R_{692.5})$ (Peñuelas et al., 1995b) and Russian wheat aphid abundance for Field 1 on 17 May 2004, whereas $NDVI_{804.5-668.5}$ showed no relationships with aphid population density for Field 2 ($r^2 = 0.01$) and Field 1 on 21 April 2004 ($r^2 = 0.07$) (Table 5). However, this index explained significant variations in Russian wheat aphid abundance for Field 1 on 5 May 2004 ($r^2 = 0.40$) and on May 17 ($r^2 = 0.75$), for Field 3 ($r^2 = 0.72$), and for Field 4 ($r^2 = 0.42$) (Table 5). The SIPI had statistically significant relationships with Russian wheat aphid densities for Field 1

Table 5

Coefficient of determination, probability, and five vegetation indices associated with Russian wheat aphid abundance collected in four fields

Index	Field 1-DS1 ^a		Field 1-DS2 ^a		Field 1-DS3 ^a		Field 2 ^a		Field 3		Field 4		Reference
	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	r^2	p	
AI	0.78	<0.01	0.63	<0.01	0.80	<0.01	0.48	<0.01	0.62	<0.01	0.46	<0.01	Mirik et al. (2006b)
SIPI	0.12	0.20	0.48	<0.01	0.91	<0.01	0.33	<0.01	0.61	<0.01	0.42	<0.01	Peñuelas et al. (1995b)
$NDVI_{748.5-708.5}$	0.11	0.23	0.44	<0.01	0.73	<0.01	0.23	0.03	0.76	<0.01	0.46	<0.01	Gitelson and Merzlyak (1994)
$DSSI_2$	0.31	0.03	0.71	<0.01	0.46	<0.01	0.28	0.03	0.58	<0.01	0.52	<0.01	Mirik et al. (2006a)
PSSR	0.45	0.01	0.76	<0.01	0.10	0.17	0.30	0.01	0.47	<0.01	0.03	0.47	Blackburn and Steele (1999)
$NDVI_{804.5-668.5}$	0.07	0.33	0.40	<0.01	0.75	<0.01	0.01	0.66	0.72	<0.01	0.42	<0.01	Daughtry et al. (2000)

Field 1: Deaf Smith County near Amarillo, TX. DS1–DS3: Data sets 1–3 because this field sampled three times on 21 April, 5 and 17 May 2004; $n = 15$, 20, and 20, respectively, Field 2: Baca County near Springfield, CO, sampled on 19 May 2004; $n = 20$, Field 3: Prowers County near Lamar, CO, sampled on 20 May, 2004; $n = 25$, Field 4: Cimarron County near Boise City, OK, sampled on 18 May 2005; $n = 20$, sample size = 0.25 m² for all fields except Field 4 that was 1 m², $AI = (R_{756.5} - R_{908.5}) / (R_{756.5} - R_{716.5})$; $R_{756.5}$ and $R_{908.5}$: reflectance values of wavebands centered at 756.5 and 908.5 nm, $SIPI = (R_{804.5} - R_{508.5}) / (R_{804.5} - R_{692.5})$, $NDVI_{748.5-708.5} = (R_{748.5} - R_{708.5}) / (R_{748.5} + R_{708.5})$, $DSSI_2 = (R_{716.5} - R_{868.5} - R_{508.5} - R_{540.5}) / ((R_{716.5} - R_{868.5}) + (R_{508.5} - R_{540.5}))$, $PSSR = R_{868.5} / R_{804.5}$, $NDVI_{804.5-668.5} = (R_{804.5} - R_{668.5}) / (R_{804.5} + R_{668.5})$.

^a Russian wheat aphid abundance weighted.

on 5 May 2004 ($r^2 = 0.48$), for Field 2 ($r^2 = 0.33$), for Field 3 ($r^2 = 0.61$), and for Field 4 ($r^2 = 0.42$) but was insignificant for Field 1 on 21 April 2004 ($r^2 = 0.12$) (Table 5).

The aphid index ($AI = (R_{576.5} - R_{908.5}) / (R_{756.5} - R_{716.5})$) developed by Mirik et al. (2006b) showed consistent and statistically significant relationships with Russian wheat aphid abundance across the fields (Table 5). The AI, among others, had the strongest relationship with Russian wheat aphid abundance for Field 1 on 21 April 2004 ($r^2 = 0.78$) and for Field 2 ($r^2 = 0.48$). Good relationships between AI and Russian wheat aphid abundance were revealed for Field 1 on 5 May 2004 ($r^2 = 0.63$) and on 17 May 2004 ($r^2 = 0.80$), for Field 3 ($r^2 = 0.62$), and for Field 4 ($r^2 = 0.46$) (Table 5). The $NDVI_{748.5-708.5}$ proposed by Gitelson and Merzlyak (1994) exhibited the highest relationship with Russian wheat aphid abundance for Field 3 ($r^2 = 0.76$). The $NDVI_{748.5-708.5}$ displayed significant relationships with aphid densities for Field 1 on 17 May 2004 ($r^2 = 0.73$) followed by Field 4 ($r^2 = 0.46$) and Field 1 on 5 May 2004 ($r^2 = 0.44$), while the relationships were insignificant for Field 1 on 21 April 2004 ($r^2 = 0.11$) and for Field 2 ($r^2 = 0.23$) (Table 5).

The damage sensitive spectral index₂ ($DSSI_2 = (R_{716.5} - R_{868.5} - R_{508.5} - R_{540.5}) / ((R_{716.5} - R_{868.5}) + (R_{508.5} - R_{540.5}))$) developed by Mirik et al. (2006a) produced the highest significant relationship with Russian wheat aphid abundance for Field 1 on 5 May 2004 ($r^2 = 0.71$), whereas the relationships were significantly good for Field 4 ($r^2 = 0.52$) and on 17 May 2004 ($r^2 = 0.46$), and for Field 3 ($r^2 = 0.58$). The regression models generated for the relationships between $DSSI_2$ and Russian wheat abundance collected in Field 1 on 21 April 2004 ($r^2 = 0.31$) and in Field 2 ($r^2 = 0.28$) were weak but were statistically significant. The pigment specific simple ratio ($PSSR = R_{868.5} / R_{804.5}$) proposed by Blackburn and Steele (1999) had the strongest significant relationship with Russian wheat aphid density for Field 1 on 5 May 2004 ($r^2 = 0.76$), while this index produced insignificant or no relationships with Russian wheat aphid abundance for Field 1 on 17 May 2004 ($r^2 = 0.10$) and for Field 4 ($r^2 = 0.03$) (Table 5). The Russian wheat aphid abundance showed statistically significant but moderate to good relationships with PSSR for Field 1 on 21 April 2004 ($r^2 = 0.45$), for Field 2 ($r^2 = 0.30$), and for Field 3 ($r^2 = 0.47$) (Table 5).

4. Discussion

A significant increase in the reflectance from the Russian wheat aphid-infested canopies in the visible region (400–700 nm) was clear evidence that Russian wheat aphid feeding reduced the photosynthetic pigment concentrations in particular chlorophylls, which led to a lowered photosynthetic rate of wheat (Richardson et al., 2004; Riedell and Blackmer, 1999; Peñuelas and Filella, 1998). The reflectance peak from the undamaged wheat at around 550–560 nm occurred due to green light (500–600 nm) being reflected by the green leaf pigments (Riedell and Blackmer, 1999). The trend of lower reflectance from the noninfested wheat canopies switched in the red edge spectrum (730–750 nm). From around 730–750 nm to 900 nm, the Russian wheat aphid-infested wheat canopies had lower reflectance than noninfested wheat. This was basically due to modified leaf tissue, reduced leaf area, and stunting plants caused by Russian wheat aphid feeding (Richardson et al., 2004; Riedell and Blackmer, 1999; Peñuelas and Filella, 1998). Variations in reflectance values among the fields presented in Fig. 1 for infested and noninfested wheat can be attributable to the growth conditions and spectrometer heights from the canopy surface. Different wheat growth stages (Table 1) and varieties, soil types and coverage, and nutrient and water contents of wheat and soil may influence the amount of reflectance from the canopy surface across the fields.

Spectral responses of field bean leaf infected by *Botrytis fabae* (Malthus and Madeira, 1993) and winter wheat infested by greenbug (Riedell and Blackmer, 1999; Mirik et al., 2006b) showed similar patterns in reflectance shift. *Botrytis*-infested leaf reflectance was higher in the visible and lower in the NIR spectrum than uninfested leaves, which was quite similar to the spectral properties of greenbug-damaged wheat leaves or canopies (Riedell and Blackmer, 1999; Mirik et al., 2006b) and Russian wheat aphid-infested wheat found in this study. However, Riedell and Blackmer (1999) found a contrasting result that Russian wheat aphid-damaged leaves reflected more energy than the control leaves in the NIR wavelengths. They pointed out that higher reflectance from Russian wheat aphid-damaged leaves when compared to the control in the NIR region might be due to water stress. Another possible reason for the differences between that study and ours may be reflectance recorded from leaves versus canopy measurements. Canopy reflectance is the combination of signals from soil, shadows, dead material, litter, healthy, and unhealthy plants for a given unit area. The overall conclusion derived from Fig. 1 and Table 4 is that remote sensing is a useful tool to track Russian wheat aphid-infestation in a wheat crop because statistical differences occurred for all segments of the spectrum from 400 to 900 nm. This indicates that broad- and narrow-band imaging sensors have the capacity to delineate Russian

wheat aphid-infestation in field crops using an appropriate scale because image classification methods are based on the similar and dissimilar information contained in an image.

Linear regression analyses showed varying relationships between Russian wheat aphid abundance and spectral indices calculated using the reflectance at certain waveband centers. The relationships between Russian wheat aphid abundance and spectral indices were improved by weighting the aphid densities collected in Fields 1–2. This indicates the problem of heteroskedasticity in Russian wheat aphid abundance. Namely, not all observations contribute equally to the regression fit. The only consistent and statistically significant relationships were found between Russian wheat aphid abundance and AI for all fields. Mirik et al. (2006b) developed this index to estimate greenbug, *S. graminum* (Rondani), abundance collected in two production winter wheat fields and a greenhouse experiment. In that study, AI had consistent and significant relationships with greenbug densities across the fields and the greenhouse experiment although there were higher relationships between other vegetation indices and greenbug abundance. However, the relationships between greenbug abundance and vegetation indices compiled from the literature were not consistent across the fields and the greenhouse experiment as was the case for the present study. The r^2 values between AI and greenbug abundance reported by Mirik et al. (2006b) ranged from 0.59 to 0.69. Therefore, the results found in this study closely agreed with the findings of Mirik et al. (2006b). Similar correlation between vegetation indices and greenbug abundance were reported by Yang et al. (2005) that the correlation coefficients (r) ranged from -0.74 to -0.98 .

DSSI₂ proposed by Mirik et al. (2006a) to estimate percentage greenbug damaged in wheat also revealed statistically significant relationships with Russian wheat aphid abundance across the fields although there were weak relationships. Since the percentage damage caused by aphid may be correlated with its density and DSSI₂ developed to predict aphid damage, this index appears to be useful to estimate Russian wheat aphid abundance in wheat. The SIPI and NDVI_{748.5–708.5} showed statistically significant relationships with Russian wheat aphid densities except for Field 1 on 21 April 2004. The NDVI_{804.5–668.5} and PSSR had significant relationships with Russian wheat aphid abundance collected in four fields out of six. The linear regression results of this study were strongly supported by the findings of Niño (2002) who reported weak to robust relationships between vegetation indices and greenbug densities in wheat (r^2 ranged from 0.10 to 0.95).

In general, the relationships between Russian wheat aphid abundance and spectral indices were weaker for Field 1 on 21 April 2004 and Field 2 than for Field 1 on 5 and 17 May 2004 and Fields 3–4. Perhaps the inconsistent relationships between spectral indices and Russian wheat aphid abundance could have resulted from one or more of several reasons. Atmospheric differences could have influenced the results, as could variations in edaphic factors such as exposed soil, soil type, and soil moisture, and biotic variability such as plant height and health, concentrations of moisture, chemicals and pigments, vegetative growth stages, differences in wheat variety, and damage severity. It was not possible to control these types of factors in this study, and, in fact, it would not be feasible to control them for an operational pest monitoring system in production wheat fields. It is clear evident in Table 5 that the sensitivity of a spectral index is affected by variability differing from one place to another. Despite the inconsistent relationships between five spectral indices presented in Table 5 and Russian wheat aphid abundance across the fields, the AI had good to strong associations with Russian wheat aphid density for all fields. In addition, the regression models generated based on the relationships between DSSI₂ and Russian wheat aphid densities were statistically significant across the fields even though relationships were weak for Field 1 on 21 April 2004 and Field 2. The SIPI also had significant relationships with Russian wheat aphid densities collected in the fields with one exception for Field 1 on 21 April 2004. Peñuelas et al. (1995b) argued that SIPI minimized the confounding effects of leaf surface and mesophyll structure and useful for assessment of physiology and phenology of vegetation. The indices in Table 5 demonstrated to be more useful to quantify Russian wheat aphid abundance, with varying success across the fields than other indices presented in Table 2. Therefore, these indices, preferably AI because it had good relationships with all data sets, are suggested to monitor Russian wheat aphid abundance in production wheat fields.

Reflectance responses of the wheat canopy indicated that remote sensing can detect damage caused by Russian wheat aphid feeding. Russian wheat aphid feeding significantly increased the visible reflectance and decreased the NIR reflectance at the canopy level when compared with noninfested plants. This indicates that the spectral properties of wheat plants are markedly modified by Russian wheat aphid feeding. The relationships between Russian wheat aphid abundance and spectral indices showed that remotely sensed data transformed into spectral indices provides a method for detecting Russian wheat aphid numbers and discriminate its damage to wheat in production fields. In addition, once applied to the image, the relationships between Russian wheat aphid abundance and vegetation indices and spectral signatures of undamaged and damaged wheat by this aphid will produce damage and density maps. These

maps provide detailed temporal and spatial information on Russian wheat aphid abundance and its damage, which can be a very useful tool for aphid management in site specific agriculture. Therefore, future studies using image data acquired by satellite or aircraft platforms for its ability to detect Russian wheat aphid infestations in wheat at broader spatial scales are needed.

Acknowledgments

Our special thanks to Karl Steddom, Robert Bowling, Roxanne Bowling, and Vasile Catana for their help and beneficial discussion. We are thankful to Vanessa Carney, Johnny Bible, Robert Villarreal, David Jones, Joy Newton, Nartay Kassymzhanov, Daniel Jiminez, Karl Barfoot, Timothy Johnson, Aaron Miller, and Thia Walker for technical assistance. This study was funded by the USDA-ARS Areawide Pest Management Program. Project Number: 500-44-012-00.

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