DETECTION OF GREENBUG INFESTATION ON WHEAT USING GROUND-BASED RADIOMETRY

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CHAPTER 1

Introduction

This chapter aims to give background information about greenbug (Schizaphis graminum (Rondani)) infestation and significance of this research. Research goal and objectives for this study are also defined.

1.1 Greenbug infestation and its problems

The greenbug belongs to a group of insects known as aphids, which are small, soft-bodied, sucking insects (Brooks, 1991). The greenbug is a green to yellow-green aphid with a dark green stripe down the middle of its back. It is a vector of barley yellow dwarf virus (University of California, 2002). Greenbugs are important pests of major crops, such as wheat, barley and sorghum. They usually feed in colonies on the undersides of leaves and suck sap and during feeding inject a toxic substance into the plant (Knutson and Ree, 1998). Infestation symptoms initially appear as groups of small, reddish, pinpoint spots on infested leaves. Later, as feeding continues, leaves turn yellow and begin to die (Brooks, 1991). Figure 1-1 shows the photos of greenbug infestation. Crop damage by greenbug infestation is related to the number of greenbugs and the length of time they persist on the plants. It also depends on plant size, vigor and growth stage and moisture conditions. Plants infested by greenbugs also show some physiological and metabolic changes, such as decrease of water potential and chlorophyll, and lower rates

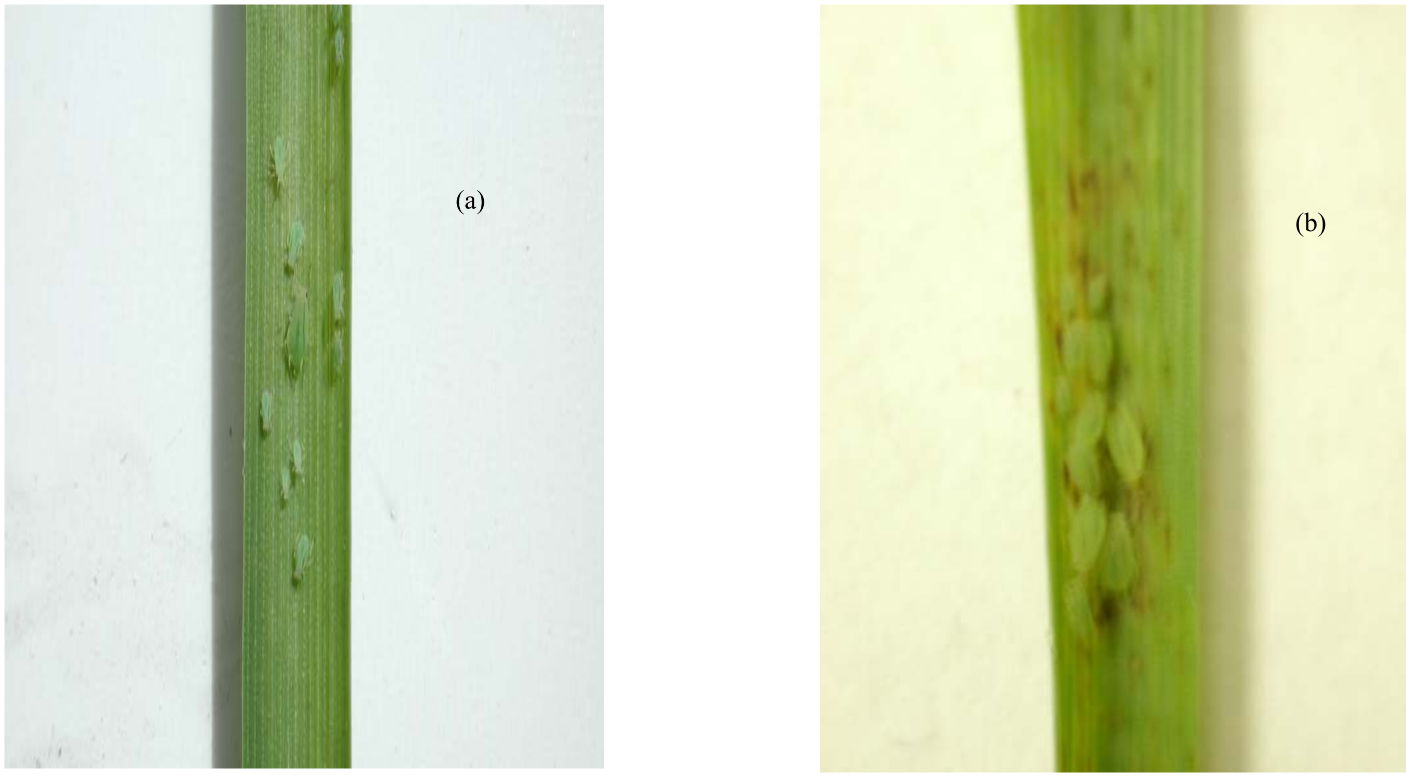


Fig 1-1. Photographs showing greenbug infestation on wheat leaves (a) at the beginning stage; (b) at the middle stage.

of CO_2 assimilation (Cabrera et al., 1995). If greenbug infestation could not be controlled in time, yield losses become inevitable. In addition, heavy feeding by greenbugs causes typical "greenbug spots" in a field (Elliot and Kieckhefer, 1987). The centers of the spot are made up of dead plants and skins of greenbugs, surrounded by living plants which are heavily infested and beginning to turn yellow.

In the Central Great Plains area, greenbug outbreak have caused significant economic loss to many farmers (Brooks, 1991). In 1976-77, a severe outbreak of greenbugs, combined loses of growers from reduced yields and insecticide applications exceeded $135 million in Oklahoma (Starks and Burton 1977). During 1992-93, an extremely low greenbug year, the pest caused $321,000 in losses in Oklahoma (Webster, 1995). During a major outbreak of greenbugs on wheat and extreme drought in the spring of 1996 wheat growers in Oklahoma experienced the lowest per-acre yield since 1967 (Peters et al., 1997). During the 1997-1998 growing season in Kansas and Oklahoma, yield losses due to greenbug infestation were 2.5% and 0.18 % respectively (Webster et al., 2000). The severe damage to wheat, sorghum, and barley caused by the greenbug makes it the key insect pest of these crops in much of Oklahoma, Texas, and Kansas.

Chemical insecticides are used almost exclusively for controlling the greenbug and losses are closely tied to insecticide costs for control (Patrick and Boring, 1990; Webster, 1995). The more commonly used insecticides for treating greenbug infestation (chlorpyrifos, dimethoate, disulfoton, ethyl parathion, and methyl parathion) are among the most toxic chemicals currently used for insect control. During widespread severe greenbug outbreaks millions of acres are sprayed with these compounds in Oklahoma in an effort to save wheat crops (Browning et al., 1982). This high insecticide use poses problems to the environment, especially as it relates to conservation of migratory waterfowl on prairie potholes, playas, and other wetlands in the Great Plains that frequently become contaminated with insecticides in run-off from agricultural fields and from improper application (Flickinger et al., 1991; Grue et al., 1988; Klass, 1982). Currently, many fields are treated without sufficient knowledge of greenbug density or plant injury. Insecticides are often applied when greenbug populations are too low to cause sufficient yield loss, or they are treated so late in the growing season that most yield loss has already occurred (Wratten et al., 1995). Widespread greenbug outbreaks occur every 5-7 years and result in heavy insecticide use and greatly reduced yields. These losses present an impediment not only to the economic viability of wheat production, but also to environmental integrity and sustainability. Integrated pest management (IPM) has emerged as the dominant paradigm for managing pests and diseases in agriculture (Pedigo, 1995). The main goal of IPM goes beyond that of simply eradicating pests, but includes reducing pests to densities below which appreciable damage occurs, thereby maintaining environmental quality and increasing grower's profits. IPM involves a holistic approach that integrates multiple tactics to manage pest populations. A critical component of IPM is monitoring fields to determine whether there is a pest problem. To minimize economic and environmental loss and conduct timely and effective control, early detection of greenbug infestation is desirable for farmers.

1.2 Current research on detecting greenbug infestation

Although many research projects related to greenbug infestation are being conducted, few researchers focus on the detection of crop stress induced by greenbug infestation. Currently, field scouting is a major method to identify if there is a need to apply greenbug control in a field. The performance of field scouting mainly depends on correct identification of the pests. Crop pests can be identified through a combination of direct recognition, knowing where and when the insect is likely to be found, and recognizing injury symptoms on the plant. It is normal that greenbug scouting is time and labor consuming because it needs to provide enough information to make an economically sensible decision.

In the United States, there are many scouting and decision-making methods for greenbug IPM. In Oklahoma, there is a greenbug scouting and decision-making system called "The Cereal Aphid Pest Management Expert System". It was developed through the cooperative efforts of the USDA Agricultural Research Service, Site Specific Technology Development Group of Stillwater (SST), and Oklahoma State University. This system consists of a set of computer programs designed to help the user manage cereal aphids in winter wheat. It can help farmers identify cereal aphids and determine the economic threshold for greenbugs in wheat using a new scouting technique called Glance 'n Go, which was developed from data collected in over 120 wheat fields in Oklahoma over 3 years (Elliott et al., 2001). Glance 'n Go does not need to count actual numbers of greenbugs but only keep track of the number of infested tillers. Thus, it saves time and money on scouting. With this system, a grower can quickly detect greenbug infestations and make control decisions based upon the value of the crop and the costs associated with production. This system is a big step forward for controlling greenbugs in winter wheat.

Remote Sensing techniques began to show the potential to be used for detection of greenbug infestation. It was found that remote sensing can identify pest infestations in agricultural fields (Hatfield and Pinter, 1993). Such techniques rely on the indirect indication of the pest through visual manifestation of the plant injury because pest-induced crop stress can be visualized using some wavelengths such as red ® and near infrared (NIR) bands (Riley, 1989). Deol et al. (1997) and Ma et al. (1998) demonstrated that damage caused by greenbug infestation could be detected by some techniques that can indirectly measure the content of chlorophyll of leaves infested by greenbugs. Riedell et al. (1999) reported that at leaf level, bands ranging 625-635 nm and 680-696 nm were most sensitive to greenbug infestation through a greenhouse study. Michels et al. (1999) found that it is possible to use IRT (Infrared thermometer) to detect greenbug infestation if it is sure that wheat plants are not under water stress. But none of the previous research results could be directly applied to detection of greenbug infestation. Because the detection of greenbug infestation requires knowledge on sensitive bands at canopy level. Also, it is difficult to know whether wheat plants are under water stress or not before conducting detection of greenbug infestation.

1.3 Challenges for studies on detecting greenbug infestation

Greenbug outbreaks often appear at times when the wheat crop is under water stress (Michels and Undersander, 1986; Michels and Behle, 1998; Ortman and Painter, 1960). Michels and Undersander (1986) reported that the number and distribution of greenbugs on host plants were strongly affected by water stress. Thus plants under water stress are more sensitive to greenbug infestation and water stress affects the level of greenbug infestation. In addition, the combination of water stress and greenbug stress did not cause more changes on host plants than water stress alone (Ryan et al., 1987). Cabrera et al. (1995) also reported that greenbug infestation of barley produced changes similar to those observed in plants subjected to water stress. So it is hard to separate and differentiate water stress and greenbug infestation, considering their coexistence under field conditions. Therefore, the key problem for detecting greenbug infestation is how to differentiate these two kinds of stresses under the field conditions.

It is well known that the greenbug (GB) is a major pest of wheat plants in Great Plains. However, Russian wheat aphid (RWA), *Diuraphis noxia* (Mordvilko), is also a serious threat to wheat production throughout the western United States west of the 100th meridian (Hein et al., 1990). The economic impact from this pest can be devastating and has been estimated at $893 million for 1987-1993 (Morrison and Peairs, 1998). Besides, two kinds of infestations may coexist in the same field. Therefore, how to differentiate wheat damage caused by these two kinds of aphids is also important and necessary.

Riddell and Blackmer (1999) identified wavelengths sensitive to greenbug infestation at leaf level but it is necessary and important to identify wavelengths that are most sensitive to greenbug infestation at canopy level. It is likely that different stresses such as water stress and greenbug infestation coexist under the field conditions. It will be useful to differentiate water stress and greenbug infestation. In addition, vegetation indices such as Normalized Difference Vegetation Index (NDVI) need to be examined for their potential to detect greenbug infestation.

Plant damage symptoms caused by greenbug infestation are closely related to the growth stage of host plants, the infestation levels, such as abundance level of greenbugs and infestation length (Brooks, 1991). More research needs to be done to define the reflectance profile of plants under different growth stages and infestation levels.

Environmental conditions, such as air temperature, humidity and wind, are important factors that influence greenbug infestation (Brooks, 1991). It is necessary to study the relationship between canopy reflectance and greenbug infestation under different environmental conditions. In addition, the special spatial patterns of greenbug infestation, “greenbug spots”, might also be useful for detecting greenbug infestation. Field research needs to be done to examine differences of spatial patterns among different stresses.

Therefore, the purpose of this study is to identify bands and vegetation indices sensitive to greenbug infestation at canopy level by observing the change in spectral characteristics of greenbug-induced stress on wheat plants using hand-held radiometers under greenhouse conditions. This will provide useful information for detecting wheat stress induced by greenbug infestation and lay the groundwork for field studies to develop airborne remote sensing methods for identifying fields threatened by Greenbug infestation, thereby obtaining both economic and environmental benefits.

1.4 Significance of this research

Research findings from this study will help develop a directed scouting approach used for greenbug scouting and control in IPM. For traditional field scouting methods, it is difficult to cover the entire field area given economic and time constraints. It may not be possible to estimate the full extent of damage through visual methods of identification. Since there is a certain spatial pattern -greenbug spot in the infested field, if greenbug spots could be detected using sensitive band or vegetation indices determined in this study by satellite images or aerial photos, it will be possible to identify these areas as targets for intensive sampling and initiate directed scouting**.** Targeted scouting of greenbug spots will help reduce the number of samples required and thus save time and labor for scouting. It also allows site-specific pesticide applications to targeted areas of greenbug outbreaks and protect non-infested and lightly infested crop before infestation spreads across the whole field or to adjacent fields. Thus it could reduce the amount of pesticide applied and decrease the damage to beneficial insects in order to obtain the goal of IPM. In this case, it is likely that natural enemies would suppress the greenbug populations in the rest of the untreated areas of the field. Adopting a directed scouting approach will lower costs to the farmer and benefit the environment. In this way, this study will help build a new approach to greenbug IPM.

Until now the spectral responses of wheat plants to greenbug infestation were poorly studied. This research will provide detailed and dynamic data on canopy reflectance of wheat under greenbug infestation. It intends to address both the onset of greenbug infestation and the spectral patterns associated with the greenbug infestation. This could benefit NASA and various private enterprises in their endeavors to deploy sensors with specific applications on future satellite payloads.

Finally, this research study has the potential to initiate and integrate other studies involving detection of other crop stresses such as water, nutrient, and pathogen stress. In return, the detection of crop stress will be greatly improved and developed.

1.5 Research goal and objectives

The overall goal of this study is to characterize wheat stress caused by greenbug infestation using ground-based radiometry. Specific objectives include:

1.5.1 Identifying wavelengths most sensitive to greenbug infestation

It is rare that there is only a single crop stress and different stresses may often coexist under field conditions. Riedell and Blackmer (1999) identified some wavelengths that were sensitive to greenbug infestation on wheat. However, the reflectance measurements of their study were at leaf level not canopy level. To conduct field detection of greenbug infestation, it is necessary to identify wavelengths that are most sensitive to greenbug infestation at canopy level.

1.5.2 Identifying vegetation indices most sensitive to greenbug infestation

Currently, various vegetation indices, e.g. NDVI and NPCI (Normalized total Pigment to Chlorophyll Index), are being used for crop stress detection but no vegetation indices specially used for greenbug infestation at canopy level have been reported. Riedell and Blackmer (1999) found that NPCI was significantly correlated with total chlorophyll concentration in infested leaves. Adams et al. (1999) reported that the Yellowness Index (YI) was a good measure of leaf chlorosis, which is typical symptom of greenbug infestation, in stressed plants. But their study is only at the leaf level. Thus, it is important to examine sensitivities of various vegetation indices to greenbug infestation at canopy level.

1.5.3 Differentiating greenbug infestation from water stress

Due to co-existence of greenbug infestation and water stress on wheat, it is hard to separate and differentiate water stress and greenbug infestation. Thus, an important issue for detecting greenbug infestation on wheat is how to differentiate these two kinds of stresses. Therefore, it will be important to test if sensitive bands and vegetation indices can be used to differentiate greenbug infestation from water stress.

1.5.4 Examming the impact of growth stage on the detection of greenbug infestation

Plant damage symptoms caused by greenbug infestation are closely related to the growth stage of host plants (Brooks, 1991). However, there is no study involving monitoring change of canopy reflectance of infested plants at different growth stages. Also, plant coverage on the soil varies at different stages. Plant cover differences due to growth stages may have impact on reflectance measurements. Thus, it is not clear that sensitive band/vegetation indices determined at one stage can be used for detection of infestation at another stage. Research needs to be done to define the reflectance profile of plants at different growth stages.

1.5.5 Distinguishing greenbug infestation and infestation by Russian wheat aphid

As mentioned before, two kinds of infestations may coexist in the same field. Also, chlorosis and necrosis are typical symptoms for aphid infestation in small grains and there is a similarity of the spectral responses of plants between these two kinds of infestation (Riedell and Kieckhefer, 1995). Thus, how to differentiate wheat damage caused by these two kinds of aphids is also important and necessary. Therefore, it will be necessary to examine if sensitive band and vegetation indices could be used to distinguish greenbug infestation with the infestation induced by Russian wheat aphid.

CHAPTER 2

Literature Review

The main purpose of this chapter is to review the application of ground-based radiometry on crop stress detection and examine some ways for detecting wheat stress induced by greenbugs.

2.1 Introduction

2.1.1 Leaf responses to plant stress

Plant stress is considered to be a significant deviation from the conditions optimal for plant growth and thus could cause harmful effects when the limit of a plant's ability to adjust is reached (Larcher, 1995). Plant stress can affect almost every part of a plant although normally one or some parts of a plant are influenced at the beginning. Leaf responses to different stresses are very important when considering remote sensing techniques used to detect crop stress.

When water content of plant cells is lower than optimum and causes some degree of metabolic disturbance, a plant is said to be suffering water stress (Fitter and Hay, 1981). Leaf curling, wilt or drastic decreases of leaf area expansion are general symptoms of water stress (Alscher et al., 1990). The extent of stress impact on plant leaves depends on the occurrence of the water stress relative to the phenological stage of the plant and severity of the water deficit (Chaney, 2000).

Nitrogen deficiency is the most common and widespread nutrient deficiency. When the required amount of nitrogen is not available, plants are said to be under nitrogen deficiency or nitrogen stress (Larcher, 1995). Plant leaves generally turn yellow (overall chlorosis*)* under N stress. In young plants the whole plant turns yellow while in older plants the deficiency is more pronounced in older leaves (Reid, 1999).

A plant disease is a continuous harmful process that is usually caused by a microorganism and is characterized by visible morphological changes (Nyvall, 1979). Many diseased plants show symptoms on leaves, such as leaf discoloration or yellowing in localized or distinct patterns caused by virus, and small rusty-red, brown or black spots and stripes caused by fungi (Mikkelson, 1999).

Pest infestation refers to the presence of unusually large numbers of pests on the surface of plants and the damage to plants caused by these insects (British Society for Plant Pathology, 1973). Change in leaf color is a common symptom of pest infestation, and some changes involve cellular and tissue deterioration leading to leaf aging and death (Fogal et al., 1997).

Ozone (O_3) injury refers to injury or damage to plants due to high concentration of ozone in the atmosphere. The injury caused by ozone is characterized by the appearance of chlorotic to pale tan or whitish lesions on the affected leaf. Extent of damage is related to the degree of leaf maturation and older leaves are more easily damaged by ozone (Treshow and Anderson, 1989).

Heat and cold, depending on their intensity and duration, could impair the metabolic activity, growth and variability of plants and thus limits the distribution of a species. Thus there are threshold temperatures for most crops. When critical temperature threshold is crossed, cell structures and cellular functions may be damaged (Larcher, 1995). Heat stress refers to harmful effects caused by high temperature. Plants under heat stress are darker when compared to non-stressed plants and damaged plants have dry or yellow-dry spots on the leaves (Staub, 1990). Chilling injury is the physical and/or physiological changes that are induced by exposure to very low temperatures (Saltveit and Morris, 1990). During chilling, the loss of chlorophyll, apparent as leaf yellowing or purpling, may occur as a consequence of photo-oxidation.

When salt content in soil exceeds the capacity of plants to cope, plants are under salinity stress (Larcher, 1995). Plants suffering from salinity stress show reduced leaf size, scorching of leaf tips or margins, and premature discoloration and abscission of the leaves. Salt stress may have been the first chemical stress factor encountered during the evolution of life on earth.

2.1.2 Principles of crop stress detection

Remote sensing is "the science and art of obtaining information about objects through the analysis of data acquired by a device that is not in contact with the object" (Lillesand and Kiefer, 2000*)*. Detection of crop stress by remote sensing is based on the assumption that stress factors that interfere with photosynthesis process or the physical structure of the plant affect the absorption of light energy and thus alter the reflectance spectrum, by reliably measuring the reflectance of spectrum the health state of a plant can be determined. Leaf reflectance is governed by leaf surface properties, internal structure, the concentration and distribution of biochemical components, such as chlorophyll and water content, and thus remote sensing analysis of reflectance has been used to assess both biomass and physiological status of a plant (Penuelas et al., 1997). Generally, leaf chlorophyll content is the primary factor affecting leaf reflectance in the visible and near infrared wavelengths from roughly 500 to 900 nm and leaf water content is the primary factor from 1300 to 2500 nm (Carter, 1991). Many researchers (Carter, 1993; Malthus and Madeira, 1993; Shibayama et al., 1993) reported that plants under stress have a decrease in reflectance of the near infrared band (750-1300 nm), a reduced red absorption in the chlorophyll active band (680 nm), and a consequent shift of the red edge. Therefore, leaf reflectance can be used to derive indicators that are representative of crop conditions and to assess different stresses (Fernandez et al., 1994). Furthermore, vegetation indices such as NDVI combining the R and NIR information are also useful for characterizing crop stress (Hatfield and Pinter, 1993).

Since a major role of transpiration is leaf cooling, canopy temperature and its reduction relative to ambient air temperature is an indication of how capable transpiration is in cooling the leaves under a demanding environmental load. It was reported that plants subjected to water stress have higher leaf temperature than normal plants and other types of crop stress related to water uptake by plant roots or translocation of water to the leaves for evaporation also have similar symptoms (Michels, et al., 1999; Moran et al., 1994; Pinter, 1979). The use of canopy temperatures to detect water-related stress in plants is based upon the assumption that, as water becomes limited, transpiration is reduced and plant temperature increases. The “Crop Water Stress Index” (CWSI) that was based on infra-red thermometry has often been used to quantify water-related crop stress. So crop stress can also be detected by using infrared thermometry. It is clear that remote sensing techniques can detect crop stress due to such factors as insect infestation, disease, moisture deficiency, and lack of required nutrients.

2.1.3 Status of current research on crop stress detection by remote sensing

Image-based remote sensing, such as airborne systems and satellites, has been successfully used in detection of crop stresses, such as pest infestation and nitrogen stress (Bell, 1995, Hugh-Jones et al., 1992; Maas et al, 1999; Royle and Lathrop, 1994). For example, Landsat satellite images were used to map the western tarnished plant bug (*Lygus hesperus* (Knight)) that is a key pest in many crops (including cotton, dry beans, seed alfalfa, and various fruits and vegetables) in the San Joaquin Valley (Goodell et al., 2002). They also identified areas of senescing natural vegetation that were in close proximity to cultivated areas. GopalaPillai et al. (1998) used high-resolution color infrared (CIR) aerial images to detect in-field spatial patterns of nitrogen stress in a corn field and found that the canopy reflectance was well correlated to the applied nitrogen and the yield from 75 days after sowing. There are, however, still a lot of technical limitations that affect image-based application on crop stress detection. Currently, no satellite sensor that has both sufficient spectral resolution and spatial resolution for with-in field analysis is available. Lower temporal resolution for satellites is also a big obstacle for satellite-based detection of crop stress. For aircraft-based sensors, calibration and geometric correction are often difficult for large area coverage (Moran et al., 1997).

On the contrary, by using ground-based radiometry techniques, such as hand-held radiometers, people can control monitoring conditions and measurements can be easily quantified and repeated under the same or similar conditions. It also allows more precise analysis and interpretation because the crop can be sampled directly to measure composition and other properties affecting leaf reflectance or temperature (Goetz and

Srivastava, 1985). These are very useful for site-specific crop stress detection. Therefore, ground-based radiometry has been widely used in crop stress detection (Hatfield, 1990).

2.2 Crop stress detection using ground-based radiometry

2.2.1 Ground-based radiometry

Ground-based radiometry is a quantitative measurement of radiance, irradiance, reflectance or transmission of objects by using hand-held spectroradiometers, radiometers or infrared thermometers (IRT) in a field and greenhouse, or a laboratory. It measures both irradiance and radiance of an object and correlates them to the biological, chemical and physical attributes of the object. Ground-based sensors are often hand-held or mounted on a tripod, ladder, scaffolding, tall building, tower, etc. Compared to image-based remote sensing, field spectra of target materials are collected to allow for more precise image analysis and interpretation (Goetz and Srivastava, 1985). Ground-based radiometry sensors can be used to record detailed information about the surface that is compared with information collected from aircraft or satellite sensors. They also can be used to better characterize the target that is being imaged by these sensors.

2.2.2 Nitrogen deficiency

Although a chlorophyll meter is often used for assessing crop N status, there is a lot of research that involves the use of hand-held radiometers or spectcroradiometers to detect nitrogen deficiency. Vouillot et al. (1998) used a field radiometer to conduct field measurement of N deficiency of wheat and spectral bands: 500-590 nm (green), 610- 680 nm (red), 790-890 nm (near infrared) were used. They found that ratio of near infrared to red was closely related to nitrogen concentration. Schepers et al. (1998) utilized Li-Cor canopy sensors designed to measure reflectance of green and NIR portions of the spectra and a chlorophyll meter to monitor the N status of irrigated corn in the field. They found that green NDVI = (NIR-green)/ (NIR+green) was a good indicator of yield potential because it theoretically integrates crop N status (greenness) and biomass.

To increase spectral resolution, Blackmer et al. (1994) conducted reflectance measurements of corn leaves cut from corn planted in research plots by using a Hunter tristimulus colorimeter from 400-700 nm in 10 nm bandwidths in the lab and found that 550 nm was the best wavelength to differentiate different N treatments. They concluded that the measurement of light reflectance near 550 nm was promising to detect N deficiencies in corn leaves. Sembiring et al. (1999) used a PSD 1000 Ocean Optics fiber optic spectrometer (345-145 nm) to detect winter wheat stress due to N and P deficiency at Tipton and Perkins, Oklahoma. It was found that NDVI and the ratio index = NIR/red were good indices to predict biomass, and N and P uptake.

Wavelengths that are most sensitive to nitrogen deficiency might be crop-type dependent because red band and near infrared band were used for winter wheat but the band centered at 550 nm or infrared portion were used for corn. These differences could be explained by many factors, including differences in water content, plant anatomy, and the concentration of cell constituents. NDVI and VI (Vegetation Index) are often used and green NDVI might be a good indicator of yield potential. Compared to other sensors, the Li-Cor sensor can detect cumulative effects of plant vigor and monitor immature leaves that might indicate current N status better than more mature leaves (Schepers et al., 1998). All above studies except the study of Blackmer et al. (1994) were conducted under field conditions. Detection of N deficiency by ground-based radiometry holds increased potential in the near future.

2.2.3 Water stress

Compared to other stresses, water stress has been most widely studied using ground-based spectroscopy/radiometry, and hand-held multi-spectral radiometers were usually used. There are also numerous studies involving the use of hyperspectral spectroscopy by spectroradiometers to detect crop water stress.

Ripple (1986) measured reflectance of snapbean leaves collected from one greenhouse at three spectral regions: 630-690, 760-900, and 2080-2350 nm. The results showed that the red and middle infrared bands are sensitive to changes in both leaf cover and relative water content of leaves while the near infrared was sensitive to only changes in leaf cover. Mahey et al. (1991) monitored radiance of wheat canopies in the field at two bands: 625-689 nm and 760-897 nm and found that NDVI was a good indicator for water stress. Fernandez et al. (1994) studied radiometric characteristics (ranging from 400 to 2200 nm) of wheat under water and nitrogen stress in the field. The results revealed that except for LAI (Leaf Area Index), relations between canopy reflectance and most physiological parameters were dependent on plant treatment, and NDVI was the most powerful index for water stress.

To get detailed information about spectral response of crop water stress, some researchers used field spectroradiometers to do numerous experiments. Shibayama et al. (1993) observed radiometric characteristics of rice canopy in the wavelength range 400-1900 nm in the field. Based on analysis of spectral reflectances and calculation of NDVI, it was concluded that reflectance measurements and their first derivatives in near infrared and mid-infrared ranges are better ways to detect water stress in rice canopies. Penuelas et al. (1993) conducted measurements of spectral reflectance and water status variables, such as RWC (Relative Water Content), on three experimental objects: irrigated gerbera in one greenhouse, pepper and bean in a chamber, detached bean leaves at bands from 390 to 1100 nm. The results illustrated that reflectance in the 950-970 nm region is a good indicator of plant water status. Field radiometric measurements of two deep-rooted shrubs (*Quercus coccifera and Arbutus unedo*), two shallow-rooted shrubs (*Cistus albidus and Cistus monspeliensis*), and a grass (*Brachypodium retusum*) were made by Penuelas et al. (1997) and it was found that indices: WI (Water Index = R900 nm/R970 nm) and NDVI were closely related to plant water concentration. Penuelas and Inoue (1999) conducted measurement of reflectance on detached leaves of two plants, peanut and wheat in the spectral range from 400 to 2500 nm and computed several indices: WI, NDVI, WI/NDVI, SIPI (Structural Independent Pigment Index = (R800-R445)/ (R800-R680)). The results showed that the ratio of WI to NDVI was a best indicator of RWC.

Based on field radiometric/ polarimetric data of wheat canopies measured using one spectropolarimeter, Manjul (2000) described new spectral vegetation indices calculated from spectral reflectance and spectral degree of polarization. Spectral ranges from 650 to 1000 nm and 650 to 800 nm were found very useful for crop water stress detection.

Based on the above-mentioned literature, spectral wavelengths that are most sensitive to water stress depend on species. Because red and middle infrared bands were used for snapbean, red and near infrared bands were used for wheat, and near infrared (960 nm) band was used for rice. Carter (1991) reported that visible reflectance was most sensitive to water stress at 535-640 nm and 685-700 nm but Penuelas et al. (1993 and

1997) found that change in reflectance at 950-970 nm was more effective for detection of water stress at canopy levels. All the differences described above may be caused by differences in the anatomical structure and water content of leaves from different crop species.

Different indices were also used for detecting water stress. Among them, NDVI has been widely used (Fernandez et al., 1994; Mahey et al., 1991; Shibayama et al., 1993), although specific wavelengths used for calculation of NDVI differ among studies. New Spectral Vegetation Indices (SVI) may eliminate the effects of soil background (Manjul, 2000). In addition, WI (Water Index) is also helpful to characterize crop water stress (Penuelas et al., 1993, 1997; Penuelas and Inoue 1999; Riedell and Blackmer, 1999).

Foliage temperature can be incorporated into crop water stress indices that have been related to soil water availability and leaf water potential (Hatfield, 1990). Plant water stress in the energy balance method can be quantified by one of two methods: an empirical approach developed by Idso et al. (1981) and a theoretical approach by Jackson et al. (1983). Both methods are based on comparison between foliage and air temperature. Infrared thermometers (IRT) are often used to detect water stress. Stark and Wright (1985) conducted field studies to detect soil water deficits in potato. Concurrent measurements of foliage – air temperature differences, leaf water potential and vapor pressure deficit- were obtained from differentially irrigated potato during the growing season. The results showed that Plant Water Stress Index (PWSI) was linearly related to water potential caused by moderate to severe water deficits. Yazar et al. (1999) evaluated the Crop Water Stress Index (CWSI) for irrigated corn in the field and found that CWSI was a useful tool to measure water stress in corn. Carcova et al. (1998) conducted two field measurements on maize. It was found that there was a good relationship between CWSI and available soil water. Based on field measurement of iceberg lettuce, Alves and Pereira (2000) provided a new approach for non-water-stressed baselines for irrigation scheduling using IRT. Compared to water stress detection by measuring leaf reflectance, IRT and CWSI seem more likely to be used in practice, considering degrees of maturity of techniques and cost.

2.2.4 Plant diseases

There are a number of studies in which hand-held multispectral radiometers were used to detect plant diseases. Nutter (1989) reported that plant disease gradients in a peanut crop could be quantified by measuring percent leaflet defoliation with respect to distance from the sources of leaf spot and by measuring percent canopy reflectance at the 800 nm wavelength in the field. It was also found that the relationship between leafspot defoliation, canopy reflectance and pod yield in field peanut (Nutter et al., 1990; Nutter and Littrell, 1996). Nilsson (1991) measured reflectance of cereal leaves, such as barley infected by net blotch, wheat infected by Glume blotch *Septoria nodorum,* in different seasons and varying weather conditions. They found that there were good correlations between spectral reflectance and disease incidence, plant height and weight.

Malthus and Madeira (1993) used a spectroradiometer to detect the fungus *Bortrytis Fabae* (chocolate spot) infection of beans in the field by scanning at 2 nm intervals over the 400-1100 nm range. The results showed that the most significant change of reflectance was a flattening of the response in the visible region and a decrease in the near infrared reflectance shoulder at 800 nm.

It was found that band at 800 nm was often selected to detect plant stress due to diseases. Since canopy reflectance at 800 nm was closely related to plant disease gradients and plant biomass and in near infrared wavelengths, there was significant decline in reflectance at about 800 nm (Malthus et al., 1993; Nutter, 1989; Nutter et al., 1990; Nutter and Littrell, 1996). However, no stress index was used in the above studies.

Since higher leaf temperature or change of foliage reflectance usually appears when plants are infested with disease, many researchers adopted IRT to detect plant disease (Mengistu et al., 1987). Pinter (1979) studied biological stresses in sugar beets infected with Pythium aphanidermatum (Pythium root rot) and cotton infected with Phymatotrichum (Cotton root rot) in the field. The results showed that green leaves of infected plants had midday radiant leaf temperatures 3-5^{o} C warmer than adjacent plants with no sign of disease. Nilsson (1991) measured leaf temperature of different infected plants, such as barley infected by net blotch, wheat infected by Glume blotch, and roses infected by rust, under various weather conditions. It was found that leaf temperature of the infected host plants could increase by infectious disease, in some cases up to 100 C. These findings illustrate that plant diseases can be detected by using IRT.

2.2.5 Ozone injury

With the increase in ozone pollution, a lot of research was done to measure crop damage caused by ozone injury. Most researchers used spectrophotometers, monochromators or spectroradiometer with hyper-spectral bands to detect leaf injury caused by ozone. Runeckles and Resh (1975) used a spectrophotometer at band 550-650 nm to monitor damage caused by ozone on bean plants grown in pots in a greenhouse and found a significant increase of reflectance in bean leaves exposed to sub-acute levels of ozone. Cure et al. (1998) conducted an open-top chamber study to measure ozone injury to soybean using a scanning monochromator (400-1100 nm). The results showed that O_3 treatments were closely related with changes in reflectance at visible wavelengths and at near infrared wavelengths up to 720 nm. Similar studies were conducted by Cure and Heagle (1985) using a spectroradiometer to measure the leaf response of soybean to ozone. It was found that wavelengths at 560 and 620 nm were promising to assess the response of soybean to ozone stress. Penuelas et al. (1995) also used a spectroradiometer to measure ozone damage on white pine seedlings in the field and calculated spectral reflectance indices: NDVI = (R900-R680)/(R900+R680), SIPI (Structural Independent Pigment Index), and SIXI (Structural Independent Xanthopyll Index). They found that the biological parameters including chlorophyll concentration correlated well with spectral reflectance indices. There are greater chlorophyll degradation and lower photosynthetic and growth rates in the summer, compared to winter and spring.

To estimate ozone stress on wheat and corn, Rudorff et al. (1996) conducted an open-top chamber study using a radiometer with Landsat TM bands in the field under controlled atmospheric environments. It was found that the Normalized Difference (ND) index had lower values for plants grown under the high-O3 level and reduced ND values were related to the appearance of visual O3 damage symptoms on wheat leaves.

Wavelengths or spectra that are most sensitive to ozone stress might be also dependent on crop types. Because green and red bands were used for bean plants such as soybean and blue, red and near infrared bands are used for wheat and corn (Cure and Heagle, 1985; Heagle et al., 1998; Penuelas et al., 1995; Rudorff et al., 1996; Runeckles and Resh, 1975). However, visible bands are mostly selected. Few researchers used vegetation indices to study ozone stress. NDVI or ND was often selected to measure ozone injury on plants (Penuelas et al., 1995; Rudorff et al., 1996).

2.2.6 Heat stress

High temperature stress occurs in some countries such as India and has caused some wheat yield loss (Maheswari et al., 1999). Very few researchers, however, use field spectroscopy/ radiometry techniques to detect heat stress. Blum et al. (1982) used an infrared thermometer to measure the wheat canopy under heat stress in the field. Within a given year and site, under conditions of water stress, the extreme difference among wheat selection in midday temperature reached 8^{o} C, at a mean ambient temperature 26^{o} C.

2.2.7 Salinity stress

High levels of soil and water salinity can inhibit plant growth and reduce crop yield in agricultural food production. Wang et al. (2003) did a study that was designed to measure canopy spectral reflectance of soybean plants under salinity and irrigation treatments (drip, sprinkler, and furrow), and to relate the reflectance characteristics to salinity-induced alterations in leaf chlorophyll, specific leaf mass, and above-ground biomass. The reflectance measurement was made with a hand-held spectral radiometer, which establishes the signature plant responses to salinity. Results from this study indicate that background salinity stress can be delineated from reflectance and temperature measurements of soybean plants. Canopy reflectance in the NIR spectrum region (810 to 950 nm) was significantly lower for soybeans grown under salinity stress.

2.2.8 Pest infestation

Detection of pest infestation often involves the use of hand-held radiometers or thermometers. Nicolas et al. (1991) evaluated the potential of radiothermometry for the detection of infestations by the nematode *Heterodera avenae* Woll. in winter wheat (*Triticum aestivum* L.) and they found that cumulative canopy temperature difference was useful for detecting the presence of nematodes and thermal images allowed precise delimitation of infested areas, and thus should be extensively applied to the detection of nematode attacks by remote sensing in large wheat fields. Yang and Cheng (2001) studied spectral characteristics of rice plants at various levels of infestation by the brown planthopper, *Nilaparvata lugens* (Homoptera: Delphacidae) using a spectroradiometer. It was found that there were significant differences in reflectance among infestations at wavelengths of 755 and 890 nm and the normalized difference vegetation index (NDVI) and cumulative reflectance were also useful to discriminate levels of infestation.

Although a lot of research is being done on greenbug infestation, few researchers focus on how to detect crop stress induced by greenbug infestation. Deol et al. (1997) developed a rapid and nondestructive technique to estimate the loss of chlorophyll in sorghum leaves caused by greenbug feeding. By measuring chlorophyll content of uninfested and infested leaf areas using a chlorophyll meter it was found that chlorophyll loss increased as the feeding duration of the greenbugs increased (Deol et al., 1997). Similarly, using a chlorophyll meter, Ma et al. (1998) observed chlorophyll loss in sorghum infested by greenbugs. These experiments demonstrated that damage caused by greenbug infestation could be detected directly or indirectly by techniques that measure the chlorophyll content of leaves infested by greenbugs.

Riedell and Blackmer (1999) conducted a greenhouse study aiming to find wavelengths most sensitive to greenbug infestation measured using a portable ASD spectroradiometer. In this study reflectance of detached wheat leaves infested with greenbugs was measured across from 350-1075 nm at about 1.4 nm intervals. NPCI and Water Band Index (WBI) were calculated. Results showed that reflectance values at the 625-635 nm and 680-696 nm range and NPCI were significantly correlated with total chlorophyll concentrations in infested leaves. However, results of this study might be different under field conditions, since this research was done only at leaf level and not canopy level.

Michels et al. (1999) used IRT to monitor the temperature difference of leaves of wheat under four regimes: normally-watered and not infested, normally-watered and infested, water-stressed but not infested, and infested and water-stressed in a greenhouse. The experiment illustrated that there was a significant and distinguishable temperature difference between non-infested and infested wheat and the differences increased with the abundance of greenbugs. However, it was hard to use IRT alone to differentiate water stress and greenbug infestation because it was found that there was no significant difference between normally-watered but infested plants and non-infested and water-stressed plants (Michels et al., 1999).

Sensitive bands to various crop stresses are summarized in Table 2-1. It can be seen that different stresses on the same plants have been measured using different bands. For different crops under the same stress, sensitive bands are also different. This variance indicated that the most sensitive wavelengths used to detect crop stress might be crop-dependent.

Table 2-1 Sensitive bands to various stresses

Stress type	Sensitive band (nm)	Crop	References
Nitrogen deficiency	550	wheat	Blackmer et al.(1994)
Water stress	950-970	gerbera, pepper, bean	Penueles et al.(1993)
	650-800, 1000	wheat	Manjul (2000)
	535-640	wheat	Carter (1993)
Plant disease	800	peanut	Nutter et al.(1990)
Ozone injury	560-620	soybean	Cure and Heagle (1985)
Heat stress	Thermal band	wheat	Blum et al.(1992)
Salinity stress	810-950	soybean	Wang et al.(2003)
Pest infestation	755-890	wheat	Yang and Cheng (2001)
	625-635	wheat	Riedell and Blackmer(1999)
	680-696	wheat	Riedell and Blackmer(1999)

2.3 Vegetation indices

Numerous vegetation indices were involved in the study of crop stress detection. A Vegetation Index (VI) is a quantitative characterization of remotely sensed temporal and spatial data. To enhance the plant stress signal, the measured spectral reflectance data from two or more spectral wavelengths are combined into vegetation indices based on different mathematical formulae. Spectral vegetation indices are mainly designed to improve vegetation sensitivity by reducing “noise” from soil and atmosphere and could be used as quantitative indicators of vegetation amount. They reduce the multidimensional spectral space of the vegetated scene to one dimension in order to sense variability in such properties as biomass, (LAI) Leaf Area Index, and fractional cover and types. During the past decades, most vegetation indices were derived using visible bands and near-infrared (NIR) spectral region. The main purpose using these vegetation indices is to capture i) the relatively high radiation absorption of red light by leaves due to the presence of chlorophyll and ii) the high reflectance of NIR light due to scattering in the leaf internal structure (Curran, 1980). Jordan (1969) developed the first RVI (Ratio-Based Index), which is the ratio of near infrared (NIR) and red bands. Later, the NDVI was widely used for crop stress detection because of its high correlation with vegetation parameters such as biomass and green leaf area (Curran, 1980). While NDVI seemed promising, soil background and BRDF (Bidirectional Reflectance Difference Factor) limited its application (Huete, 1988). To minimize the impact of soil background, Huete (1988) developed the soil-adjusted vegetation index (SAVI) and Qi et al. (1994) created the Modified Soil Adjusted Vegetation Index (MSAVI). The Atmospherically Resistant Vegetation Index (ARVI) of Kaufman and Tanre (1996) and the Global Environmental Monitoring Index (GEMI) of Pinty and Verstraete (1991) were reported to be less sensitive to the atmosphere. Penuelas et al. (1993 and 1997) developed the Water Band Index (WBI) to quantify water stress on crops. Adams et al. (1999) suggested the Yellowness Index (YI) as a good measure (at leaf level) for chlorosis in stressed plants. In addition, vegetation indices derived from the chlorophyll-centered bands, such as the NPCI = (R680-R430) / (R680+R430), are becoming valuable tools in the evaluation of plant status both in agricultural and natural plant communities (Penuelas et al., 1993).

Comparisons of sensitivities and abilities for stress detection among various vegetation indices were conducted by several researchers. Jackson et al. (1983) did a study on discrimination of growth and water stress in wheat using various vegetation indices. It was found that sensitivity of the various indices to vegetation depended on plant growth stage and atmospheric path radiance. Wanjura and Hatfield (1987) reported that among three commonly used vegetation indices - RVI, NDVI and GVI (Greenness Vegetation Index) - RVI was more sensitive to high levels of biomass and LAI (Leaf

Area Index) but NDVI and GVI were best estimators of LAI and ground cover when crops were at early growth stage. Mickelson et al. (1998) studied the impact of variations in soil texture and moisture on the green vegetation index (GVI) and the NDVI for targets with specific vegetation cover amounts and varying soil backgrounds. They found that GVI values were much less influenced by soil background variation than NDVI. After examining the use of seven types of vegetation indices in field studies, Lawrence and Ripple (1998) found that among the ratio-based vegetation indices, the simple ratio (RVI) and NDVI are best indicators for vegetation cover under conditions of high substrate and vegetation heterogeneity. Thenkabail et al. (2000) examined three types of vegetation indices (NDVI, Optimum Multiple Narrow Band Reflectance (OMNBR), and soil-adjusted vegetation indices such as SAVI. They found that OMNBR had the “over fitting” problem and twelve types of narrow band NDVI were better predicators for crop variables.

All studies above suggest that the performance of vegetation indices was highly associated with crop variables examined, the plant species, the atmospheric condition and optical properties of the soil background. Different vegetation indices should be chosen for specific studies on crop stress detection. However, it is not known whether any band or vegetation index could be used to detect greenbug-induced crop stress. Various vegetation indices from relevant literature were summarized in Table 2-2.

Table 2-2. Various vegetation indices compiled from literature

Vegetation Index	Formula
1. Atmospheric Resistant Vegetation Index, ARVI (Kaufman and Tanre, 1996)	ARVI = (NIR – (2red – blue))/(NIR + (2red – blue))
2. Difference Vegetation Index, DVI (Tucker, 1979)	DVI = NIR-Red
3. Enhanced Vegetation Index, EVI (Verstraete and Pinty, 1996)	EVI = (1+L) (NIR-red)/(NIR+C1*red -C2*blue+L) C1=6.0, C2=7.5, L=1.0
4. Global Environmental Monitoring Index, GEMI (Pinty and Verstraete, 1991)	GEMI = $\eta(1-0.25\eta)$-(red - 0.125)/(1-red)
	$\eta = [2(NIR^2-red^2)+1.5NIR-0.5red] /(NIR+red+0.5)$
5. Leaf Moisture Index, LMI (Parkes, 1997)	LMI = R1650/R830
6. Modified Soil Adjusted Vegetation Index Two, MSAVI2 (Qi et al., 1994)	MSAVI2 = $1/2 * [(2*(NIR+1)) - (((2*NIR)+1)^2 - 8 (NIR-red))^{1/2}]$
7. Optimized Soil Adjusted Vegetation Index, OSAVI (Rondeaux et al., 1996)	OSAVI = ((NIR-red)/(NIR+red+L))*(1+L); L = 0.16
8. Normalized Difference Vegetation Index, NDVI (Rouse et al., 1973)	NDVI = (band1-band2)/(band1+band2)
9. Normalized total Pigment to Chlorophyll Index, NPCI (Riedell and Blackmer, 1999)	NPCI = (R680-R430) / (R680+R430))
10. Ratio Vegetation Index, RVI (Jordan, 1969)	RVI = band1/band2
11. Soil-Adjusted Vegetation Index, SAVI (Huete, 1988)	SAVI = (1+L)* (band1-band2) /(band1+band2+L); L = 0.5
12. Structural Independent Pigment Index, SIPI (Penuelas and Inoue, 1999)	SIPI = (R800-R450)(R800-R680)
13. Specific Leaf Area Vegetation Index, SLAVI (Lymburner et al., 2000)	SLAVI = NIR/ (Red + MIR)
14. Visible Atmospherically Resistant Index, VARI (Gitelson, 2002)	VARI = (green-red)/(green+red-blue)
15. Vegetation Index One, VI1 (Viña, 2002)	VI1 = NIR/green -1
16. Vegetation Index Two, VI2 (Viña, 2002)	VI2 = R800/R694 -1
17. Yellowness Index, YI (Adams et al., 1999)	YI = $(R580 – 2R630+R680)/ \Delta^2$, Δ = 50 nm
18. Water Band Index, WBI (Riedell and Blackmer, 1999)	WBI = R950/R900

2.4 Factors influencing reflectance measurements

2.4.1 Viewing angle

It is well recognized that viewing angle affects on reflectance measurements. Shibayama and Wiegand (1985) studied view azimuth and zenith effects on wheat canopy reflectance. They found that the ratio of off-nadir to nadir radiance increases or decreases as view zenith angle increases depending on view azimuth angle. Ranson et al. (1985) stated that position of the sensor relative to the sun was an important factor for determining the angular reflectance characteristics of crop canopies. Pinter et al. (1987) reported that off-nadir viewing significantly influenced spectral band ratios. Thus, the nadir is a very popular viewing angle selected for reflectance measurements across relevant literatures.

2.4.2 Solar angle

The effect of solar angle on reflectance measurements has been studied for many years. Shibayama and Wiegand (1985) observed that the rate of change in the radiance ratio increased with increasing solar zenith angle. Pinter et al. (1987) found that the NIR/red ratio of winter wheat was significantly influenced by changes in solar angles. They reported that the NIR/red ratio was highest in mid-morning and mid-afternoon, and lowest with the high solar position near midday. Lord (1988) studied the relationships between daily variations in sun angles and red and near infrared reflectance measured throughout a growing season over different types of crop canopies. It was found that for wheat canopies visible reflectance is roughly constant throughout the day and infrared reflectance increases when angle from solar azimuth increases. Therefore, reflectance measurements are often performed near the solar zenith (at noon) to decrease the effects of solar angle on canopy reflectance (Asrar et al., 1985; Ranson et al., 1985; Serrano et al., 2000).

2.4.3 Soil background

It is well known that soil background has big impact on the measurement of canopy reflectance. This is especially evident at early stages of growth because the soil constitutes a large portion of canopy reflectance. Thus, some vegetation indices such as NDVI are sensitive to soil background because ground cover affects red and NIR reflectance. Elvidge and Lyon (1985) found that the NIR and red based indices have pronounced soil background influences at low vegetation cover. Mickelson et al. (1998) reported that GVI (green vegetation index) values were much less influenced by soil background variation than NDVI. Huete et al. (1984 and 1985) found that spectral differences between soils may be closely associated with variations in surface moisture, particle size distribution, soil mineralogy, soil structure, and surface roughness. Different soils may have different impact on canopy reflectance. Dark, low-reflecting soils influence vegetation indices less than high reflecting, light-colored soils (Jackson et al., 1983). Jackson et al. (1983) observed that there were little changes in soil reflectance ratios as soil moisture changed because a change in soil reflectance due to water concentration is about the same in the visible and near-infrared (NIR) regions of the spectrum. This fact shows soil moisture might not have a big effect on some derived vegetation indices.

2.4.4 Atmosphere

Atmosphere is also an important factor for reflectance measurements. Goetz (1992a) found that the incoming solar irradiance could be significantly changed by absorbing molecules in the atmosphere. Among absorbing molecules, water vapor has the biggest impact on the incoming solar spectrum (Gao and Goetz, 1990). Its absorption could extend the solar reflected region of the spectrum and varies both spatially and temporally (Goetz, 1992b). During reflectance measurements, if a reference panel is used and atmospheric conditions are unstable, variability of atmospheric water vapor between the time when the reference panel and target measurements are made may induce significant errors in the resultant spectrum Thus, Gao and Goetz (1992) pointed that it is important to minimize the length of time between the measurement of the reference panel and the target in order to reduce the error due to water vapor variability. Lord et al. (1985a) studied the possibility of using reflectance data collected under both cloudy and sunny conditions. They found that the reflectance measured under cloudy conditions with relatively constant irradiance values was constant and approximately 10% larger than the ones measured at similar sun angles during sunny conditions. This result indicated that it would be better to take all reflectance measurements under the similar cloud conditions to minimize the impact of atmosphere.

2.4.5 Wind

Wind can be a source of error if the material being measured moves during the time the reflectance is measured. Vegetation canopies are especially susceptible to wind induced errors, due to their large proportion of shadow (Analytical Spectral Devices, Inc., 2004). Lord et al. (1985b) did a study was to quantify and minimize the variability from wind on spectral reflectance. They found that within the windy and calm periods, extreme values of spectral reflectance differed by 60% and 12%, respectively, in the red, and by 40% and 8% in the far-red for the barley canopy. The plant canopy architecture, the wind conditions, and the spectral regions all affected the magnitude of the influence of wind on crop canopy spectral reflectance.

2.5 Conclusions

Crop stress, such as nitrogen deficiency, water stress, plant disease, and ozone injury, can be detected using ground-based radiometry techniques at specific wavelengths using vegetation indices such as NDVI. NDVI is the most widely used vegetation index and some new spectral vegetation indices, such as YI, seem more promising in the near future. Different stresses on the same plants have been measured using different wavelengths or spectra. The most sensitive wavelengths used to calculate vegetation indices are crop-dependent. For different crops under the same stress, different wavelengths might be chosen for calculating vegetation indices. Ground-based sensors, such as radiometers, spectroradiometers and IRT, have been widely used to detect crop stress, such as water stress and plant diseases. There are a large number of vegetation indices that were used in crop stress detection. More research needs to be done to test their application for detecting greenbug-induced wheat stress.

Some progress has been made on the detection of greenbug infestation on crops because the spectroradiometer or IRT can be used to detect greenbug infestation with some limitations (Riedell and Blackmer, 1999; Michels et al, 1999). None of these studies, however, can be directly applied to detect greenbug infestation in the field without further testing. Sensitive band and vegetation indices to greenbug infestation at canopy levels need to be identified. Also, those sensitive bands and vegetation indices must have the capabilities to differentiate greenbug infestation with water stress and infestation by Russian wheat aphid. In addition, sensitivities of sensitive band and vegetation indices at different growth stages have to be examined.

It is noted that very few stress studies involved continuous monitoring of canopy reflectance of plants under different stresses. Thus, it is difficult to identify the onset time at which there is significant difference in band reflectance/vegetation indices between stressed and control plants. However, this onset time is very necessary and important to determine the time to initiate greenbug control measures such as the use of pesticides. Continuous monitoring of canopy reflectance of wheat under greenbug infestation might help to provide sufficient information for decision-making.

In addition, since many factors such as viewing angle, soil and cloud cover have impacts on reflectance measurements, these factors have to be taken into consideration when designing and conducting reflectance measurements.

CHAPTER 3

Materials and Methods

The main purpose of this chapter is to introduce materials and methods of research and experiments used in this study.

3.1 Experiment facilities and materials

The greenhouse experiments were conducted using USDA Agricultural Research Service facilities in Stillwater, Oklahoma (Longitude 97 ^{o} 5 ′, Latitude 36 ^{o} 8 ′). The experiment facilities used for this study are shown in Fig 3-1. They include (a) The greenhouse; (b) Sensors of Cropscan radiometer (Cropscan Inc., Rochester, MN, USA); (c) Data logger of Cropscan radiometer; (d) Hand terminal of Cropscan radiometer; (e) HOBO temperature and humidity sensor (MicroDAQ.com, Ltd., Warner, NH, USA); (f) Watchdog soil moisture sensor (Spectrum Technologies, Inc, Plainfield, IL, USA); (g) CR-10 weather station (Campbell Scientific, Inc., Logan, UT, USA); and (h) Artificial Lamp. Cropscan MSR-16 multi-spectral radiometer system was used in this study. It consists of a radiometer, DLC or A/D converter, terminal, telescoping support pole, connecting cables and operating software. This radiometer uses silicon or germanium photodiodes as light transducers and filters of wavelengths from 450 up to 1720 nm are available (Cropscan Inc., 2004). The Cropscan radiometer used in this study has sixteen bands that include five bands simulating Landsat TM bands and eleven narrow bands Band distribution of a Cropscan radiometer is shown in Table 3-1. The field of view for

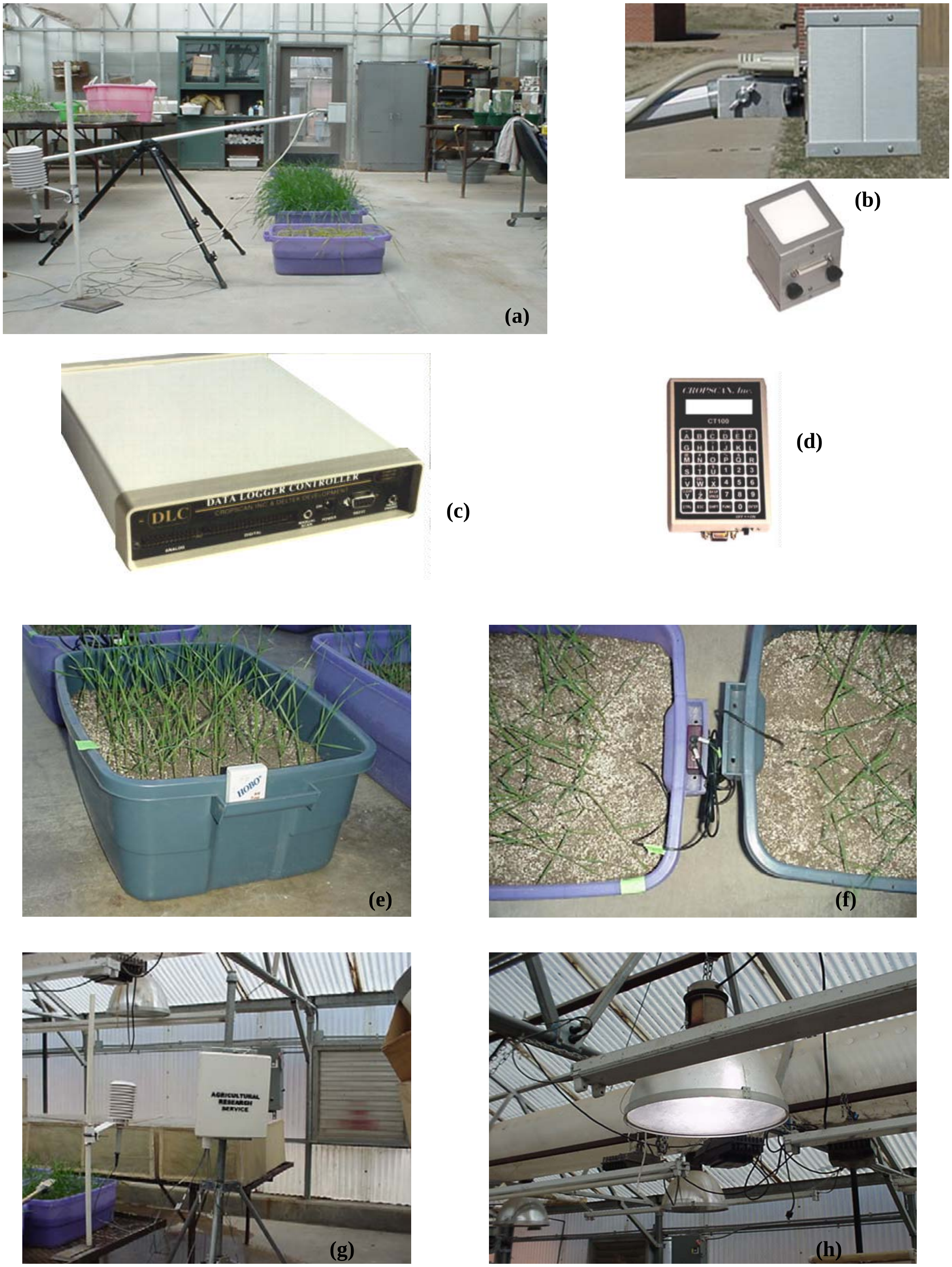


Fig 3-1. Experiment facilities-(a). Greenhouse; (b). Sensor head; (c). Data Logger (DLC); (d). Hand terminal; (e). HOBO temperature and humidity sensor; (f). Watchdog soil moisture sensor; (g). CR-10 weather station; (h). Artificial Lamp.

this radiometer is 28 ^{o} and thus the diameter of the field of view is one half of the height of the radiometer above the canopy.

Table 3-1. Band distribution of a Cropscan radiometer

Band name	Portion	Narrow (±5 nm)	Broad (>±30 nm)
Visible	Blue	450	485
	Green	580	560
	Red	620	660
		630	
		670	
		680	
		694	
NIR(Near Infrared)		800	830
		900	
		950	
MIR(Middle Infrared)		1480	1650

It is assumed that the irradiance flux density incident on the top of the radiometer (upward facing side) is identical to the flux density incident on the target surface (Cropscan Inc., 2004). The advantage of using a Cropscan radiometer is that it allows for near simultaneous inputs of voltages representing incident as well as reflected irradiation. Thus, measurements of percent reflectance could be conducted during cloudy conditions (cirrus to light stratus) with incident irradiance levels down to approximately 300 watts per square meter.

For the Cropscan radiometer, a data acquisition device-DLC Model 2000 (CROPSCAN, Rochester, MN) equipped with sun angle cosine correction capacity was used to record reflectance data from the canopy at 16 pass bands. During operation, the photodiodes output current and this electrical current was converted to a voltage and amplified by the circuitry in the radiometer (Cropscan Inc., 2004). The Data Logger

Controller measured and logged these sensor millivolt readings. Data of percent reflectance at each pass band were processed subsequently by a computer program using the calibration and correction constants through a minicomputer connected to the sensor. The sensor head was mounted on an adjustable pole. At each sampling, three measurements were taken within each flat and averaged.

3.2 Experiment methods

3.2.1 General methods

Flat-grown wheat (variety-TAM 107) was used for all experiments. In each experiment, wheat seeds were planted (seed spacing 1in. x 3 in.) in plastic flats with dimension 24 in. x 16 in. x 8.75 in. containing Redi-earth® plug and seedling Mix (Scott-Sierra Horticultural Products Co., Marysville, OH, USA) and fritted clay (Absorb-N-Dry, Balcones Minerals Corp., Flatonia, TX, USA) as the growth media. All flats were randomly arranged in the greenhouse to minimize shading effects (see Fig 3-2). Fifteen days after sowing, wheat seedlings in flats were applied to different treatments such as infesting with greenbugs (biotype-E). Measurement of canopy reflectance started the day after infestation and lasted until most infested wheat plants were dead. Canopy reflectance was measured once per day from nadir angle (90^o) between 13:00 and 14:00 hours using a Cropscan radiometer with an up-looking and a down-looking sensor. The distance between sensors and canopy was set as 0.5 m to keep the sensed area fully within each flat. After measurements, all raw data were downloaded from Cropscan data logger and preprocessed using two Excel VB scripts (see Appendix A) to calculate vegetation indices. During the experiments, temperature and humidity in the greenhouse were monitored using a Campbell Scientific CR-10 weather station or HOBO sensors. All flats were watered 1-2 times per week and fertilized every two weeks using Peters

Fig 3-2. Experiment layout.

Professional All Purpose Plant Food (Spectrum Group, Division of United Industries Corp., St. Louis, MO, USA). Every three days, ten plants in each flat in which plants were infested were randomly selected and greenbugs per plant were counted and results were averaged to get the greenbug density (greenbugs per plant) for each flat.

3.2.2 Sensitivity experiments

Sensitivity experiments were used to examine which bands/vegetation indices are more sensitive to wheat damage caused by greenbug infestation in order to identify sensitive bands and vegetation indices. The sensitivity experiments involved three treatments: (1) greenbug-infested without pesticide; (2) non-infested with pesticide; (3) control (non-infested without pesticide). The purpose of pesticide treatment was to examine if use of pesticide affects reflectance of wheat canopy. Since Greenbug infestation in one field can quickly spread to neighboring fields (Brooks, 1991), to keep control plants (in this study) free of greenbug infestation, one effective method is to apply pesticides. Thus, pesticides (% granular Marathon) were applied to the soil in which control plants were planted. There were three replications for each treatment. Experiments were repeated three times during three time periods: Jan 16–Mar 12, 2002 (SEex1), Mar16–May 1, 2002 (SEex2) and Nov 11–Dec 24 (SEex3). Here SE stands for sensitivity.

In each experiment, fifteen days after sowing wheat seedlings in three flats were infested with greenbugs (biotype-E) at a density of one per plant. Soil in another three flats was treated with granular Marathon (1%) (Olympic Horticultural Products Co., Mainland, PA, USA) and the remaining three control flats were kept free of greenbugs and pesticide. During the experiments, temperature and humidity in the greenhouse were monitored using a Campbell Scientific CR-10 weather station. All flats were watered 2 times per week and fertilized every two weeks.

3.2.3 Differentiating experiments

The purpose of differentiating experiments was to examine if water stress and greenbug infestation on wheat could be distinguished using reflectance of wheat canopy at sensitive bands and sensitive vegetation indices. The experiments involved four treatments: (1) non-water-stressed but infested (NW+I); (2) water-stressed but non-infested (W+NI); (3) control (non-infested and non-water-stressed) (NW+NI). (4) infested and water-stressed (W+I). There were three replications for each treatment. Experiments were repeated three times during three time periods: Nov 5–Dec 8, 2002

(DIex1), Mar17–Apr 13, 2003 (Diex2) and Nov11– Dec 24, 2003 (Diex3). Here DI stands for differentiating.

In each experiment, fifteen days after sowing, wheat seedlings in six flats were infested with greenbugs (biotype-E) at a density of one per plant. Among these six flats, plants in three flats were chosen for water stress treatment. To keep non-infested plants getting infested by greenbugs, granular Marathon (1%) was applied to soil in all other flats. Water stress treatment was applied to plants in six flats as below: withholding water until most plants show water stress symptoms such as leaf wilting, curling and rolling. Non-water stressed plants were watered once a week. During the experiments, temperature and humidity in the greenhouse were monitored using a HOBO sensor. Soil moisture was monitored using four Spectrum Watchdog sensors. All flats were fertilized every two or three weeks using Peters Professional All Purpose Plant Food.

3.2.4 Growth stage experiment

The purpose of growth stage experiment was to test the impact of plant growth stage on detection of greenbug infestation. The growth stage experiment involved four treatments: (1) greenbug-infested at two-leaf stage; (2) greenbug-infested at tillering stage; (3) control (non-infested) at two-leaf stage. (3) control (non-infested) at tillering stage. It means that infestation was applied to plants at two growth stages: two-leaf and tillering. There were three replications for each treatment. This experiment was conducted during Jan 18 – Feb 26, 2003. This experiment was labeled as STex (ST stands for stage).

On Dec 18, 2002, wheat seeds were planted (seed spacing 1in. x 3 in.) in six-plastic flats with dimension 24 in. x 16 in. x 8.75 in containing planting seedling mixture as the growth media. On Jan 2, 2002, wheat seeds were planted in other six flats in the same way. All flats were randomly arranged in the greenhouse to minimize shading effects. In this way, by the middle of January 2003 earlier-planted wheat plants reached tillering stage and late-planting wheat plants reached two-leaf state. On Jan 18, 2003 wheat plants in six flats (three from tillering groups and three from two-leaf group) were infested with greenbugs (biotype-E) at a density of one per plant. Soil in remaining six flats was treated with granular marathon (1%) to keep free of greenbugs. During the experiment, temperature and humidity in the greenhouse were monitored using a HOBO sensor.

3.2.5 Comparing experiment

Comparing experiment was used to compare greenbug infestation and infestation induced by Russian wheat aphid. This experiment involved three treatments: (1) greenbug-infested; (2) Russian wheat aphid -infested; (3) control (non-infested). There were three replications for each treatment. This experiment was conducted during Oct 30 – Nov 20, 2003. This experiment was labeled as GRex. Here GR stands for greenbug and Russian wheat aphid.

In this experiment, wheat seeds were planted (seed spacing 1in. x 3 in.) in nine-metal flats with dimension 24 in. x 16 in. x 4.75 in containing Redi-earth® plug and seedling mix as the growth media. Nine flats were randomly arranged in the greenhouse to minimize shading effects. Fifteen days after sowing, wheat seedlings in three flats were infested with greenbugs (biotype-E) and wheat seedlings in other three flats were infested with Russian wheat aphids at a density of four aphids per plant. Soil in left three flats was treated with granular marathon (1%) to keep them free of aphids. During the experiment, temperature and humidity in the greenhouse were monitored using a HOBO sensor. All flats were watered once a week and fertilized using Peters Professional All Purpose Plant Food every two weeks. Every three days, ten plants in each flat were randomly selected and aphids per plant were counted and results were averaged to get the aphid density (aphids per plant) for each flat. All experiments used for this study were summarized in Table 3-2.

Table 3-2. Experiments conducted in this study

Experiment Name	Denotation	Purpose	Time Periods
Sensitivity experiment 1	SEex1	Test sensitivities of bands	Jan16–Mar 12, 2002
Sensitivity experiment 2	SEex2	and vegetation indices	Mar16–May 1, 2002
Sensitivity experiment 3	SEex3		Nov 11–Dec 24, 2003
Differentiating experiment 1	DIex1	Differentiate greenbug infestation	Nov 5–Dec 8, 2002
Differentiating experiment 2	DIex2	and water stress	Mar17–Apr 13, 2003
Differentiating experiment 3	DIex3		Nov 11–Dec 24, 2003
Growth stage experiment	STex	Test impact of growth stage	Jan 18–Feb 26, 2003
Comparing experiment	GRex	Compare greenbug infestation and infestation by Russian wheat aphid	Oct 30–Nov 20, 2003

3.3 Data processing and analysis

3.3.1 Selection of SAS programs

All reflectance measurements are repeated measures because of daily-based reflectance measurements on the same subject in each experiment. Thus, the data of reflectance measurements and vegetation indices were processed and analyzed using relevant models in statistical software SAS in order to account for within-subject co-variability. The SAS procedures PROC MIXED and PROC GLM (General Linear Model) (SAS Institute, 1990) are frequently used for repeated measures. “PROC GLM was designed to fit fixed effect models and later amended to fit some random effect models by including RANDOM statement with TEST option”. “The PROC MIXED was specifically designed to fit mixed effect models. It can model random and mixed effect data, repeated measures, spacial data, data with heterogeneous variances and autocorrelated observations" (University of Kentucky, 2001). PROC MIXED allows many covariance structures that are particularly useful in repeated measures and random effect models but in PROC GLM all computations are done under the assumption that there is only one variance component in the model, the error term (University of Kentucky, 2001). In addition, PROC GLM requires balance data (i.e. there are no missing data and all treatments have equal sample sizes) but PROC MIXED handles missing data and applies multiple comparison procedures to both between and within-subjects factors (Little, et al., 1996, William et al., 1997). Considering advantages of PROC MIXED and the possibility of experiment data possessing variety of variance components, PROC MIXED was used for statistical analysis in this study (see Appendix B).

3.3.2 Threshold Day and Maximum Day

In the statistical analysis of this study, the selection of covariance structure for each band and vegetation index was based on the comparisons of absolute AIC (Akaike Information Criteria) values of several covariance structures, such as autoregressive, compound symmetry and toeplitz, from SAS outputs (See examples in Appendix C). The covariance structure with the least (absolute) AIC value was selected for further analysis. In SAS Program, the REPEATED statement was used to address the data dependency problem and to specify the covariance structure. The SLICE option was chosen to test the significance level of interaction between treatment and time. The analysis of this interaction allowed us to examine the treatment effect for each time and to observe how differences among different treatments develop with time. By checking the p values shown in outputs of SAS PROC MIXED, the Threshold Day (time) - the initial day subsequent to which there was always a significant difference among the treatments – was determined.

For convenience, the Maximum Day is defined as the day at which greenbug density on infested plants reaches maximum. They were determined from temporal data in greenbug density. Based on comparisons between the Threshold Days determined from SAS outputs (see examples in Appendix C) and the Maximum Day, all bands and vegetation indices were initially divided into two groups: sensitive and non-sensitive. A band or vegetation index was considered sensitive if its Threshold Day was not larger than Maximum Day.

3.3.3 Correlation analysis

This step is the analysis of correlation between the greenbug density (until Maximum Day) and differences in reflectance or vegetation indices between infested plants and control plants. Correlation is a statistical technique which can show whether and how strongly pairs of variables are related (Watt, 1993). The purpose of the correlation analysis is to test if differences in reflectance or vegetation indices between infested plants and control plants were caused by greenbug infestation. Two main methods of calculating correlations are Spearman's Rank Correlation Coefficient and Pearson's Correlation Coefficient**.** The most commonly used measure for linear relationship between two variables is the Pearson correlation coefficient. The values of the coefficient can range from -1 to +1. If there is no linear relationship between two variables, the value of the coefficient is 0. If there is a perfect positive relationship, the value is +1. If there is a perfect negative relationship, the value is -1. However, Pearson correlation is a measure of the strength of a relationship between two variables and any relationship should be assessed for its significance as well as its strength. So the significance of correlation coefficients has to be tested before any further interpretation. The simple method to test significance is to apply Student's t-test using the following formula: t = $\frac{r \times \sqrt{N-2}}{\sqrt{1-r^2}}$, where N is the number of samples, in which the null hypothesis is the product moment correlation coefficient is zero and r is correlation coefficient.

In this study, Pearson's correlation coefficients were calculated for the correlation analysis and their significances were tested based on N value (the number of pairs) and significance level. Then absolute values of correlation coefficients for different bands/vegetation indices were compared to see which band/vegetation index is more sensitive to greenbug infestation.

3.3.4 Relative Sensitivity analysis

After correlation analysis, the relative sensitivities of the bands and vegetation indices in the sensitive group were compared. Sensitivity analysis is used to measure the extent the wheat canopy spectrally responds to greenbug infestation. Sensitivity indicates the wavelengths or vegetation indices at which a linear response detector or sensor would most likely detect a response to plant stress (Cibula and Carter, 1992). The purpose of sensitivity analysis is to identify which band or vegetation index could best capture spectral signature of greenbug-induced wheat stress. Relative Sensitivity at a given wavelength or band was computed using the following formula (Carter, 1993)

$$\text{Sensitivity}_{\text{band}} = (\text{Ref}_{\text{inf}} - \text{Ref}_{\text{ctrl}})*100 / \text{Ref}_{\text{ctrl}} \text{, where}$$

Sensitivity $_{band}$ – Sensitivity for a given band or wavelength;

Ref $_{inf}$ – Canopy reflectance of infested plants;

Ref $_{ctrl}$ – Canopy reflectance of control plants.

Similarly, sensitivity for a given vegetation index was calculated using the following formula:

Sensitivity $_{VI}$ = (VI $_{inf}$ – VI $_{ctrl}$) *100 / VI $_{ctrl,}$ where

Sensitivity $_{VI}$ – Sensitivity for each vegetation index;

VI $_{inf}$ – Vegetation index of infested plants;

VI $_{ctrl}$ – Vegetation index of control plants.

The comparisons of relative sensitivities are based on the absolute values of differences in reflectance or vegetation index between greenbug-infested and control plants. The higher the absolute value of difference, the higher the sensitivity of each band or vegetation index. The band or vegetation index that has highest absolute difference between infested and control plants is defined as the most sensitive band or vegetation index.

3.3.5 Testing impact of growth stages and differentiating various stresses

As mentioned before, it is necessary to examine the impact of plant growth stage on detection. This was done through two steps. First, for each stage, sensitive bands and vegetation indices were determined using the same procedures mentioned above. Next, their Threshold Days, correlation coefficients and relative sensitivities for two stages were compared to see if greenbug infestation at different growth stages could be detected using the same sensitive bands and vegetation indices.

Since greenbug outbreaks often appear at times when the wheat crop is under water stress, it is necessary to check if sensitive band and vegetation indices identified by above-mentioned procedures could be used to differentiate greenbug infestation with water stress. Thus, the next step is to examine the sensitivities of bands and vegetation indices to differences between greenbug infestation and water stress. In this step, the Threshold Days for differences between plants under greenbug infestation and water stress were also compared to Maximum Day mentioned before. A band or vegetation index was considered sensitive to differences between greenbug infestation and water stress if its Threshold Day for differences between plants under greenbug infestation and water stress was not larger than Maximum Day. The same procedures were used to compare infestation by Russian wheat aphid with greenbug infestation.

Finally, sensitive band and vegetation indices were determined by summarizing all results above. A band or vegetation index was determined as sensitive if it is not only sensitive to greenbug infestation at different stages but also could be used to differentiate greenbug infestation with water stress and to distinguish greenbug infestation and infestation caused by RWA.

CHAPTER 4

Results and Discussions

The main purpose of this chapter is to introduce results obtained from experiments in this study and discussions on results. Band and vegetation indices that are more sensitive to greenbug infestation were identified and the impact of stage and other stresses such as water stress on their sensitivities were examined and tested.

4.1 Bands and vegetation indices sensitive to greenbug infestation

4.1.1 Impact of pesticides on reflectance of wheat plants

To keep control plants (in this study) free of greenbug infestation, pesticides (% granular Marathon) were applied to the soil in which control plants were planted. Therefore, it is necessary to examine the effect of the pesticide (% granular Marathon) on reflectance of wheat plants at each band before proceeding to further experiments and analysis. Data from the first experiment SEex1 were analyzed using PROC MIXED to test reflectance difference at each band between control and pesticide-treated plants. Results are listed in Table 4-1.

Results in Table 4-1 demonstrated that there was no significant reflectance difference between control and pesticide-treated plants in any of 16 bands of Cropscan radiometer. Thus the use of 1 % granular Marathon on wheat plants does not cause significant impact on reflectance of wheat plants in any bands of Cropscan radiometer.

Therefore, pesticide-treated (by 1 % granular Marathon) wheat plants in this study can be treated as control plants in further experiments and analysis.

Table 4-1. Threshold Days for differences between control and pesticide-treated plants

	95% confidence	99% confidence
BAND1480	no	no
BAND1650	no	no
BAND450	no	no
BAND485	no	no
BAND560	no	no
BAND580	no	no
BAND620	no	no
BAND630	no	no
BAND660	no	no
BAND670	no	no
BAND680	no	no
BAND694	no	no
BAND800	no	no
BAND830	no	no
BAND900	no	no
BAND950	no	no

no: there is no Threshold Day.

4.1.2 Temporal changes in greenbug density

Data for three sensitivity experiments: SEex1, SEex2, SEex3 were analyzed below. Figure 4-1 shows the photos of plants under three treatments in experiment SEex1. It can be seen that at the end of experiment SEex1, infested plants had severe damage but control plants and pesticide-treated plants looked healthy. All leaves of infested plants turned yellow and wilted but leaves of control and pesticide-treated plants were still green and spread at the end of the experiment. In addition, no significant difference has

a. Control b. Infested c. Pesticide-treated

Fig 4-1. Photographs showing different treatment effects at the end of sensitivity experiment (SEex1).

been observed from photos. Figure 4-2 shows densities of greenbug over time during the three experiments. As shown in the figure, greenbug densities of 85, 251 and 297/per plant were observed at 33, 21 and 33 days respectively for each experiment.

Based on Figure 4-2, greenbug densities had similar developmental patterns in the three experiments. Greenbug population increased with time at the early stage of greenbug infestation. When damage on infested plants became serious and these plants began to die, the greenbug population declined, mostly due to the shortage of food.

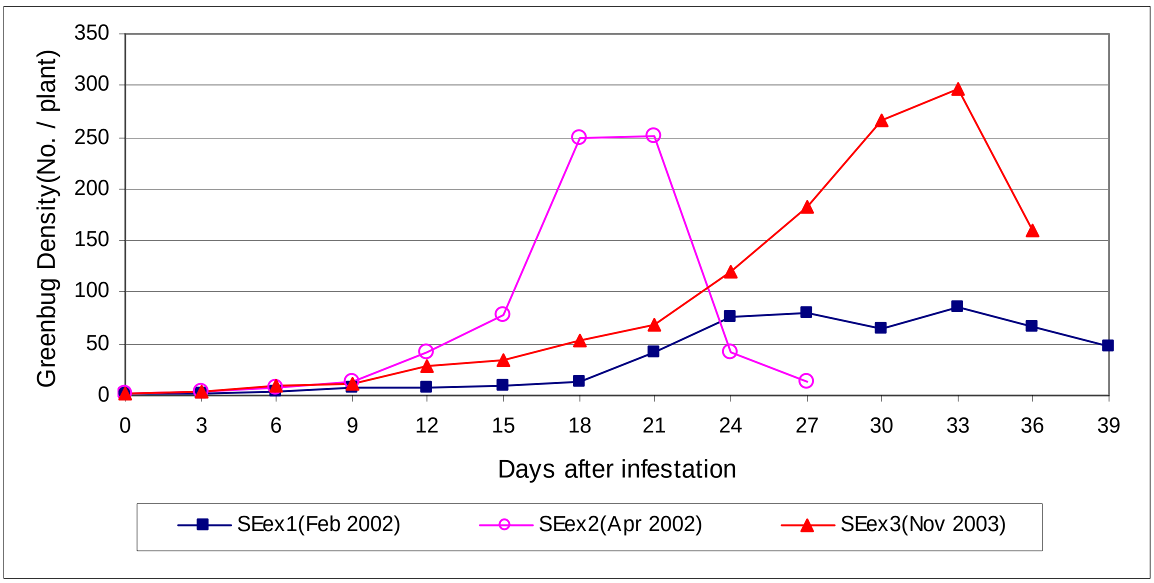


Fig 4-2. Densities of greenbug over time for three sensitivity experiments.

However, the number of greenbugs increased and decreased more quickly in the SEex2 than in other experiments. This could most likely be due to the fact that the three experiments were conducted at different temperatures. The average daily temperatures over time during three experiments are shown in Figure 4-3. The average daily temperature over the experiment period was 12.9-21.6 ^{o}C for SEex1, 15.0-24.6 ^{o}C for the

SEex2 and 14.3-23.6 ^{o}C for SEex3. Mostly, the average daily temperatures were higher for SEex2 than other experiments. Previous studies have shown that the growth of greenbug populations is very sensitive to temperature (Kindler et al, 2001; Walgenbach et al, 1988). Thus, higher temperatures in SEex2 increased the greenbug populations more quickly, thereby causing more rapid damage to wheat plants in SEex2 than in other experiments. When the growth of infested plants was seriously limited, food availability for greenbugs also decreased quickly. Consequently, the greenbug population decreased more quickly in SEex2 than in other experiments.

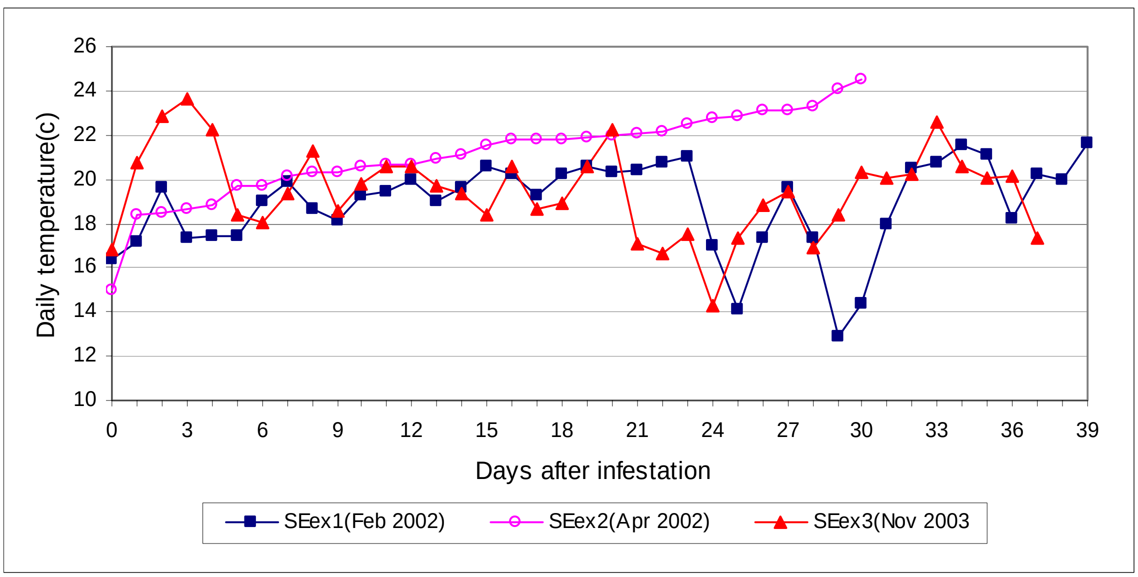


Fig 4-3. Average daily temperatures (^{o}C) over time for three sensitivity experiments.

4.1.3 Band sensitivity to greenbug infestation

Figure 4-4 shows the Threshold Days for 16 bands estimated from outputs of PROC MIXED. As mentioned before, the Threshold Day is the starting day subsequent to which there were always significant differences among treatments (at significance level=0.05).

For example, for band 450 nm, a Threshold Day of 39 (SEex1) means that the 39th day is the initial day subsequent to which there was always a significant difference in reflectance among differently-treated plants. Based on section 4.1.1, there were no significant differences in reflectance between control and pesticide-treated plants at any band. Thus, the Threshold Day in Figure 4-4 was the Threshold Day subsequent to which there were significant differences of reflectance between control and infested plants. The Threshold Day identifies the initiation of significant difference in reflectance between control and infested plants. From Figure 4-4, it can be seen that for all bands Threshold Days were smaller for the experiment SEex2 than the experiment SEex1 and SEex3. It

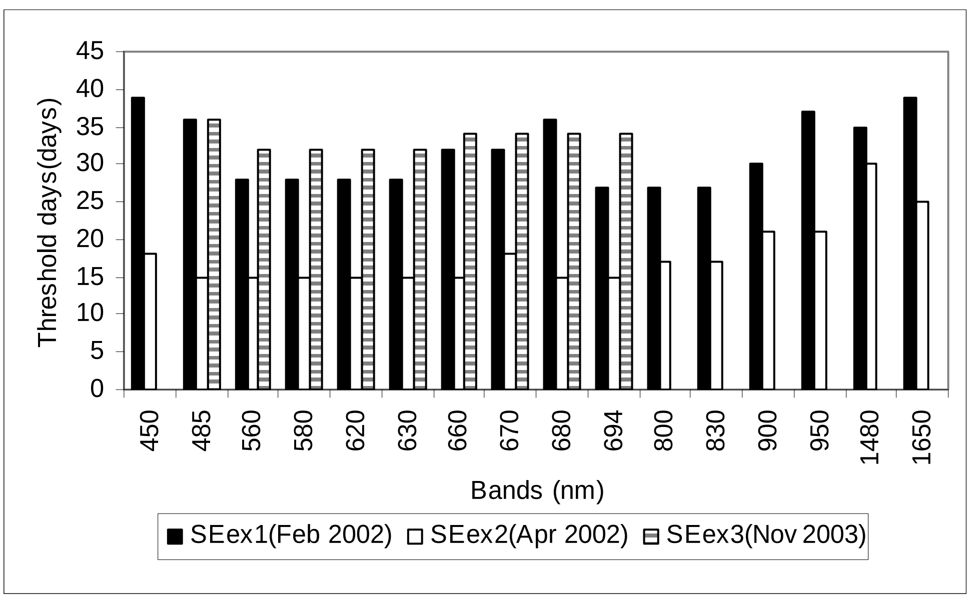


Fig 4-4. Threshold Days of bands for three sensitivity experiments.

means that infested plants and control plants showed statistically significant differences later for the experiment SEex1 and SEex3 than the experiment SEex2. This difference was likely to be caused by different environmental conditions such as different temperatures. As mentioned before, average daily temperatures were higher for SEex2 than other experiments and it caused the greenbug populations to develop more quickly for SEex2 than other experiments. Thus, the faster growth of the greenbug population caused more serious damage to plants in SEex2 than in other experiments. This could possibly explain why differences in reflectance between infested plants and control plants could be detected earlier for SEex2 than SEex1 and SEex3. In addition, the differences among the three experiments might be caused by other factors such as different sun light conditions in the three experiments because these three experiments were conducted in different seasons. It is evident that the day length is longer for SEex2 (April) than SEex1 (February) and SEex3 (November). Macedo et al. (2003) studied the impact of light on feeding damage caused Russian wheat aphid, *Diuraphis noxia* (Mordvilko). It was found that the development of *D. noxia* feeding damage symptoms (i.e., leaf rolling and chlorotic streaks) on wheat seedlings is a light-activated process. There is no study involving the impact of light on greenbug feeding damage on wheat. But it is possible that light has similar impact on greenbug feeding damage because these two aphids (GB and RWA) belong to the same group of aphids (Brooks, 1991) and cause similar damage symptoms on crops: canopy chlorosis and necrosis. Thus, longer day length could contribute more to reproduction of greenbugs for SEex2 than SEex1 and SEex3. Therefore, more feeding damage occurred to SEex2 than SEex1 and SEex3.

There were some consistent results from the three experiments. Based on Fig 4-4, most visible bands were more sensitive to greenbug infestation than the near infrared and middle infrared bands because they have smaller Threshold Days. For example, band 580 nm were more sensitive to greenbug infestation than band 900 nm and 1480 nm in three sensitivity experiments. This may be due to leaf chlorosis that is a typical damage caused by greenbug feeding (Dorschner et al., 1987). Thus, changes in canopy reflectance of wheat plants were larger for visible bands than near infrared and middle infrared bands.

For effective detection of greenbug-induced stress on wheat plants, a sensitive band should not have its Threshold Day later than Maximum Day, the day at which greenbug population reaches maximum. According to Fig 4-2, Maximum Days for three sensitivity experiments were 33, 21 and 33 days respectively for each experiment. Based on comparison between Threshold Days and correspondent Maximum Days, band 560, 580, 620, 630, 660, 670, 680, 694, 800, 830 nm were initially identified as sensitive to greenbug infestation because their Threshold Days were earlier than that of the day greenbug densities peaked. The reflectance of these seven bands was subjected to sensitivity analysis and correlation analysis mentioned in the methods section. The results are shown in Table 4-2.

Table 4-2. Band sensitivities and correlation coefficients

Band (nm)	Correlation coefficient			Difference (%)#			
	SEex1^	SEex2	SEex3	SEex1	SEex2	SEex3	Average
BAND560	0.7924*	0.9647*	0.9211*	20.29	36.49	31.68	29.49
BAND580	0.7104*	0.9632*	0.9310*	20.12	46.35	39.8	35.42
BAND620	0.6785*	0.9122*	0.8800*	21.76	67.42	28.76	39.31
BAND630	0.7318*	0.9459*	0.8877*	23.88	66.43	34.30	41.54
BAND660	0.7701*	0.9039*	0.8741*	20.56	62.59	28.71	37.29
BAND670	0.6924*	0.9592*	0.9066*	17.65	55.09	32.29	35.01
BAND680	0.7804*	0.9480*	0.8373*	20.42	66.92	17.34	34.89
BAND694	0.8288*	0.9093*	0.8992*	22.85	73.79	30.31	42.32
BAND800	-0.7271*	-0.9255*	0.1552^{Δ}	-6.32	-19.59	-12.47	-12.79
BAND830	-0.7099*	-0.9313*	0.2272^{Δ}	-5.27	-17.07	-9.49	-10.61

^ Average value for three replicates
# Differences in reflectance between control and infested plants at Maximum Day
$^{\Delta}$ Not significant
* Significant at the 0.05 level (Critical value=0.602 when n=11; Critical value=0.754 when n=7).
SEex1: Feb 2002, SEex2: Apr 2002, SEex3: Nov 2003

Based on Table 4-2, except the band 800 and 830 nm, for all initially selected sensitive bands the reflectance differences between infested and control plants were significantly correlated with the greenbug density in the three experiments. Thus, the band 560, 580, 620, 630, 660, 670, 680 and 694 nm were identified as sensitive bands for detecting greenbug infestation. It is noted that these bands are all visible bands, predominantly in the green and red portion. Carter (1993) found that there is an evident increase in visible reflectance as a response to stress among the various stress agents and species. Results from this study further validate Carter's findings. Among these sensitive bands, the band 694 and 630 nm were more sensitive to greenbug infestation because there were larger differences (42.32% and 41.54% respectively)in reflectance between infested and control plants. Similar results were obtained by Riedell and Blackmer (1999), who found that reflectance at wavelengths ranging 625-635 and 680-696 nm were most sensitive to greenbug infestation. Horler et al. (1983) also reported that plant stress changed the absorption maximum of chlorophyll in the visible band and the near-infrared shoulder of the red-edge. Additionally, the Landsat TM band - 560 nm (Green band) and 660 nm (Red band) also displayed higher sensitivity to greenbug infestation in three experiments. This result shows high potential for detecting greenbug-induced stress on wheat plants using Landsat TM images.

4.1.4 Vegetation indices sensitive to greenbug infestation

The spectral data collected were further analyzed to identify sensitive vegetation indices using SAS. First of all, a total of 114 vegetation indices including NDVI, RVI, SAVI and LMI (Leaf Moisture Index) were calculated using different band combinations.

Table 4-3. Threshold Days of NDVI, RVI, and SAVI for three sensitivity experiments

Band Combination		NDVI			RVI			SAVI		
		SEex1	SEex2	SEex3	SEex1	SEex2	SEex3	SEex1	SEex2	SEex3
	1480 , 450	no	25	no	no	30	no	38	25	35
	1480 , 580	no	27	no	no	30	no	no	30	no
	1480 , 620	no	29	36	no	no	no	no	30	no
Middle	1480 , 630	no	29	36	no	no	36	no	30	no
Infrared,	1480 , 670	no	29	36	no	no	no	no	30	no
Visible	1480 , 680	no	29	36	no	no	36	no	30	no
And	1480 , 694	no	30	35	no	no	36	no	30	36
Near	1650 , 485	36	no	no	39	no	no	no	29	no
Infrared	1650 , 560	27	no	30	28	no	no	no	29	no
	1650 , 660	27	20	30	25	18	no	37	no	no
	1650 , 830^	26	18	35	32	18	no	26	18	no
Visible,	560 , 485	no	25	no	34	25	no	28	no	28
Visible	660 , 485	34	17	30	34	17	31	27	17	32
	660 , 560	38	20	34	38	20	34	no	21	34
	800 , 450	32	14	34	26	14	34	25	14	no
	800 , 580	26	14	28	31	no	no	25	13	no
	800 , 620	26	13	31	23	13	30	25	13	no
	800 , 630	25	10	30	23	13	28	25	10	no
	800 , 670	26	14	28	25	14	28	25	14	no
	800 , 680	25	12	33	25	13	30	25	12	no
	800 , 694	25	12	30	23	13	27	25	12	34
	830 , 485	27	15	33	25	14	33	25	14	no
	830 , 560	25	13	31	24	14	30	25	13	no
Near	830 , 660	26	14	30	25	14	30	25	13	no
Infrared,	900 , 450	33	14	36	26	14	34	26	15	no
Visible	900 , 580	26	15	36	25	14	34	25	15	no
	900 , 620	26	13	31	24	13	28	25	13	no
	900 , 630	25	13	30	25	13	28	25	13	no
	900 , 670	26	14	31	25	14	28	25	15	no
	900 , 680	25	13	31	25	13	28	25	13	no
	900 , 694	25	12	28	24	13	28	25	12	no
	950 , 450	33	15	34	26	14	34	25	16	no
	950 , 580	26	15	28	25	15	34	25	15	no
	950 , 620	26	13	30	24	13	28	25	13	no
	950 , 630	25	13	28	25	14	28	25	13	no
	950 , 670	26	13	28	25	14	28	25	15	no
	950 , 680	25	13	31	25	13	28	25	13	no
	950 , 694	25	13	28	23	13	28	25	13	no
Maximum Day		33	21	33						

no: there is no Threshold Day for difference between control and infested plants
Maximum Day: the day at which greenbug density reach maximum
SEex1: Feb 2002, SEex2: Apr 2002, SEex3: Nov 2003
^: Here RVI=R1650/R830 is equal to LMI= R1650/R830

These vegetation indices were subjected to PROC MIXED, and the results are tabulated in Table 4-3 for NDVI, RVI and SAVI. Compared to the reflectance of a single band, most vegetation indices have smaller Threshold Days and thus showed higher sensitivities to greenbug infestation. This is mainly because vegetation indices reduce the multiplicative noise (illumination differences, cloud shadows, atmospheric attenuation) present in multiple bands (Huete, 1998). Results obtained from this study further validated the importance of vegetation indices.

According to Table 4-3, almost all vegetation indices derived from the band 1480 nm and 1650 nm in all experiments, and most SAVI in experiment SEex3 were not sensitive to greenbug infestation because either they did not have Threshold Days or their Threshold Days were larger than Maximum Days and also close to the end of experiments. Differences between NDVI and their corresponding RVI were small because there are no substantial differences in their Threshold Days for three sensitivity experiments.

Based on the comparison between Threshold Days and the Maximum Days in each experiment, sensitive vegetation indices in the sensitive group were initially identified. These sensitive vegetation indices were then subjected to the sensitivity and correlation analysis between greenbug density and differences in vegetation indices between infested plants and control plants. Due to the large number of vegetation indices examined in this step, Table 4-4 only displays the results for vegetation indices whose differences in control and infested plants showed significant correlation with greenbug density. As can be seen, the negative correlation indicates inverse relationship between vegetation indices and greenbug densities. Interestingly, most sensitive vegetation indices were simple ratio-

Table 4-4. Sensitivities and correlation coefficients for NDVI, RVI and SAVI

vegetation indices	correlation coefficient[Δ,*]			%difference#			
	SEex1	SEex2	SEex3	SEex1	SEex2	SEex3	Average
NDVI_830_560	-0.7208	-0.9471	-0.8929	-8.01	-24.41	-19.27	-17.23
RVI_800_450	-0.8293	-0.9306	-0.794	-11.31	-40.2	-9.94	-20.48
RVI_800_620	-0.7761	-0.96	-0.9511	-14.05	-51.8	-31.9	-32.58
RVI_800_630	-0.8089	-0.977	-0.9421	-14.59	-51.58	-34.74	-33.64
RVI_800_670	-0.7849	-0.9615	-0.9413	-13.3	-47.88	-33.61	-31.60
RVI_800_680	-0.8371	-0.9652	-0.9176	-15.24	-51.49	-25.3	-30.68
RVI_800_694	-0.8536	-0.9404	-0.9547	-17.76	-53.52	-32.74	-34.67
RVI_830_485	-0.7524	-0.9698	-0.8961	-9.37	-41.35	-15.79	-22.17
RVI_830_560	-0.8109	-0.9635	-0.9419	-13.64	-39.17	-31.32	-28.04
RVI_830_660	-0.8492	-0.9326	-0.9458	-14.4	-48.76	-29.69	-30.95
RVI_900_450	-0.8033	-0.9382	-0.7377	-9.11	-35.03	-12.6	-18.91
RVI_900_580	-0.7937	-0.9524	-0.8129	-11.51	-40.18	-39.12	-30.27
RVI_900_620	-0.7682	-0.9626	-0.8655	-11.93	-47.64	-33.82	-31.13
RVI_900_630	-0.8092	-0.9808	-0.8496	-12.49	-47.4	-36.58	-32.16
RVI_900_670	-0.7798	-0.9649	-0.8616	-11.16	-43.39	-35.53	-30.03
RVI_900_680	-0.8421	-0.967	-0.8438	-13.13	-47.31	-27.45	-29.30
RVI_900_694	-0.8626	-0.9417	-0.883	-15.72	-49.51	-34.71	-33.31
RVI_950_450	-0.8123	-0.921	-0.8099	-8.85	-32.86	-9.59	-17.10
RVI_950_580	-0.8029	-0.9393	-0.8136	-11.26	-38.18	-37.03	-28.82
RVI_950_620	-0.7802	-0.9599	-0.915	-11.67	-45.9	-31.61	-29.73
RVI_950_630	-0.8196	-0.9775	-0.892	-12.23	-45.64	-34.47	-30.78
RVI_950_670	-0.7953	-0.9612	-0.885	-10.89	-41.51	-33.31	-28.57
RVI_950_680	-0.8557	-0.9643	-0.8956	-12.88	-45.56	-24.99	-27.81
RVI_950_694	-0.8715	-0.9345	-0.9287	-15.48	-47.83	-32.53	-31.95

[#] Differences in reflectance between control and infested plants on the day when greenbug density reached maximum.
[Δ] Correlation between greenbug density and difference in reflectance between infested and control plants.
* Significant at 0.05 probability level.
SEex1: Feb 2002, SEex2: Apr 2002, SEex3: Nov 2003

-based indices, and most NDVI or SAVI did not show higher sensitivities. This is possibly because the ratio of red and NIR reflectance is theoretically a good discriminator of vegetation (Jackson et al., 1983). Also most indices were derived from the bands at the red edge such as 680 and 694 nm. Among those sensitive vegetation indices, RVI_800_694 was the most sensitive vegetation index because it showed the largest difference (average difference between control and infested plants is 34.67%) when greenbug density reached a maximum for all three experiments. These results further demonstrate that greenbug infestation is closely related to chlorophyll loss in wheat plants because band 694 and 680 are all active chlorophyll absorption bands, and chlorophyll concentration is usually an indicator of photosynthetic capacity and plant growth stage.

In addition, besides NDVI, RVI, SAVI and LMI, 14 remaining vegetation indices (listed in Table 2-2) were also analyzed using PROC MIXED. They include EVI (Enhanced Vegetation Index), ARVI (Atmospheric Resistant Vegetation Index), SLAVI (Specific Leaf Area Vegetation Index), GEMI (Global Environmental Monitoring Index), MSAVI2 (Modified Soil Adjusted Vegetation Index Two), OSAVI (Optimized Soil Adjusted Vegetation Index), VARI (Visible Atmospherically Resistant Index), DVI (Difference Vegetation Index), VI1 (Vegetation Index One), VI2 (Vegetation Index Two),YI (Yellowness Index), WBI (Water Band Index), NPCI (Normalized total Pigment to Chlorophyll Index). For convenience, they were called "special vegetation indices" in the further analysis. The statistical analysis results of special vegetation indices are displayed in Fig 4-5.

Based on Figure 4-5, YI, OSAVI, SIPI, SLAVI, VARI and WBI were not sensitive to greenbug infestation. Because either there is no Threshold Days in one of three experiments or one of their Threshold Days was larger than correspondent Maximum Day. Adams et al. (1999) stated that the Yellowness Index (YI) was a good measure of leaf chlorosis in stressed plants. Since his study only involved leaf-level measurements, the contradiction in our study suggests that YI may be sensitive at the leaf level but not at the canopy level.

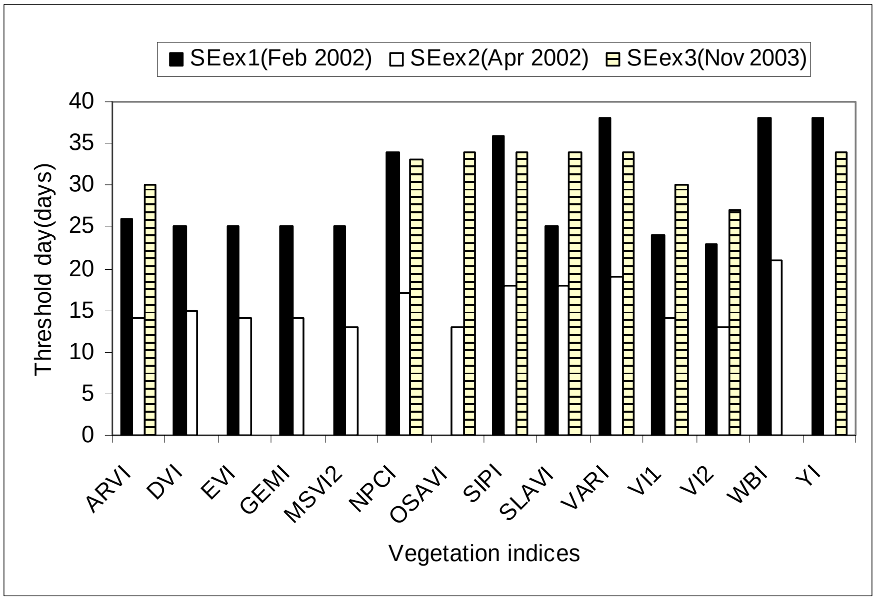


Fig 4-5. Threshold Days of special vegetation indices for three sensitivity experiments.

Table 4-5. Sensitivities of special vegetation indices for sensitivity experiments

Vegetation Indices	Correlation coefficient			Difference (%) #			
	SEex1	SEex2	SEex3	SEex1	SEex2	SEex3	Average
EVI	-0.4520	-0.7591*	-0.4075	-8.28	-34.15	-22.51	-21.65
ARVI	0.1541	-0.7152*	-0.8749*	-9.09	-40.35	-27.87	-25.77
MSAVI2	-0.7377*	-0.9140*	-0.6319*	-5.50	-18.39	-9.09	-10.99
GEMI	-0.6088*	-0.9042*	-0.1881	-4.71	-18.42	-9.56	-10.90
DVI	-0.5799	-0.9140*	-0.1757	-9.14	-33.14	-19.53	-20.61
VI1_830_560	-0.8173*	-0.9544*	-0.9286*	-25.02	-49.02	-39.86	-37.97
VI2_800_694	-0.7424*	-0.9215*	-0.9465*	-27.80	-66.15	-43.74	-45.90
NPCI	0.4765	0.9647*	0.6572*	29.73	82.43	85.65	65.94

Differences in vegetation indices between control and infested plants (3 replicates) at the day in which greenbug density reached maximum.
$^{\Delta}$ Not significant
* Significant at the 0.05 level (critical value= 0.602 when n=11; critical value=0.754 when n=7)
SEex1: Feb 2002, SEex2: Apr 2002, SEex3: Nov 2003

Based on the comparison between Threshold Days and the Maximum Days in each experiment, sensitive special vegetation indices in the sensitive group were initially identified. They are EVI, ARVI, MSAVI2, GEMI, DVI, VI1, VI2, and NPCI. These sensitive vegetation indices were then subjected to the sensitivity and correlation analysis between greenbug density and differences in vegetation indices between infested plants and control plants. Table 4-5 displays their correlation coefficients and differences when plants reached Maximum Days.

Based on Table 4-5, again for most vegetation indices, there were negative relationships between the differences in vegetation indices (between infested and control plants) with greenbug densities. MSAVI2, VI1_830_560 and VI2_800_694 were determined as sensitive vegetation indices. Because in all experiments, the differences in vegetation indices between infested and control plants were significantly correlated with greenbug densities. VI2_800_694 was the most sensitive vegetation index because it showed the largest difference when greenbug density reached a maximum for all three experiments. Again, this result demonstrates that greenbug infestation is closely related to chlorophyll loss in wheat plants because band 694 and 680 are all active chlorophyll absorption bands. Furthermore, vegetation indices derived from broad Landsat TM bands, such as VI1_830_560, show similar sensitivities as VI2_800_694. In addition, according to Table 4-5, there are positive relationships between differences in NPCI and greenbug densities in two experiments but not all experiments. This shows NPCI may not be sensitive to greenbug infestation at canopy level. Riedell and Blackmer (1999) concluded that Normalized total Pigment to Chlorophyll Index (NPCI) was significantly correlated with total chlorophyll concentrations in infested leaves. The discrepancy in our study suggests that NPCI may be sensitive at the leaf level but not at the canopy level.

In general, after 28 days (SEex1), 15 days (SEex2) and 32 days (SEex3) of greenbug infestation, there were statistically significant differences ($p<0.05$) in sensitive band reflectance between infested plants and control plants. Also, after 25 days (SEex1), 13 days (SEex2) and 28 days (SEex3) of infestation, there were marked differences in sensitive vegetation indices between infested plants and control plants. Furthermore, broad Landsat TM bands such as 560 nm (green portion in TM spectrum) and derived vegetation indices also showed higher sensitivities to greenbug infestation on wheat plants. This suggests that satellite images such as Landsat data could be used to detect greenbug-induced wheat stress.

4.1.5 Temporal changes in sensitive bands and vegetation indices

Temporal changes in reflectance of sensitive bands and vegetation indices were displayed in Figure 4-6 to Figure 4-13. It can be seen in Figure 4-6 and Fig 4-7 that for all treatments reflectance increases at early stages and then decreases with time. At Threshold Day, reflectance at 630 and 694 nm on infested plants increases with time. Fig 4-8 to Fig 4-13 show the temporal changes in some sensitive vegetation indices. It can be seen that in general vegetation indices increase with time. At time around Threshold Day, vegetation indices on infested plants decrease with the time. It is noted in all figures, that the difference between infested and control plants in SEex2 occurred earlier than in other experiments. Again, higher temperatures in SEex2 increased the greenbug populations more quickly, thereby causing more rapid damage to wheat plants in SEex2 than in other experiments.

4.1.6 Discussion and Conclusions

Hyper-spectral remote sensing has gone through rapid development over the past two decades and there is a trend toward the use of hyper spectral images in the application of remote sensing for precision farming (McNairn and Deguise, 2001). Findings from this study do not seem to support this trend because vegetation indices derived from narrow bands did not show substantially higher sensitivity to greenbug infestation than those of broad Landsat TM bands as shown in Table 4-3. In theory, spectral resolution describes the ability of a sensor to allow precise identification of a material, class, or feature (Natural Resource Canada, 2003). Thus, it was expected that vegetation indices derived from narrow bands would be more sensitive than vegetation indices derived from broad bands. But there is a trade-off between higher spectral resolution and reduced signal-to-noise ratio (Price, 1994). It is possible that reduced signal-to-noise ratios lower the sensitivities of vegetation indices derived from narrow bands. This could be one reason that vegetation indices derived from narrow bands were not substantially more sensitive than those derived from broad bands. Elvide and Chen (1995) reported that the narrow-band versions of vegetation indices had only slightly better accuracy than their broad-band counterparts in one field spectra study on rooted pinyon pine canopy with five different gravel backgrounds. Results from three sensitivity experiments in this study further supported the finding of Elvide and Chen (1995). Secondly, the lack of higher sensitivities by narrow bands may also be due to the difference between leaf reflectance and canopy reflectance. Most hyperspectral research has been done at a leaf level. Compared to leaf reflectance, canopy reflectance is a weighted composition of several elements such as soil, water and vegetation (Hatfield and Pinter, 1993). It does not only depend on external parameters such as illumination or viewing geometry but also on canopy architecture. It is likely that the spectral response of a canopy under stress is different from that of a leaf. Thus, one vegetation index that is sensitive at leaf level may not be sensitive at canopy level. Therefore, more canopy-level research is needed to

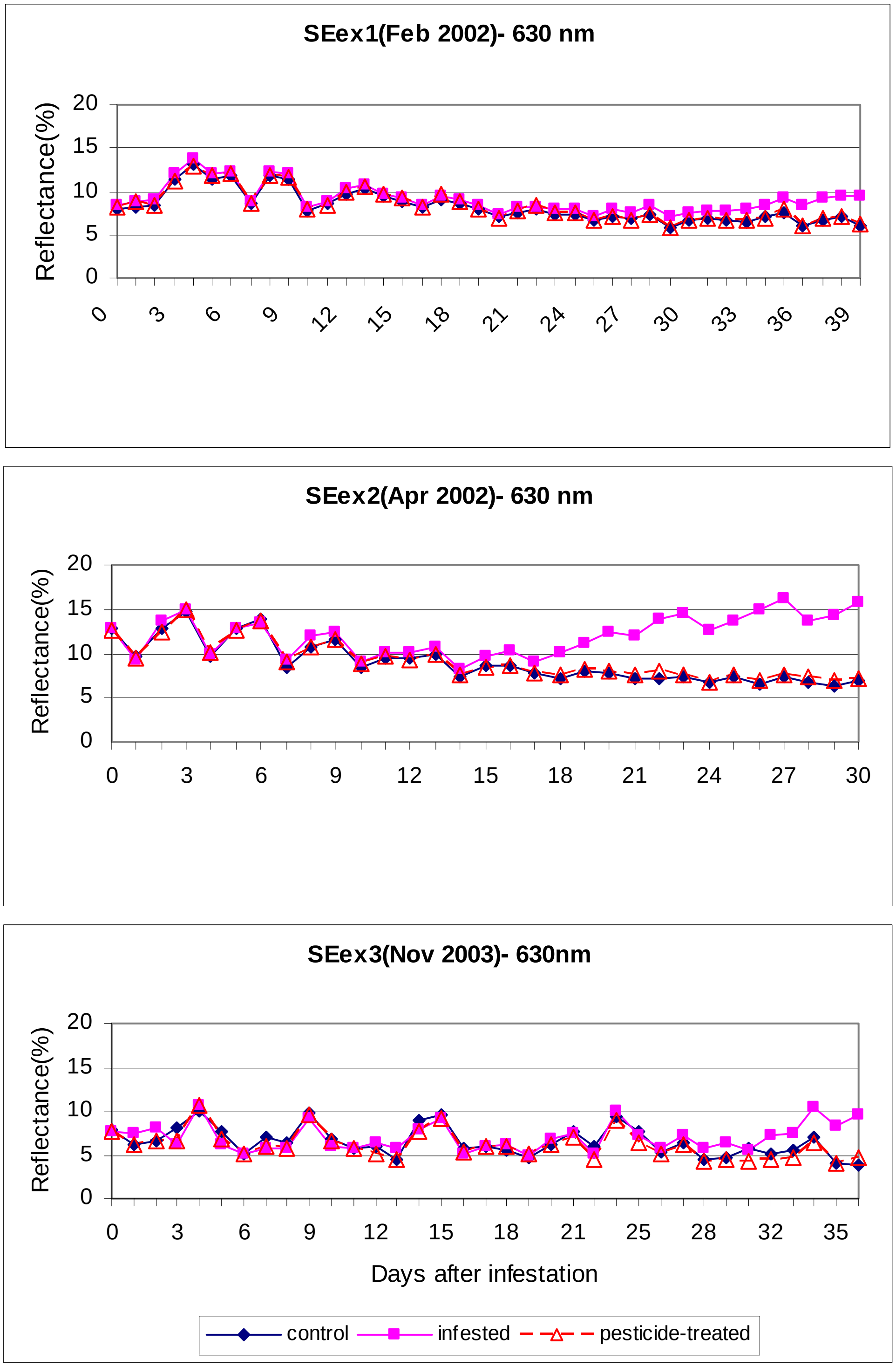
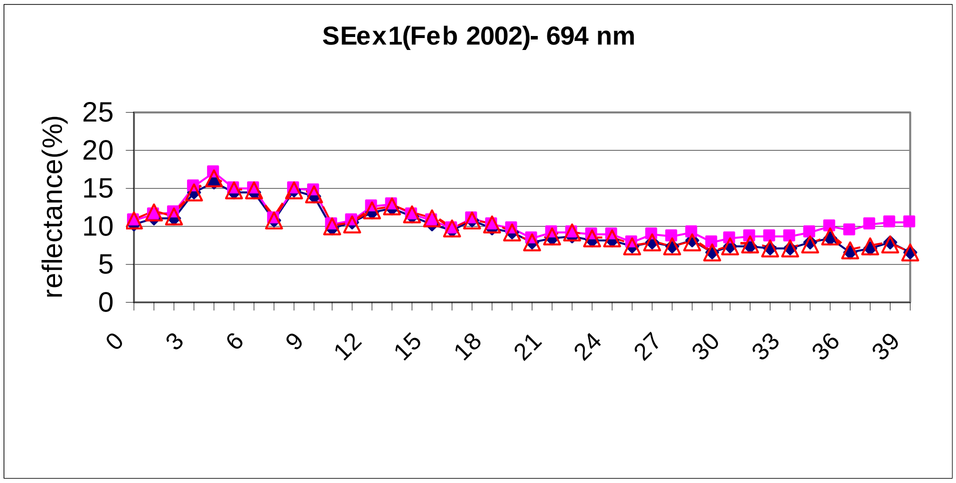
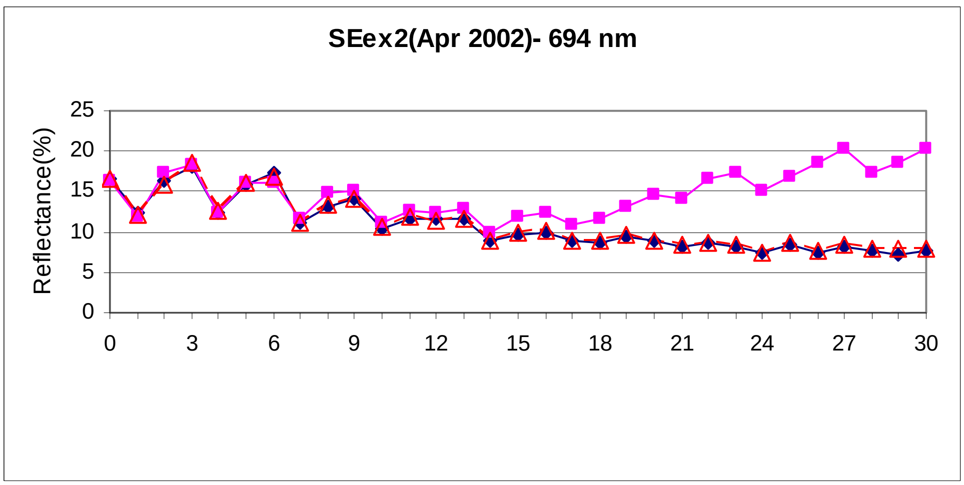


Fig 4-6. Temporal changes in reflectance at 630 nm for three sensitivity experiments.





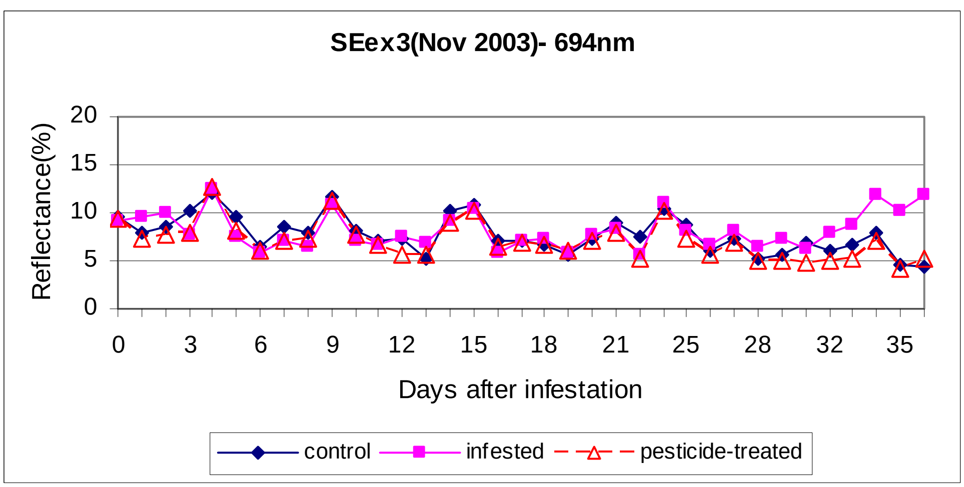


Fig 4-7. Temporal changes in reflectance at 694 nm for three sensitivity experiments.

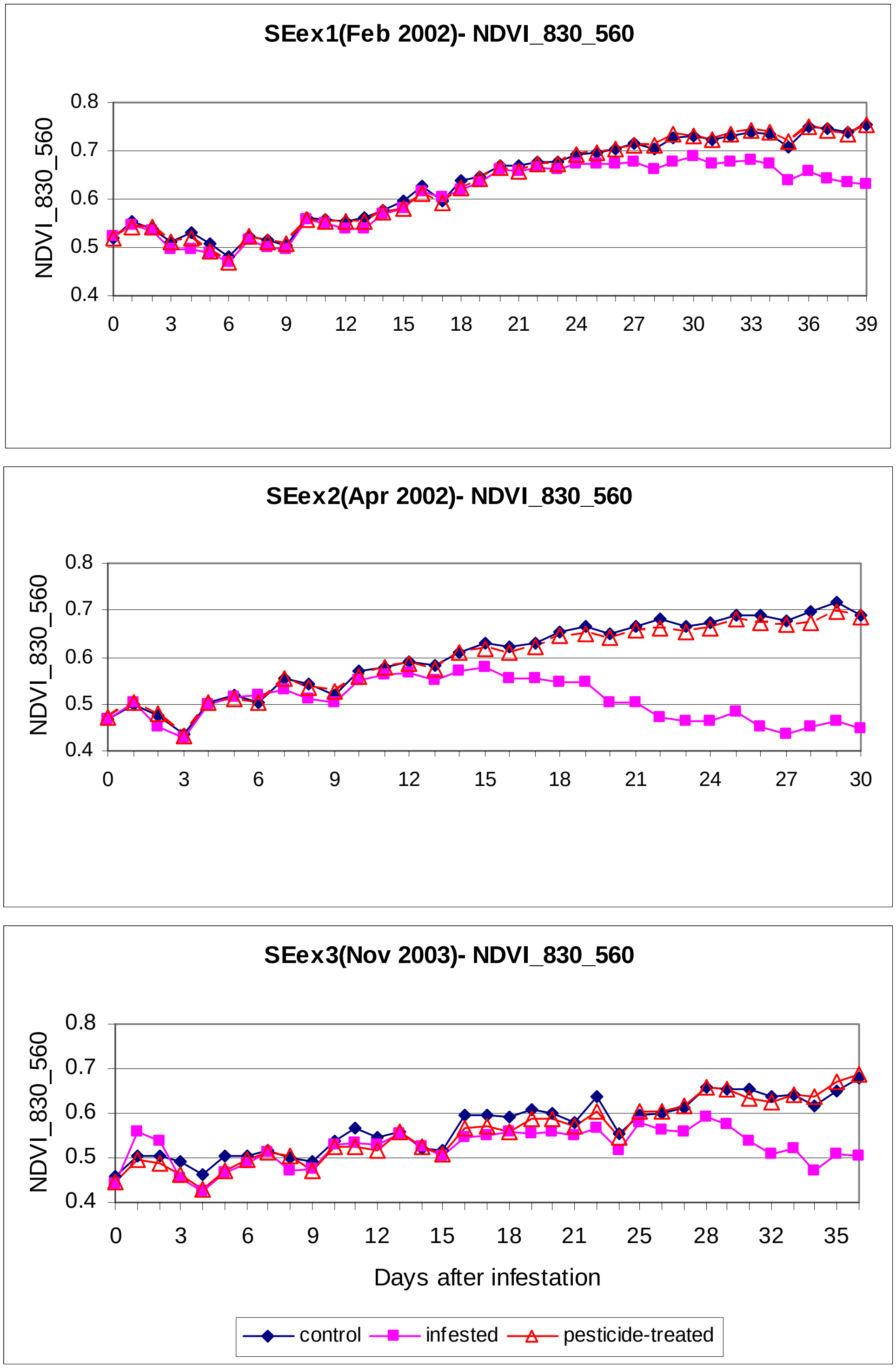


Fig 4-8. Temporal changes in NDVI_830_560 for three sensitivity experiments.

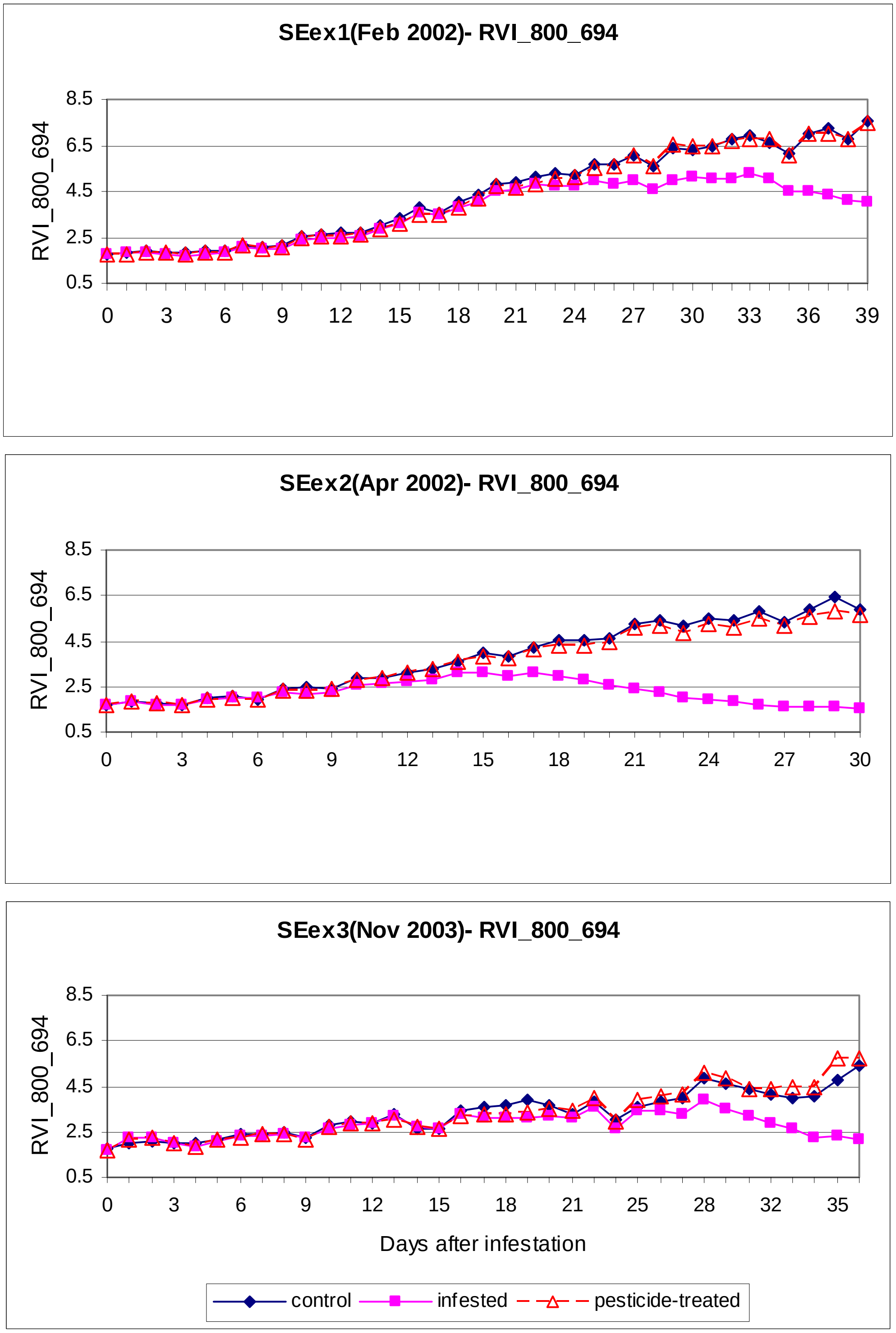


Fig 4-9. Temporal changes in RVI_800_694 for three sensitivity experiments.

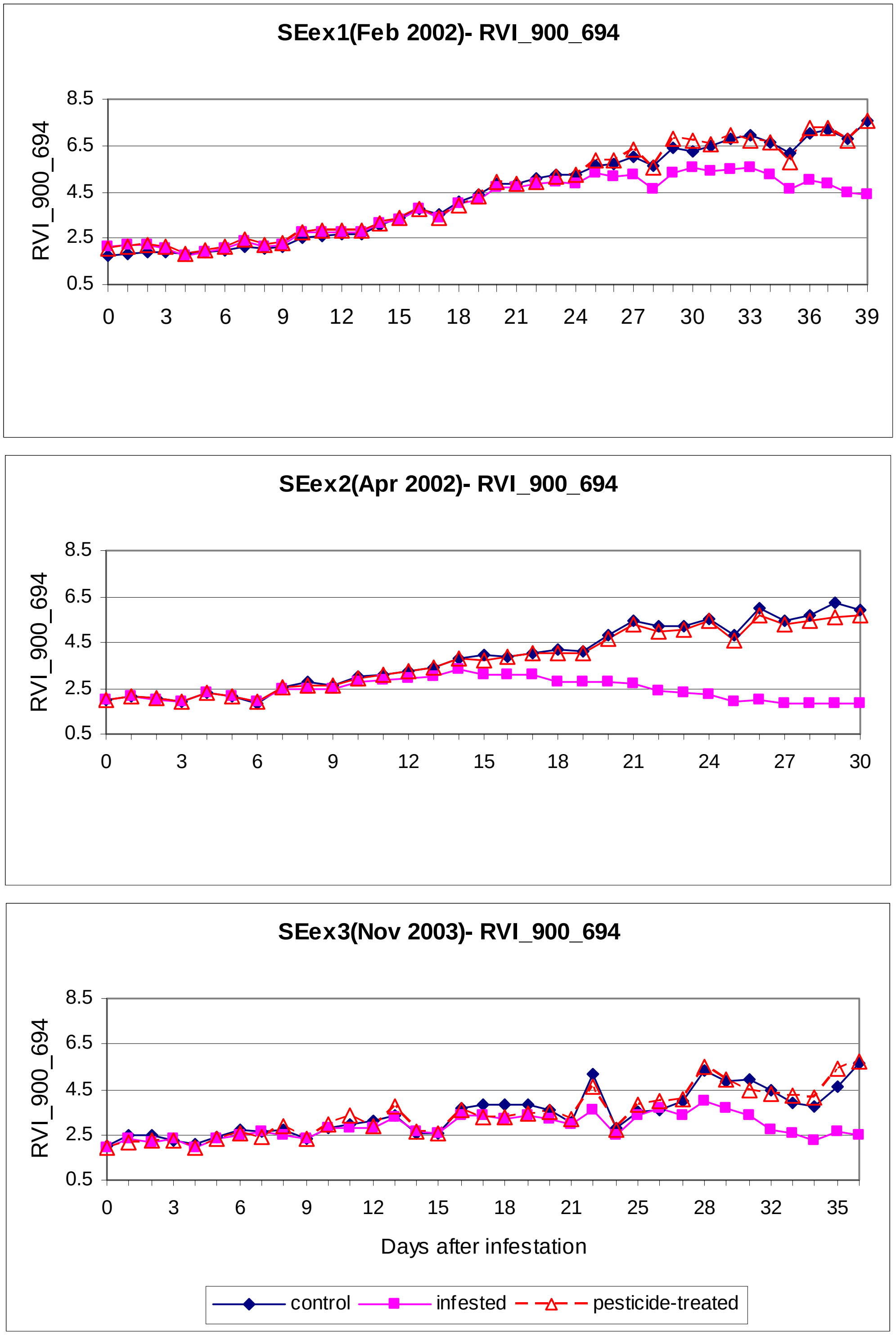


Fig 4-10. Temporal changes in RVI_900_694 for three sensitivity experiments.

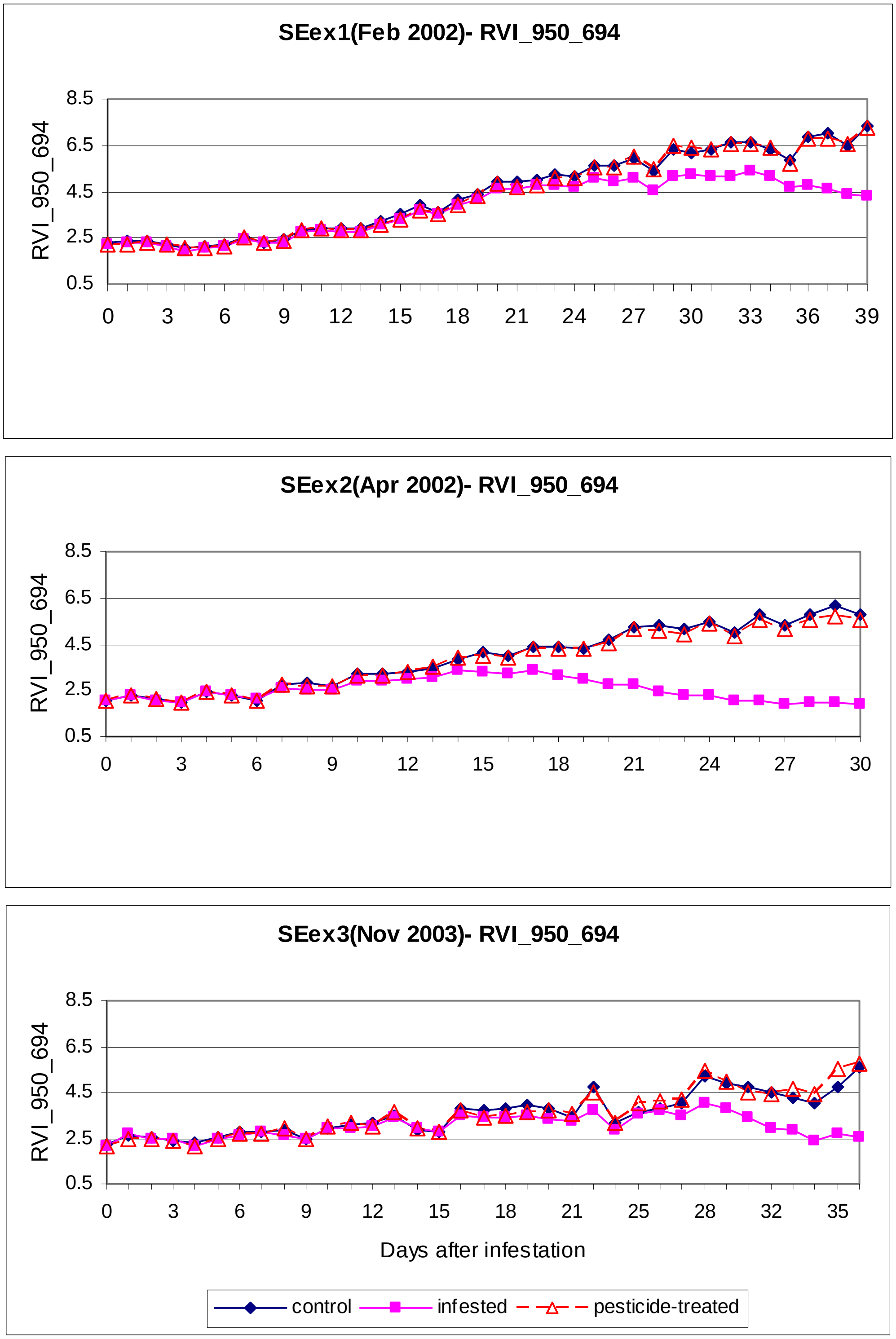
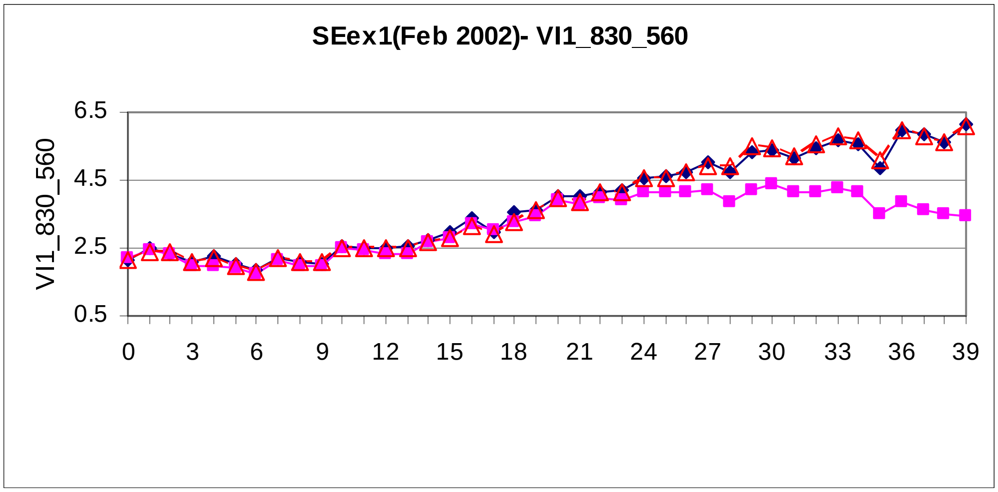
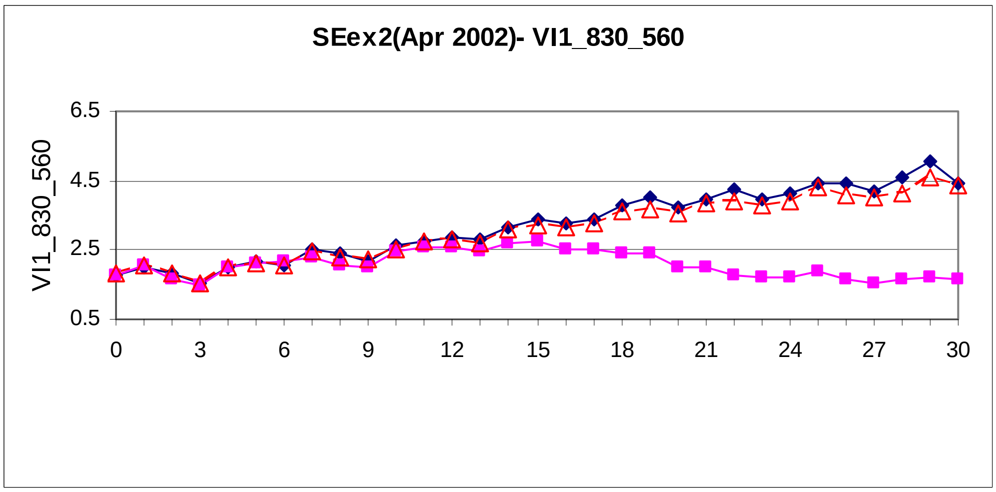


Fig 4-11. Temporal changes in RVI_950_694 for three sensitivity experiments.





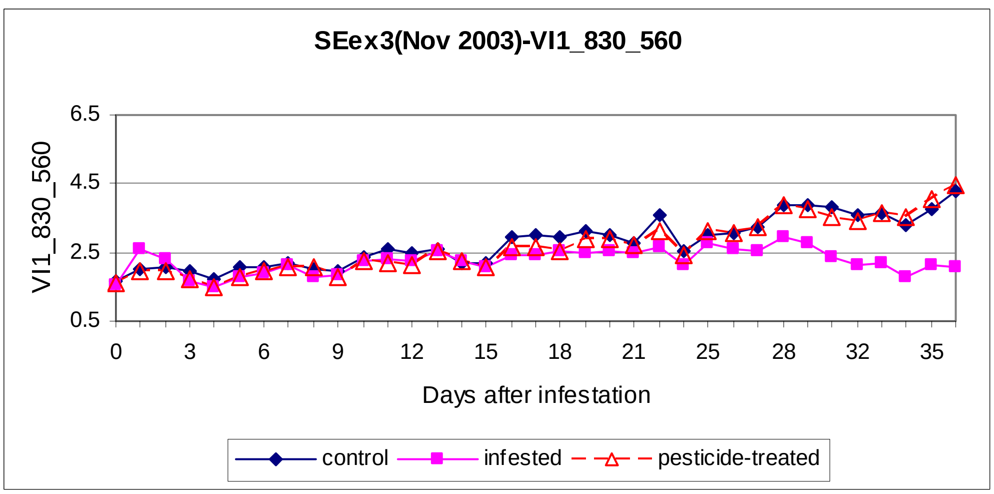


Fig 4-12.Temporal changes in VI1_830_560 for three sensitivity experiments

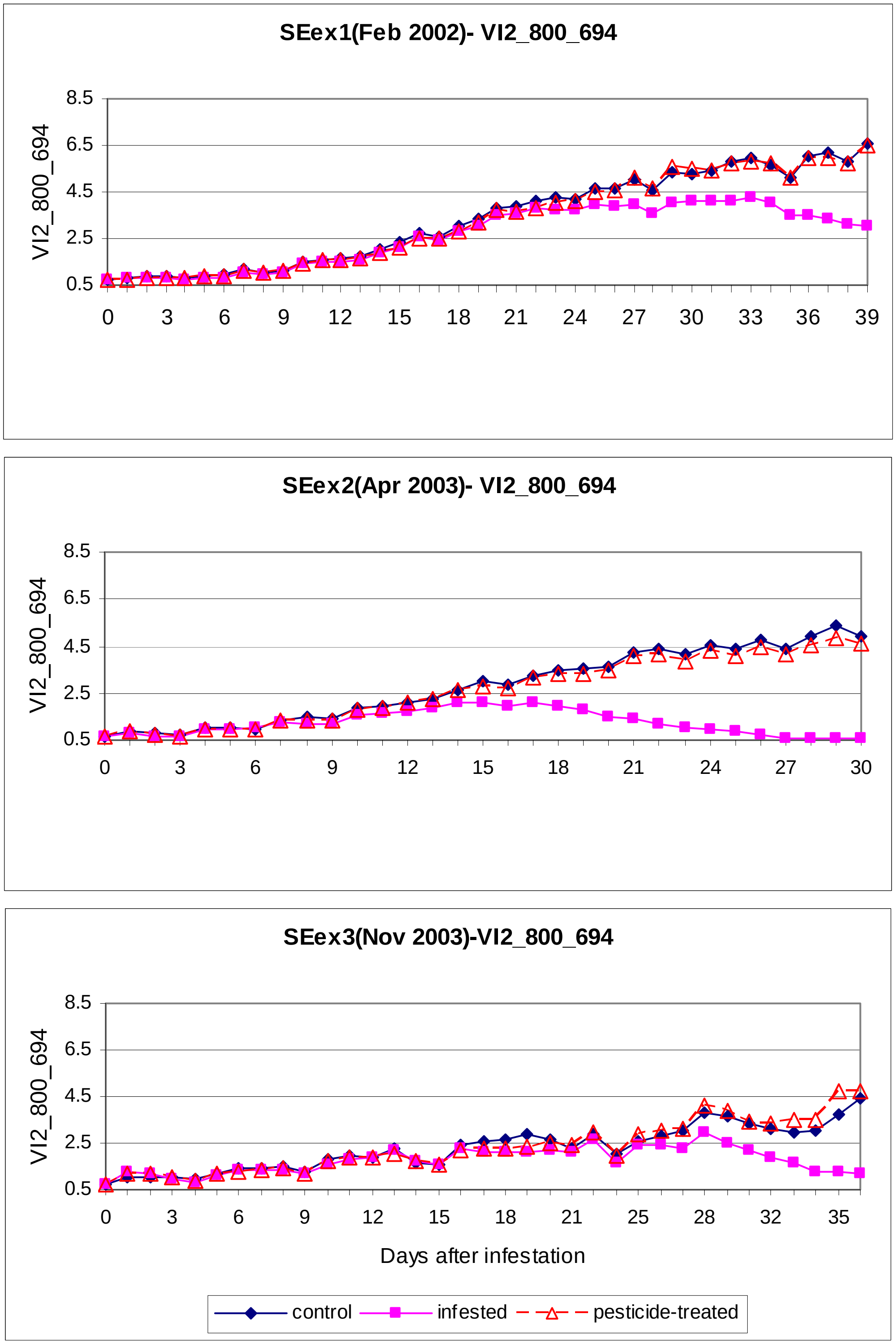


Fig 4-13. Temporal changes in VI2_800_694 for three sensitivity experiments.

successfully extend the spectral signature from the leaf level to the canopy level. This will be very helpful for detecting greenbug-induced wheat stress under field conditions.

According to Figure 4-2, Figure 4-4, Table 4-3 and Table 4-4, it is interesting to note that in all sensitivity experiments, when greenbug densities were close to maximum, there were significant differences in sensitive bands and vegetation indices between infested and control plants. This is because when greenbug densities approach maximum, the plant damage caused by greenbugs is evident to be detected. Although in this study the greenbug densities (26 per tiller) at Threshold Days for all three sensitivity experiments are much higher than typical economic threshold-12 greenbugs per tiller (Oklahoma State University, 2000), findings from this study still show great potential of using remote sensing in detecting greenbug infestation because certain spatial patterns are associated with greenbug infestation under field conditions (Elliott and Kieckhefer, 1987). The first sign of greenbug infestation is a circular, yellowish spot in the field and the center plants in these spots have higher infestations than surrounding plants and are the more severely damaged. If we could detect the greenbug spot at Threshold Day in one field using reflectance of sensitive bands or sensitive vegetation indices, we could initiate field sampling and take necessary control measures such as spraying pesticides to those plants in spots. This may protect non-infested and lightly infested crops before the infestation spreads across the whole field or to adjacent fields.

Based on the above-mentioned results and discussions, it can be concluded that it is possible to detect wheat stress caused by greenbug infestation using hand-held radiometers, such as Cropscan radiometers. All sensitive bands and vegetation indices were summarized and ranked in Table 4-6. As can been seen, bands including 560, 580, 630, 660, 670, 680 and 694 nm were identified as sensitive bands for detecting greenbug infestation. The band 694 and 630 nm were most sensitive among the 16 bands of the Cropscan radiometer. Furthermore, among the 128 vegetation indices examined in this study, 27 vegetation indices including those listed in Table 4-3, MSAVI2, VI1_830_560

Table 4-6 Sensitive band and vegetation indices determined from sensitivity experiments

Band(nm)	Ranking	Vegetation indices	Ranking
694	1	VI2_ 800_694	1
630	2	VI1_830_560	2
620	3	RVI_800_694	3
660	4	RVI_800_630	4
580	5	RVI_900_694	5
670	6	RVI_800_620	6
680	7	RVI_900_630	7
560	8	RVI_950_694	8
		RVI_800_670	9
		RVI_900_620	10
		RVI_830_660	11
		RVI_950_630	12
		RVI_800_680	13
		RVI_900_580	14
		RVI_900_670	15
		RVI_950_620	16
		RVI_900_680	17
		RVI_950_580	18
		RVI_950_670	19
		RVI_830_560	20
		RVI_950_680	21
		RVI_830_485	22
		RVI_800_450	23
		RVI_900_450	24
		NDVI_830_560	25
		RVI_950_450	26
		MSAVI2	27

and VI2_800_694 are sensitive vegetation indices. Among them, vegetation indices derived using the band 800 and 694 nm were more sensitive to greenbug infestation and VI2_800_694 was the most sensitive vegetation index. Broad Landsat TM bands and their derived vegetation indices such as RVI_830_560 were also sensitive to greenbug infestation and show potential to be used for detection of greenbug infestation.

4.2 Differentiating water stress and greenbug infestation on wheat

4.2.1 Sensitive bands

Data from three differentiating experiments: DIex1, DIex2 and DIex3 were analyzed below. Figure 4-14 shows photos of plants under four treatments at the end of experiment. It can been seen that the order of damage degree is infested and water stress (W+I), greenbug-infested without water stress (NW+I), non-infested with water stress (W+NI), control (non-infested without water stress) (NW+NI). For plants under infestation and water stress, all leaves turned yellow and wilted. For plants under infestation, most leaves turned yellow and wilted. For plants under water stress, many leaves wilted but did not turned yellow. Control plants still look healthy at the end of the experiments.

Figure 4-15 shows temporal densities of greenbugs on infested plants (no-water-stressed but infested) during the three experiments. As shown in the figure 4-14, greenbug densities of 112, 222 and 297/per plant were observed at 18, 21 and 33 days respectively for each experiment. Again, it can be seen that greenbug densities had similar patterns during the three experiments. Greenbug populations increased with the time at the early stage of infestation. When damage on infested plants became serious and these plants began to die, the greenbug population declined, mostly due to the shortage of food availability. Also, the number of greenbugs increased and decreased more quickly in the DIex2 than in other experiments. This is also likely due to temperature and seasonal differences among these three sensitivity experiments.

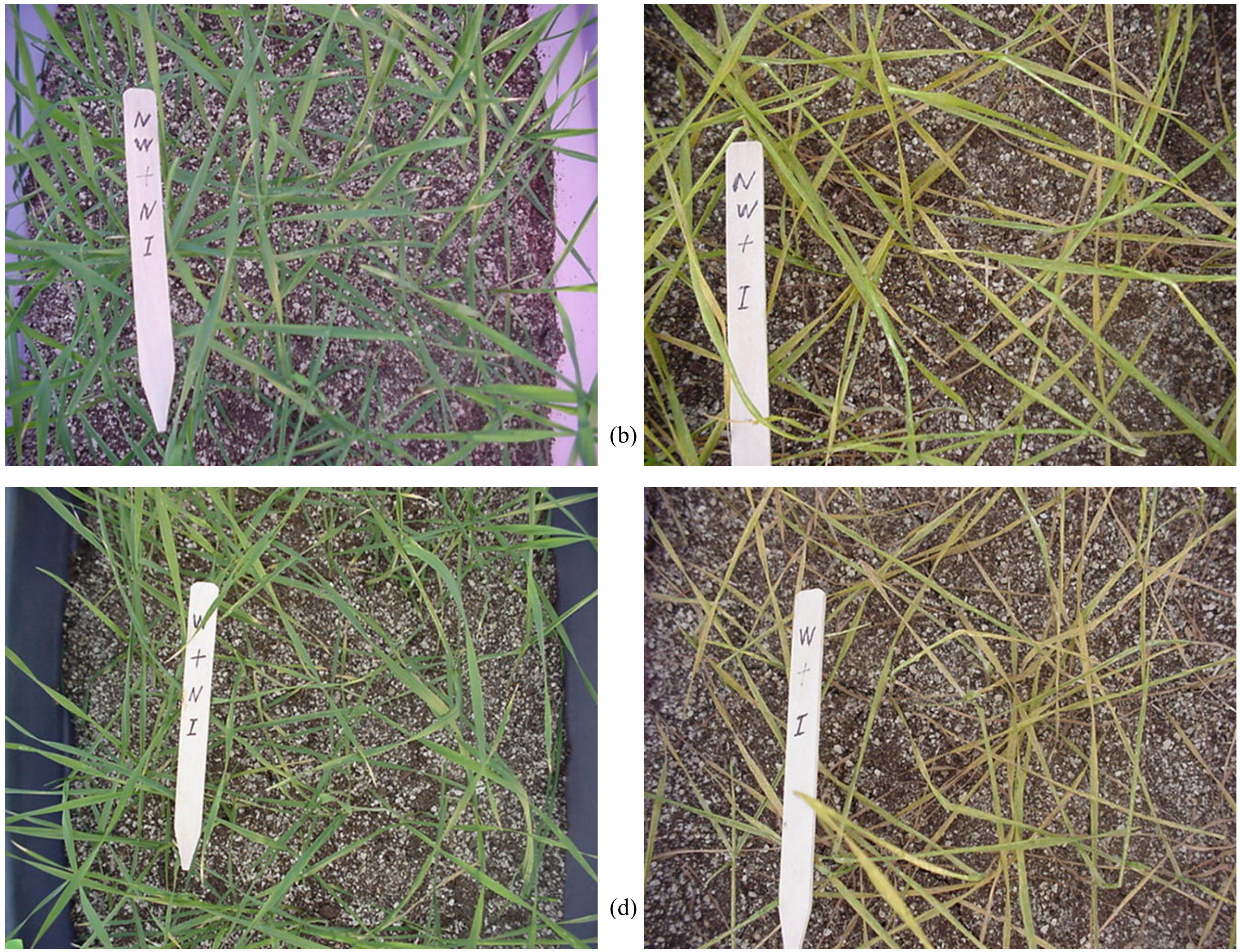


Fig 4-14. Photographs showing four treatment effects on plants at the end of experiment (DIex1).
(a: NW+NI, b: NW+I, c: W+NI, d: W+I)

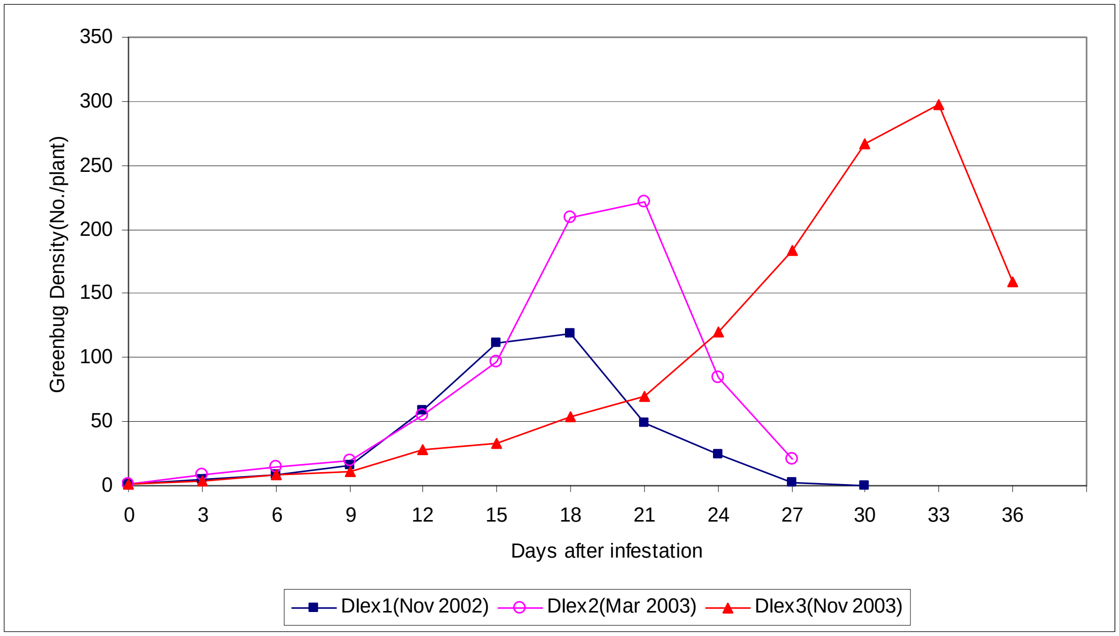


Fig 4-15. Densities of greenbug over time for three differentiating experiments.

Table 4-7. Threshold Days of sensitive bands to differentiate water stress and greenbug infestation

Band (nm)	DIex1 (Nov 2002)	DIex2 (Mar 2003)	DIex3 (Nov 2003)
560	no	27	28
580	no	24	31
620	34	27	32
630	34	27	32
660	32	27	34
670	32	27	36
680	34	27	35
694	34	27	34
Maximum Day	18	21	33

No: there is no Threshold Day for the difference between water-stressed and infested plants
Maximum Day: the day at which greenbug density reached maximum

Based on Table 4-7, there were some consistent results from the three experiments. Visible bands (620, 630, 660, 670, 680 and 694 nm) could be used to differentiate greenbug infestation from water stress at later stages of experiments and near infrared and middle infrared bands were not sensitive to differences in two stresses. Additionally, compared to narrow bands, the Landsat TM band-660 nm displayed similar capability to differentiate greenbug infestation and water stress in all experiments. These results demonstrate that there were significant reflectance differences at these bands between greenbug infestation and water stress at some time in these experiments. Carter (1991) reported that visible reflectance was most sensitive to water stress at 535-640 nm and 685-700 nm. Penuelas et al. (1993 and 1997) found that change in reflectance at 950-970 nm was more effective for detecting water stress at the canopy level. Findings from our three Differentiating experiments seem to favor Carter's conclusion but do not support Penuelas's findings. Discrepancies here show that wheat spectral responses to water stress may be different from plant species such as bean used by Penuelas et al. In addition, among these bands, there were no big differences in their thresholds. This shows that these bands have similar capabilities to differentiate greenbug infestation and water stress on wheat plants. It seems that bands including 620, 630, 660, 670, 680 and 694 nm could be used to differentiate greenbug infestation and water stress. However, based on Table 4-5, their Threshold Days are bigger than Maximum Day at which greenbug density reaches maximum. This means that in three experiments after greenbug densities of infested plants reached maximum, band 620, 630, 660, 670, 680 and 694 nm could be used to differentiate greenbug infestation and water stress. This result shows that reflectance at these bands has low practical value because it is not very useful to detect greenbug infestation after Maximum Day. Therefore, it is difficult to use reflectance at sensitive bands to differentiate greenbug infestation from water stress.

4.2.2 Sensitive vegetation indices

The sensitive vegetation indices identified in Table 4-6 were further analyzed to determine if they can be used to differentiate greenbug infestation and water stress on wheat plants for three experiments. These vegetation indices were subjected to PROC MIXED, and the results are tabulated in Table 4-8. Compared to reflectance of the single band in Table 4-4, all vegetation indices showed smaller Threshold Days and thus showed higher sensitivities to difference between greenbug infestation and water stress. This further validated the importance of vegetation indices.

Penuelas et al. (1997) found that WBI (water band index = R900 nm/R970 nm) were closely related to plant water concentration, suggesting that WBI is a good vegetation index to differentiate greenbug infestation and water stress on wheat plants. However, in this study it was found that there was no Threshold Day for the difference in this vegetation index between infested and water-stressed plants in all experiments. This suggests that WBI may be species-dependent because soybean was used in the study of Penuelas et al. Thus, it is necessary to develop a water stress index used for the particular species of plant at the canopy level.

Based on Table 4-8, most vegetation indices sensitive to greenbug infestation could not be used to differentiate greenbug infestation and water stress because they did not have Threshold Days or their Threshold Days are larger than the Maximum Day at which greenbug density reached maximum. This is possibly because wheat plants under water

Table 4-8. Threshold Days of sensitive vegetation indices for differentiating greenbug infestation and water stress

Vegetation indices	DIex1(Nov 2002)	DIex2 (Mar 2003)	DIex3 (Nov 2003)
NDVI_830_560	17	27	31
RVI_800_450	no	25	31
RVI_800_620	no	24	29
RVI_800_630	no	22	29
RVI_800_670	no	23	28
RVI_800_680	21	24	29
RVI_800_694	18	22	28
RVI_830_485	30	25	33
RVI_830_560	17	24	31
RVI_830_660	18	22	29
RVI_900_450	no	27	36
RVI_900_580	no	no	36
RVI_900_620	17	27	28
RVI_900_630	18	27	28
RVI_900_670	no	23	28
RVI_900_680	17	24	28
RVI_900_694	18	21	28
RVI_950_450	no	27	36
RVI_950_580	no	no	36
RVI_950_620	20	27	28
RVI_950_630	17	27	28
RVI_950_670	21	27	28
RVI_950_680	20	24	28
RVI_950_694	18	21	28
VI1_830_560	17	26	31
VI2_800_694	18	22	28
MSAVI2	21	28	no
Maximum Day	18	21	33

no: there is no Threshold Days
Maximum Day: the day at which greenbug density reached maximum

stress have similar spectral responses as those under greenbug infestation. Again, this result shows that those vegetation indices have low practical value because it is not very useful to detect greenbug infestation after Maximum Day. However, five vegetation indices: RVI_800_694, RVI_830_660, RVI_900_694, RVI_950_694 and VI2_800_694 have smaller or very close Threshold Days compared to Maximum Day. It means that difference in these vegetation indices between plants under greenbug infestation and water stress could be evident and detected earlier using these vegetation indices before Maximum Days. Thus, these vegetation indices could be used to differentiate greenbug infestation and water stress. The higher sensitivities of these vegetation indices show the role of the red edge. Broad chlorophyll absorption continues into the infrared with the long-wavelength side of the chlorophyll absorption occurring after 700 nm. The change in absorption is usually large, ranging from a reflectance low of about 5% at 680 nm to a reflectance maximum of about 50% at 730 nm (Curran et al., 1991). This rapid change in reflectance, which is called the “red edge”, is often used to detect crop stress. Temporal changes in VI2_800_694 were displayed in Fig 4-16. It shows that in general, VI2_800_694 increase with the time during all differentiating experiments but at some time VI2_800_694 for both plants under water stress and greenbug infestation decrease. However, at some time (Threshold Days) infestation caused greater decrease in VI2_800_694 than water stress and this is why VI2_800_694 can be used to differentiate greenbug infestation and water stress.

In addition, one vegetation index derived from broad Landsat TM bands-RVI_830_660 shows similar sensitivities as those vegetation indices derived from narrow bands because there is no substantial difference between their Threshold Days. It suggests that Landsat images could be potentially used to detect greenbug infestation on wheat and distinguish greenbug infestation and water stress on wheat.

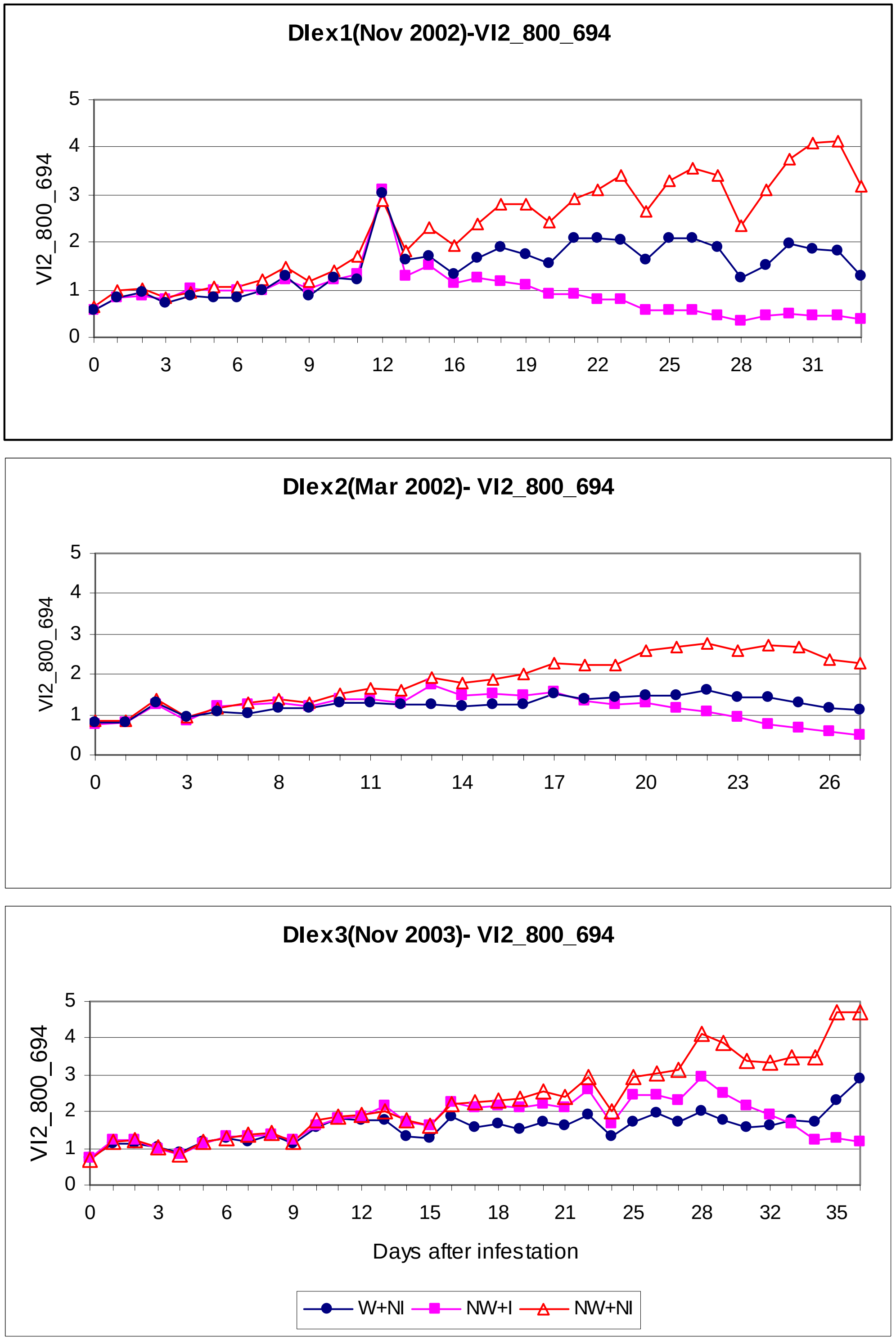


Fig 4-16. Temporal changes in VI2_800_694 during differentiating experiments.

4.3 Impact of plant growth stage on detection of greenbug infestation

4.3.1 Temporal changes in densities of greenbugs

Data from the experiment STex, which was used to examine impact of plant stage on detection, are analyzed below.

Figure 4-16 shows densities of greenbug over time during this experiment. Again, it can be seen that greenbug densities had similar developmental patterns in both treatments. The greenbug population increased with time in the early stage of greenbug infestation. But when damages on infested plants became serious and those plants began to die, the greenbug population declined because of the shortage of food.

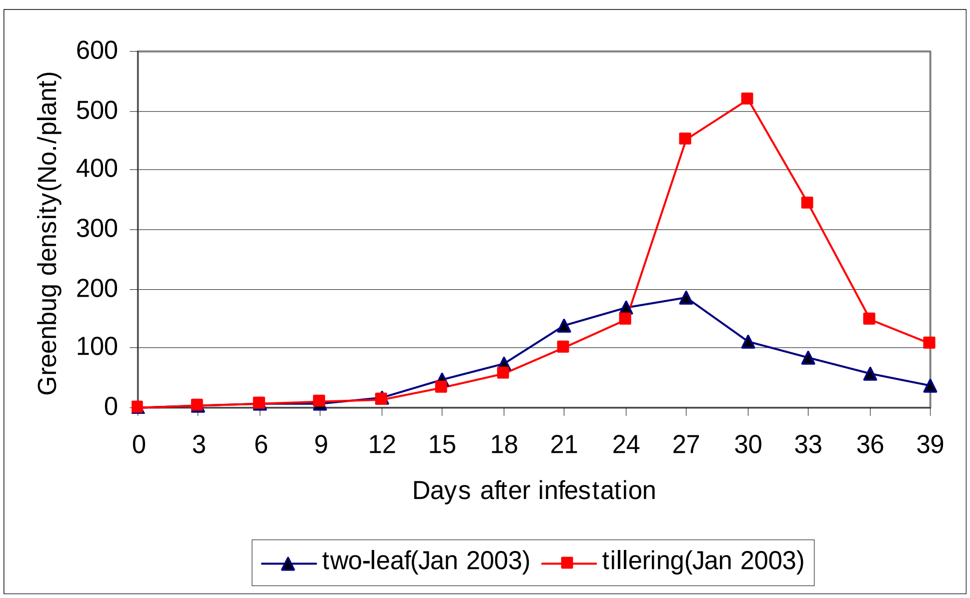


Fig 4-17. Densities of greenbug over time in growth stage experiment.

However, the number of greenbugs increased and decreased more quickly on plants infested at the tillering stage than plants infested at the two-leaf stage. This could most likely be due to the fact that the infestation began at different stages. It is normal for plants at the tillering stage to accumulate more biomass than at the two-leaf stage because plants at the tillering stage were planted earlier and their growth time was longer. Higher food availability for plants infested at the tillering stage increased the greenbug population more quickly for the plants infested at tillering stage than for plants infested at two-leaf stage. However, at the same time the faster growth of the greenbug population may cause more serious damages to the plants infested at the tillering stage than for plants infested at the two-leaf stage. Thus, food availability for greenbugs also decreased quickly. Consequently, the greenbug population decreased more quickly for the plants infested at the tillering stage than for plants infested at the two-leaf stage.

4.3.2 Sensitive bands

Figure 4-18 shows the Threshold Days for 8 sensitive bands estimated from outputs of PROC MIXED. From Figure 4-18, it can be seen that for all sensitive bands, the “Threshold Day” were smaller for the plants infested at the two-leaf stage than for plants infested at the tillering stage. This means that infested plants and control plants showed statistically significant differences later for plants infested at the tillering stage than the plants infested at the two-leaf stage. This difference could be due to the difference in vegetative coverage on the soil. Normally, plants infested at the tillering stage have larger canopy coverage on soil than plants infested at the two-leaf stage. Thus, the percentage of infested and damaged leaves in the whole canopy could be lower for plants infested at the tillering stage than plants infested at the two-leaf stage. This could possibly explain why differences in reflectance between infested plants and control plants was detected earlier for the plants infested at the two-leaf stage than for plants infested at the tillering stage.

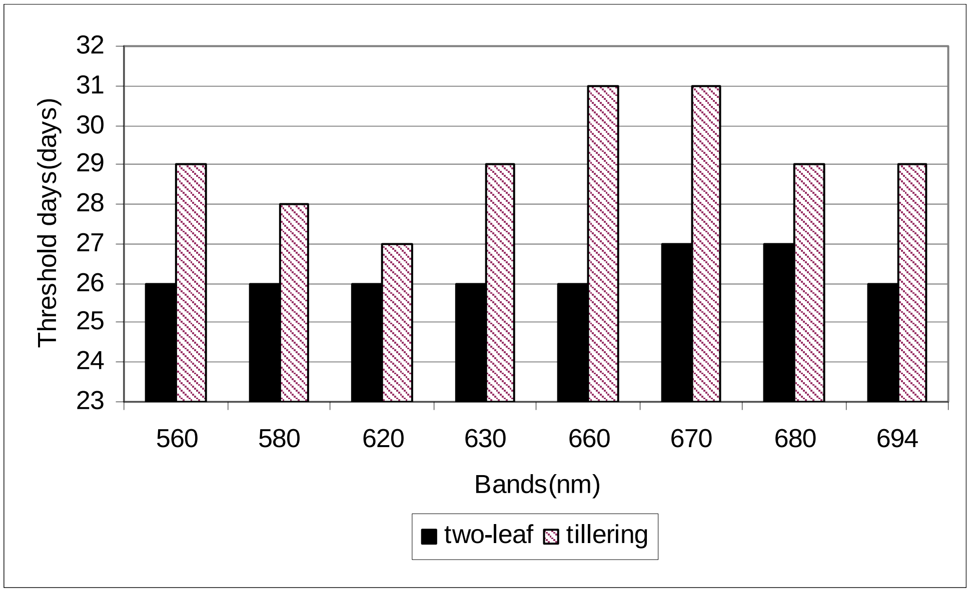


Fig 4-18. Threshold Days of sensitive bands in growth stage experiment.
* Threshold Day: the day subsequent to which there were significant differences ($p<0.05$).

For bands including 560, 580, 620, 630, 660, 670, 680, and 694 nm, reflectance was subjected to the sensitivity analysis and correlation analysis mentioned in the methods section. The results are shown in Table 4-9. In both experiments, bands including 620, 630, 660, 680 and 694 nm were more sensitive to greenbug infestation because of larger differences in reflectance between infested and control plants. These differences were significantly correlated with the greenbug density. Also, reflectance at 694 nm and 630 nm showed larger differences and they were highly correlated with the greenbug density. Thus, among the 16 bands of the Cropscan radiometer, bands including 694 and 630 nm were still the most sensitive to greenbug infestation in both plant stages. After 26 days (for plants infested at two-leaf stage) and 30 days (for plants infested at tillering stage) of greenbug infestation, there were statistically significant differences ($p<0.05$) in reflectance at bands including 620, 630, 660,680 and 694 nm between infested plants and control plants. This suggests that these bands could be used to detect greenbug-induced wheat stress at both the tillering stage and the two-leaf stage.

Table 4-9. Band sensitivities and correlation coefficients in growth stage experiment

Band (nm)	Correlation coefficient $^{\Delta}$		% Difference #		
	Two-leaf	Tillering	Two-leaf	Tillering	Average
BAND560	0.6656	0.5504	34.38	29.97	32.18
BAND580	0.6183	0.5704	47.26	32.17	39.72
BAND620	0.8214*	0.7716*	39.06	35.73	37.40
BAND630	0.8092*	0.7711*	43.37	37.44	40.41
BAND660	0.7639*	0.7171*	45.33	33.45	39.39
BAND670	0.6797	0.616	52.51	29.2	40.86
BAND680	0.8758*	0.7230*	33.3	34.39	33.85
BAND694	0.8783*	0.7789*	42.89	41.43	42.16

Differences in reflectance between control and infested plants at Maximum Day
Δ Correlation between greenbug density and difference in reflectance between infested and control plants
* Significant at the 0.05 probability level. (n=8, 0.707)

4.3.3 Sensitive vegetation indices

The Impact of plant stage on detection of greenbug infestation using sensitive vegetation indices identified in Section 4.1 was examined and results are displayed in Table 4-10 and Table 4-11. Based on Table 4-10, it also can be seen that for all vegetation indices "Threshold Days" were smaller for the plants infested at the two-leaf stage than for plants infested at the tillering stage. This means that infested plants and control plants showed statistically significant differences later for plants infested at the tillering stage than the plants infested at the two-leaf stage. Again, this difference could be caused by difference in plant coverage on the soil.

In addition, when compared to Maximum Days for two treatments in this experiment, most sensitive vegetation indices, except RVI_900_450 and RVI_950_450, have smaller Threshold Days for infestation at the two-leaf stage; most sensitive

Table 4-10. Threshold Days for sensitive vegetation indices in growth stage experiment

Vegetation indices	two-leaf	tillering
NDVI_830_560	24	27
RVI_800_450	25	27
RVI_800_620	24	27
RVI_800_630	23	27
RVI_800_670	24	27
RVI_800_680	25	25
RVI_800_694	23	25
RVI_830_485	24	27
RVI_830_560	25	27
RVI_830_660	24	27
RVI_900_450	34	33
RVI_900_580	25	31
RVI_900_620	23	28
RVI_900_630	23	27
RVI_900_670	25	32
RVI_900_680	24	27
RVI_900_694	23	28
RVI_950_450	36	33
RVI_950_580	25	29
RVI_950_620	23	27
RVI_950_630	23	27
RVI_950_670	25	29
RVI_950_680	23	27
RVI_950_694	21	26
VI1_830_560	24	28
VI2_800_694	23	26
Maximum Day	27	30

Maximum Day: the day at which greenbug density reached maximum vegetation indices except RVI_900_450, RVI_900_580 and RVI_950_450 have smaller Threshold Days for infestation at the tillering stage.

Table 4-11. Correlation coefficients for plants at the two-leaf and the tillering stages

	correlation coefficient$^{\Delta}$		% difference$^{\#}$	
Vegetation indices	two-leaf	tillering	two-leaf	tillering
NDVI_830_560	-0.8247*	-0.6550	-5.68	-22.06
RVI_800_450	-0.5080	-0.4047	-9.37	-11.23
RVI_800_620	-0.9548*	-0.8127*	-18.72	-43.09
RVI_800_630	-0.9456*	-0.8448*	-19.87	-44.50
RVI_800_670	-0.8441*	-0.7767*	-17.64	-47.72
RVI_800_680	-0.9644*	-0.8229*	-19.76	-40.81
RVI_800_694	-0.9702*	-0.8859*	-22.54	-44.38
RVI_830_485	-0.8504*	-0.5443	-11.89	-29.45
RVI_830_560	-0.8473*	-0.6932	-13.54	-36.15
RVI_830_660	-0.9342*	-0.8116*	-17.83	-40.89
RVI_900_450	-0.0443	-0.3779	-4.17	-17.27
RVI_900_580	-0.6152	-0.6098	-11.67	-50.16
RVI_900_620	-0.8462*	-0.7970*	-14.10	-46.71
RVI_900_630	-0.8327*	-0.7965*	-15.31	-48.56
RVI_900_670	-0.6852	-0.6991	-12.94	-51.99
RVI_900_680	-0.9154*	-0.8365*	-15.19	-44.49
RVI_900_694	-0.9135*	-0.8602*	-18.13	-48.48
RVI_950_450	0.0935	-0.1144	-4.12	-11.67
RVI_950_580	-0.5950	-0.5571	-11.60	-46.76
RVI_950_620	-0.8464*	-0.7494*	-14.04	-43.44
RVI_950_630	-0.8320*	-0.7652*	-15.25	-45.16
RVI_950_670	-0.6688	-0.6639	-12.88	-48.64
RVI_950_680	-0.9181*	-0.7850*	-15.13	-41.11
RVI_950_694	-0.9186*	-0.8375*	-18.08	-45.05
VI1_830_560	-0.8317*	-0.6779	-16.47	-45.27
VI2_800_694	-0.9604*	-0.8816*	-27.06	-57.42

#: Differences in reflectance between control and infested plants at Maximum Day.
Δ: Correlation between greenbug density and difference in reflectance between infested and control plants
*: Significant at the 0.05 probability level. (n=8, 0.707)

According to Table 4-11, most sensitive vegetation indices were still sensitive to greenbug infestation but some vegetation indices are not sensitive to greenbug infestation for either stage. They are NDVI_830_560, RVI_800_450, RVI_900_450, RVI_900_580, RVI_900_670, RVI_950_450, RVI_950_580, RVI_950_670 and VI1830_560. Vegetation indices derived from the bands at the red edge, such as 680 and 694 nm, are more sensitive. Among those sensitive vegetation indices, VI2_800_694 was the most sensitive vegetation index because it showed the largest difference when greenbug density reached a maximum for both treatments. These results further demonstrate that greenbug infestation is closely related to chlorophyll loss of wheat plants because band 694 and 680 are all active chlorophyll absorption bands, and chlorophyll concentration is usually an indicator of photosynthetic capacity and developmental stage.

4.4. Distinguishing greenbug infestation and infestation by RWA

4.4.1 Sensitive bands

Data from the experiment GRex, which is used to compare two kinds of aphid infestations, were analyzed below. Fig 4-19 displays temporal changes in densities of greenbugs and Russian wheat aphids. It can be seen that they have similar patterns and the same Maximum Day.

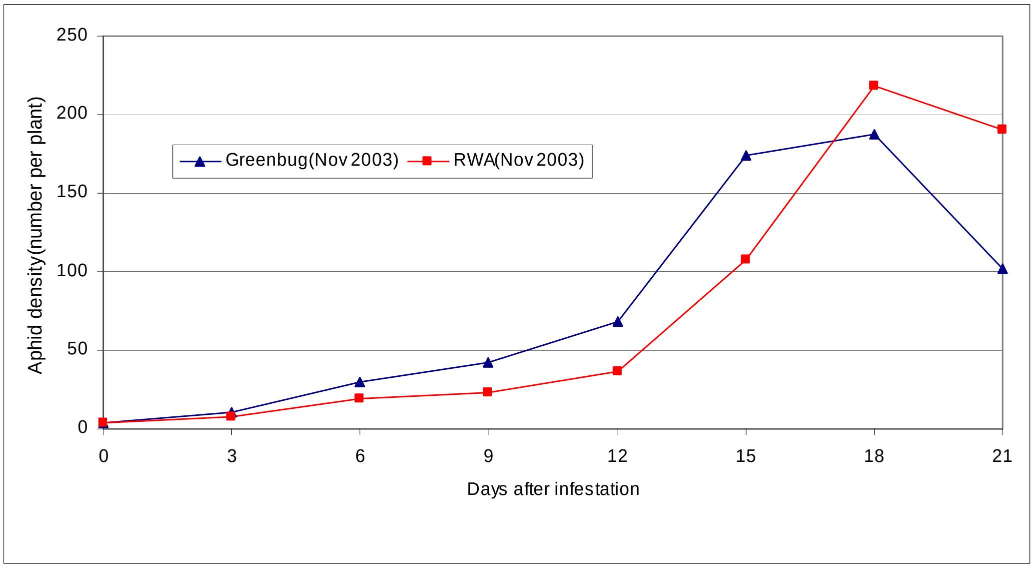


Fig 4-19. Temporal changes in densities of GB and RWA in comparing experiment.

Table 4-12 shows the Threshold Days for sensitive bands (listed in Table 4-6) estimated from output of PROC MIXED. They are the time subsequent to which there were significant differences in reflectance between two treatments, such as control and infested plants. From Table 4-12, it can be seen that for most bands, their Threshold Days were smaller for the plants infested by Russian wheat aphid than for plants infested by greenbugs. This means that infested plants and control plants showed statistically significant differences later for plants infested by greenbugs than the plants infested by

Russian wheat aphids. This difference could be caused by differences in plant responses to infestation by these two aphid species.

Table 4-12. Threshold Days of sensitive bands to compare aphid infestations

Band (nm)	GB-Control	RWA-Control	GB-RWA
560	14	13	no
580	14	13	no
620	15	13	no
630	15	13	no
660	17	9	no
670	17	13	no
680	17	13	no
694	15	13	no

GB-Control: comparison between plants infested by GB and control plants;
RWA-Control: comparison between plants infested by RWA and control plants;
GB-RWA: comparison between plants infested by GB and plants infested by RWA;
Threshold Day: the day subsequent to which there were significant differences ($p<0.05$).
no: there was no Threshold Day

Markedly different feeding damage symptoms are caused by the two aphid species. Greenbug infestation symptoms initially appear as groups of small, reddish, pinpoint spots on the upper side of infested leaves (Brooks, 1991). Greenbug feeding damage is characterized by chlorotic and necrotic lesions in and around feeding sites on older leaves (Burton, 1986; Dorschner et al., 1987). In contrast, Russian wheat aphids feed on younger leaves and infestation often causes corkscrew rolling and stunting of leaves (Burd et al., 1993; Webster et al., 1987). Rolled leaves provide smaller vegetative coverage on soil than spread leaves. Thus, the percentage of leaves in the whole canopy could be lower for plants infested by Russian wheat aphids than the plants infested by greenbugs. Therefore, spectral differences between infested plants and control plants may show earlier. This could possibly explain why differences in reflectance between infested plants and control plants could be detected earlier for the plants infested by Russian wheat aphid than for plants infested by greenbugs.

However, based on Table 4-12, none of the sensitive bands (listed in Table 4-6) could differentiate infestation by greenbugs and infestation by Russian wheat aphid. This may be caused by similarity of the spectral responses of plants to these two kinds of infestation. GB and RWA belong to the same group of aphids (Brooks, 1991). Riedell and Kieckhefer (1995) reported that crop canopy chlorosis and necrosis are typical symptoms for aphid infestation in small grains. Findings from this study further demonstrate the results of Riedell and Kieckhefer (1995). Thus, it is very difficult to use reflectance at a single band to distinguish between infestation by greenbugs and Russian wheat aphids. This may be caused by similarity of spectral responses of plants to these two kinds of infestation.

4.4.2 Sensitive vegetation indices

Table 4-13 shows Threshold Days for sensitive vegetation indices (listed in Table 4-6) and three special vegetation indices: NPCI, WBI and YI. Again, compared to reflectance of single bands, most vegetation indices showed higher sensitivities to aphid infestation. Results here further validated the effectiveness of vegetation indices.

From Table 4-13, it can be seen again that for most vegetation indices, their Threshold Days were smaller for the plants infested by Russian wheat aphid than for plants infested by greenbugs. This means that infested plants and control plants showed statistically significant differences later for plants infested by greenbugs than for plants infested by Russian wheat aphids. This difference could be caused by infestation differences mentioned before. Riedell and Blackmer (1999) reported that at leaf level

NPCI was significantly correlated with total chlorophyll concentrations in both greenbug-damaged and Russian wheat aphid–damaged plants and WBI was always higher than

Table 4-13. Comparisons of Threshold Days of sensitive vegetation indices for different aphid infestations

Vegetation indices	GB-Control	RWA-Control	GB-RWA
NDVI_830_560	14	8	no
RVI_800_450	18	9	9
RVI_800_620	15	9	no
RVI_800_630	15	9	20
RVI_800_670	16	9	20
RVI_800_680	16	9	no
RVI_800_694	16	9	20
RVI_830_485	15	9	no
RVI_830_560	14	9	no
RVI_830_660	16	9	no
RVI_900_450	18	9	no
RVI_900_580	14	9	19
RVI_900_620	15	9	19
RVI_900_630	15	9	19
RVI_900_670	16	11	20
RVI_900_680	16	9	20
RVI_900_694	15	11	19
RVI_950_450	18	9	9
RVI_950_580	14	9	19
RVI_950_620	14	9	20
RVI_950_630	15	9	19
RVI_950_670	16	9	20
RVI_950_680	16	9	no
RVI_950_694	15	9	19
VI1	14	9	no
VI2	16	9	20
MSAVI2	16	9	no
NPCI	16	no	16
WBI	18	no	19
YI	17	no	14
Maximum Day	18		

GB-Control: comparison between plants infested by GB and control plants;
RWA-Control: comparison between plants infested by RWA and control plants;
GB-RWA: comparison between plants infested by GB and plants infested by RWA;
Threshold Day: the day subsequent to which there were significant differences ($p<0.05$).
no: there was no Threshold Day

control in Russian wheat aphid-damaged plants and lower than control in greenbug-

-damaged plants. Findings from this study partially contradicted to their results because results in Table 4-13 show that NPCI and WBI are not sensitive to Russian wheat aphid infestation. Considering the study of Riedell and Blackmer (1999) was at the leaf level, it was concluded that vegetation indices sensitive to aphid infestation at the leaf level may not be sensitive at the canopy level.

In addition, results in Table 4-13 show that it is also difficult to use most vegetation indices to distinguish two kinds of infestation though infestation by Russian wheat aphid could be detected earlier than infestation by greenbugs. Some vegetation indices RVI_800_450, RVI_950_450, NPCI, and YI could be used to differentiate the two kinds of infestation. RVI_800_450 and RVI_950_450 are the vegetation indices most sensitive to differences between two kinds of infestation. It is also possible to use NPCI and YI to distinguish the two kinds of infestation because they have smaller Threshold Days. Riedell and Blackmer (1999) found that Chlorophyll *a*/*b* ratios for leaves severely damaged by greenbug feeding were significantly lower than those same leaves from the undamaged control plants. But Chlorophyll *a*/*b* ratios in leaves damaged by Russian wheat aphid did not differ significantly from the undamaged control plants. This could possibly explain why RVI_800_450, RVI_950_450, and NPCI could be used to distinguish the two kinds of infestation. Chlorophyll, the major plant pigment in wheat leaves, absorbs energy at 440 to 480 nm (chlorophyll a) and 640 to 680 nm (chlorophyll b) (Verbyla, 1995). Band 450 nm is close to 445 nm at which there is maximum absorption of chlorophyll (Penuelas and Inoue, 1999) and NPCI is used to characterize the difference of band 680 and band 430 nm. Thus, they are sensitive to the difference in chlorophyll *a*/*b* ratios. Adams et al. (1999) reported the Yellowness Index (YI) was a good measure for chlorosis of leaves in stressed plants. Results from comparing experiment GRex seem to support findings of Adams et al. (1999). Thus, NPCI is most sensitive to spectral difference between plants infested by two kinds of aphids and could be used to distinguish the two kinds of aphid infestations. Figures for temporal changes in RVI_800_450, RVI_950_450, NPCI and YI were shown in Fig 4-20 - Fig 4-23.

Based on Fig 4-20 and Fig 4-21, in general RVI_800_450 and RVI_950_450 increase with the time but after 9 days of infestation by aphids, there were significant differences in RVI_800_450, RVI_950_450 between plants under infestation by greenbugs and Russian wheat aphid though both infestations induce a decrease in RVI_800_450 and RVI_950_450. According to Fig 4-23, NPCI generally decreases with time but infestation by greenbugs causes increase in NPCI after 16 days of infestation. In conclusion, RVI_800_450, RVI_950_450 and NPCI could be used to differentiate greenbug infestation from infestation by Russian wheat aphids. YI has limited value to be used for distinguishing the two kinds of infestation because there were larger variations in YI data (Fig 4-22). At the later stage of infestation, NPCI may be reliable for use in differentiating two kinds of infestation because of stable trend.

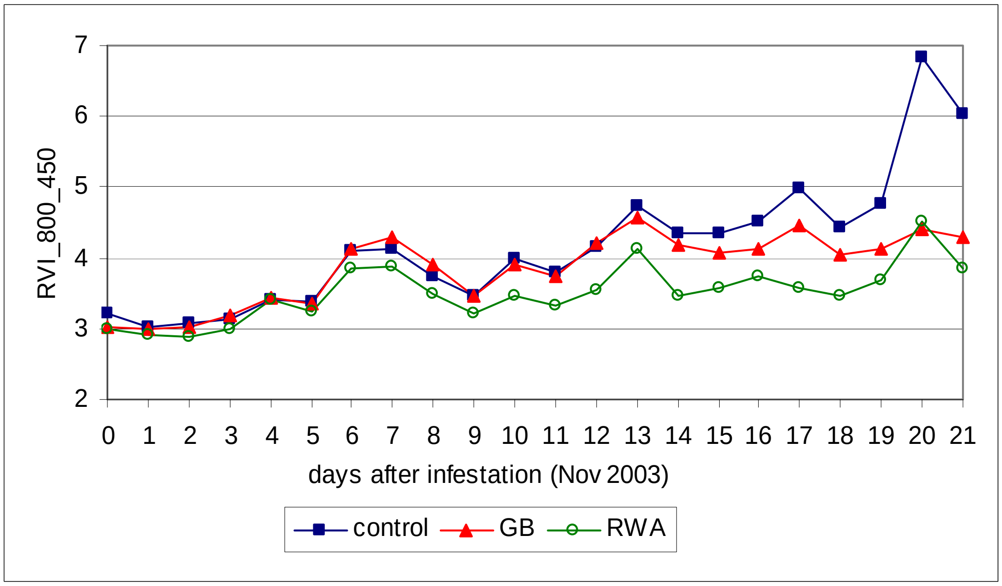


Fig 4-20. Temporal changes in RVI_800_450 for three treatments in comparing experiment.

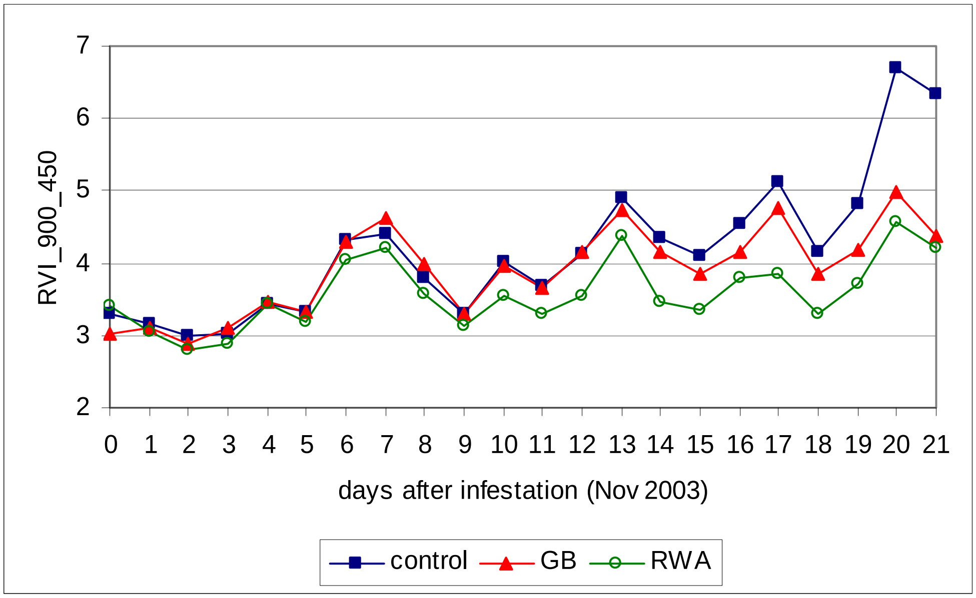


Fig 4-21. Temporal changes in RVI_900_450 for three treatments in comparing experiment.

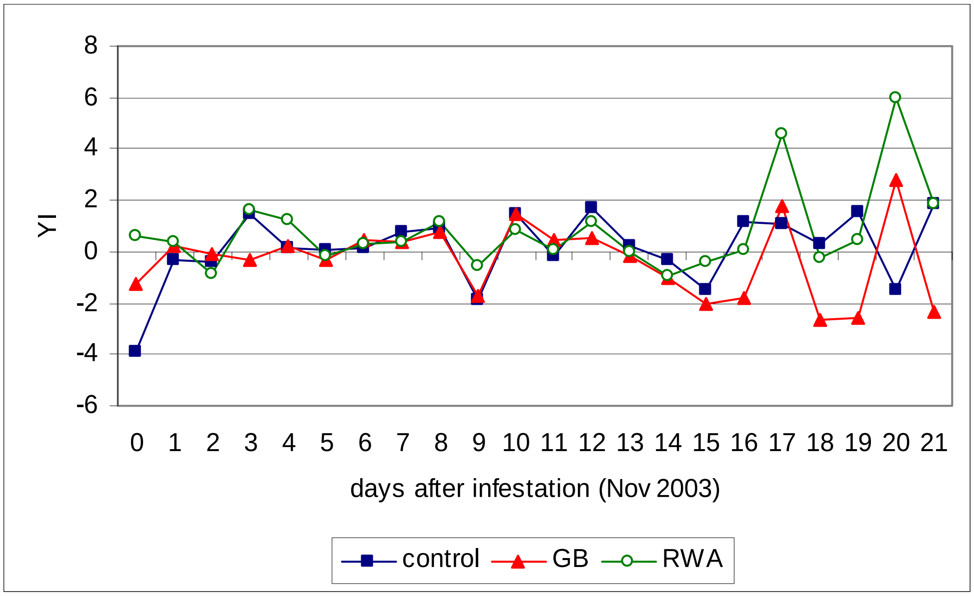


Fig 4-22. Temporal changes in YI for three treatments in comparing experiment.

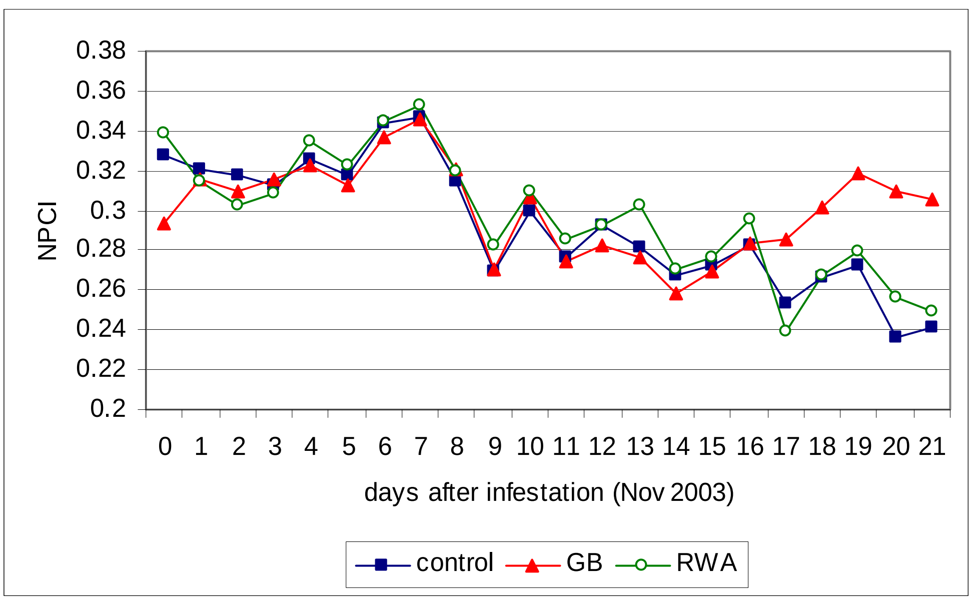


Fig 4-23. Temporal changes in NPCI for three treatments in comparing experiment.

4.5 Limitations

There are some limitations associated with the findings of this greenhouse study. First of all, reflectance measurements could be influenced by the illumination of scattered light in the greenhouse. Artificial light, structures in the greenhouse, the person who is using the Cropscan radiometer and the Cropscan radiometer are important sources of scattering light. They affect the overall illumination of the target surface by obscuring a portion of the diffuse skylight from direct solar illumination. The magnitude of both the diffuse skylight and light scattered from surrounding illumination components is determined by the solid angle subtended by these sources when viewed from the reference frame of the target surface (Curtiss and Ustin, 1988). Thus, data accuracy of reflectance may be affected.

Secondly, since reflectance measurements were conducted in the greenhouse, it is unavoidable that shading effects caused by greenhouse support structures such as beams create some unwanted shadows on the canopy and or the surface of the radiometer's up-looking sensor. In some cases, there will be large differences between irradiance on the canopy surface and the surface of the radiometer's up-looking sensor because of serious shadows and shadow variations. These phenomena violate the assumption of the Cropscan's working principle. Thus, reflectance measurements will be greatly influenced. This could impact subsequent analysis.

Thirdly, this study is basically a greenhouse study and thus research findings obtained from this study may not be directly extended to field application. Under field conditions, canopy structures, leaf orientation and plant density may be different from those in the greenhouse and could be changed due to some factors such as wind. Sensitivities of some sensitive bands and vegetation indices could change under field conditions and need to be tested in the field experiments.

4.6 Conclusions

Based on the above results and discussions, it was concluded that

(1) Among the 16 bands of the Cropscan radiometer, the bands including band 630 nm and 694 nm were most sensitive to greenbug infestation (see Table 4-6);

(2) Among the 128 vegetation indices examined in this study, the vegetation indices derived using the bands including 694 and 800 nm were most sensitive to greenbug infestation and the most effective indices are ratio-based vegetation indices (see Table 4-6);

(3) No single band could be used to differentiate greenbug infestation from water stress and infestation by Russian wheat aphids;

(4) RVI_800_694, RVI_830_660, RVI_900_694, RVI_950_694 and VI2_800_694 could be used to differentiate water stress from greenbug infestation and RVI_800_450, RVI_900_450 and NPCI could be used to distinguish greenbug infestation from infestation caused by Russian wheat aphids;

(5) Broad Landsat TM bands and their derived vegetation indices could be used to detect greenbug infestation on wheat;

(6) Since this study was based on greenhouse experiments, sensitive band and vegetation indices determined in this study may not be directly extended to field detection of greenbug infestation.

CHAPTER 5

Summary and Recommendations

The main purpose of this chapter is to summarize results obtained from experiments in this study and make recommendations.

5.1 Summary

Greenbug (*Schizaphis graminum,* Rondani) is an important pest of cereal crops. The Greenbug outbreak appears in the Great Plains almost every year and has caused significant economic impact on wheat and sorghum yield. Early detection of greenbug infestation becomes a critical part of integrated pest management (IPM) for wheat and sorghum production. Remote sensing techniques can identify pest infestations in agricultural fields, and ground-based radiometry can provide a vital tool to study such stress in crop plants. The purpose of this greenhouse study was to characterize stress in wheat caused by greenbug infestation and identify bands and vegetation indices that were sensitive to greenbug infestation.

Based on extensive literature review, crop stress due to adverse conditions, such as nutrient deficiency, pest infestation, diseases, and drought, can be detected using remote sensing techniques. It has been demonstrated that symptoms of crop stress can be visualized at wavelengths such as red and near infrared, and measured using vegetation indices such as NDVI. Ground-based radiometry is a basic way to test the feasibility of detecting greenbug-induced wheat stress by using images from satellites and aircraft. Thus, a hand-held Cropscan radiometer with 16 bands (5 bands simulating Landsat bands and 11 narrow bands) was selected to conduct a greenhouse study to identify bands and vegetation indices that are sensitive to greenbug infestation. In this study, different experiments involving treatments such as infestation and water stress were conducted on flat-grown wheat plants. The experiments conducted in this study included three experiments to test sensitivities of bands and vegetation indices, three experiments to differentiate water stress and greenbug infestation, one experiment to test impact of the growth stage on the detection of greenbug infestation, and one experiment to compare infestations by greenbugs and Russian wheat aphids.

Reflectance data and derived vegetation indices from the 16 bands of the radiometer for all experiments were analyzed using SAS PROC MIXED for statistical significance. Threshold Days for each band/vegetation index were determined by comparing p value at significance level = 0.05. Then sensitive bands/vegetation indices could be initially identified based on comparison between their Threshold Days and Maximum Day. Correlation analyses were used to test the relationship between greenbug density and differences in reflectance at each band and vegetation index between control and infested plants. Sensitivity analysis was used to compare relative sensitivities of different bands and vegetation indices. After correlation and sensitivity analysis, sensitive bands and vegetation were determined. It was found that 630 and 694 nm were the most sensitive bands to greenbug infestation. Interestingly, the most sensitive vegetation indices were simple ratio-based indices (See Table 4-4), and most NDVI or SAVI did not show high sensitivities. Particularly, the vegetation indices derived using band 800 nm and 694 nm were identified as most sensitive to greenbug infestation. Broad Landsat TM bands and their derived vegetation indices also show potential for detecting wheat stress caused by greenbug infestation.

Sensitive bands and vegetation indices were tested to see if they could be used to differentiate greenbug infestation and water stress. Results showed that it is difficult to differentiate greenbug infestation and water stress using reflectance at any single band. However, five vegetation indices - RVI_800_694, RVI_830_660, RVI_900_694, RVI_950_694 and VI2_800_694 - show high potential to differentiate greenbug infestation from water stress.

The impact of plant growth stage on the detection of greenbug infestation was explored and it was found that Threshold Days for sensitive band and vegetation indices were smaller for plants infested at the two-leaf stage than for plants infested at the tillering stage.

Finally, the comparison between greenbug infestation and the infestation by Russian wheat aphid was also conducted. Results showed that the band 450 nm and the vegetation indices: NPCI, RVI_800_450, RVI_900_450 could be used to distinguish infestation caused by greenbugs from infestation caused by Russian wheat aphids.

In practice, crop growth is very dynamic and monitoring the condition of agricultural crops is a complex issue. This study is a step toward the goal of using remote sensing technology to analyze canopy reflectance of wheat to identify greenbug outbreaks. Under field conditions, wheat canopy complexity increases and the characteristics of the spectral response to greenbug infestation as outlined above may change under other environmental factors such as wind and temperature. Other crop stresses such as disease, nutrient deficiency that result in leaf chlorosis, mottling, and necrosis, can also have similar effects on crop canopy reflectance spectra (Malthus and Madeira, 1993). Thus, the spectral relationships identified in this study may not be unique to greenbug infestation under field conditions. This may complicate the use of remote sensing to detect greenbug infestation in a crop protection context. However, this study demonstrated the feasibility of using remote sensing to detect greenbug infestation at the canopy level. It is possible that results from this study can be extended to field detection of wheat stress caused by greenbug infestation.

5.2 Recommendations

In the future, more canopy-level-studies are needed to identify sensitive bands and vegetation indices. The Cropscan radiometer used in this study only has 16 bands and one band (694 nm) in the red edge portion (680-750 nm). It is possible that a hyper-spectral sensor, such as ASD (Analytical Spectral Devices) field spectrometer, might provide better performance if used in this study because of more available bands, especially in the red edge portion. A typical ASD field spectrometer has a 0.35-2.5 μm spectral range and 10 nm spectral resolution. Thus, a hyper-spectral study should be done to define the most sensitive bands and vegetation indices using an ASD field spectrometer or similar devices.

Secondly, experiments to distinguish greenbug-induced stress and other stresses such as nitrogen stress and plant disease on wheat are necessary. Nutrient deficiency could interact with greenbug infestation on plants, and plant diseases also could have confounding effects. In addition, infestation by other aphids such as bird oat cherry aphid *(Rhopalosiphum padi)* also needs to be studied. It is possible to further define sensitive bands and vegetation indices and make them more effective in the detection of greenbug infestation.

Thirdly, field studies are necessary to test sensitivities and reliabilities of sensitive bands and vegetation indices determined in this study. Thus field studies on wheat stress caused by greenbug infestation by aircraft and satellites should be conducted to make this technique a cost-effective and practical method useful for farmers.

Fourthly, it would be very useful to investigate the unique spatial patterns associated with greenbug infestation in the field. Typical "greenbug spots" in a field are different from those of other stresses, such as water stress. The use of this fact for detecting greenbug infestation has not been tested. It is necessary to examine differences of spatial patterns among different stresses.

In addition, how remote sensing results can be integrated within decision support systems such as Cereal Aphid Expert System (CAES) needs to be explored. In other words, the detection of greenbug infestation by remote sensing needs to developed into a decision tool with which farmers can decide (a treatment threshold) where and how much pesticide should be applied or what IPM methods should be used.

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Appendix

A. Excel VB scripts

(1) Formula.xls to calculate vegetation indices

```
Public Sub calculate()

'Author: Mahesh Rao, modified by zhiming on July 03 for old dataset and Nov 13, 03
for new dataset
'Date: March 20, 2003
' code calculates various vegetation indices from the CROPSCAN data,
' indices are calculated for each sample measurement (3 measurement for each flat),
 ' and then averaged to give a mean NDVI for each flat.
' the means are transferred to another sheet - alldays.xls
' alldays.xls should be open

wb = ActiveWorkbook.Name
Nm = ActiveSheet.Name
Flatmeans = InputBox("Enter Date of Sampling", "Date", "mmddyy")

formulabook = InputBox("Enter Excel file Name in which VI formulae exist", "File
Name", "formula.xls")
   Windows(formulabook).Activate
   Range("W8:EV12").Select

   Selection.Copy
   Windows(wb).Activate
   Sheets(Nm).Activate
   Range("W8:W8").Select

   Selection.PasteSpecial Paste:=xlFormulas, Operation:=xlNone, SkipBlanks:= _
      False, Transpose:=False
With ActiveSheet
   u = .UsedRange.Rows.Count
   If .Cells(u, 1).Value = "END" Then
   .Rows(u).Delete
   End If
End With
Sheets.Add
```

```
With ActiveSheet
  ActiveSheet.Name = Flatmeans
End With

Sheets(Nm).Select

ctr = 1
With ActiveSheet
       ' Copy formula accross the sheet
       .Range("W12:EV12").Select

       Selection.Copy
       .Range("W13:EV" & u - 1).Select

       Selection.PasteSpecial Paste:=xlFormulas, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=False
 k = 15
    ' insert rows for averages
    Do While .Cells(k, 1).Value <> 0
       .Rows(k).Insert
       k = k + 4
    Loop

       For j = 12 To .UsedRange.Rows.Count
       If .Cells(j, 1).Value = "" And j <> .UsedRange.Rows.Count Then

          .Range("a" & j - 1 & ":" & "b" & j - 1).Copy Destination:=.Range("a" & j &
":" & "b" & j)
          .Range("e" & j - 1).Copy Destination:=.Range("e" & j)
          .Range("g" & j).Formula = "=Average(g" & j - 3 & ":" & "g" & j - 1 & ")"
          .Range("g" & j).Copy Destination:=.Range("g" & j & ":" & "EV" & j)

          .Rows(j).Copy
          Sheets(Flatmeans).Select
          Rows(ctr).Select
          Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, _
       SkipBlanks:=False, Transpose:=False
          Sheets(Nm).Select
          ctr = ctr + 1
       ElseIf j = .UsedRange.Rows.Count Then ' last row
          j = j + 1
          .Range("a" & j - 1 & ":" & "b" & j - 1).Copy Destination:=.Range("a" & j &
":" & "b" & j)
          .Range("e" & j - 1).Copy Destination:=.Range("e" & j)
          .Range("g" & j).Formula = "=Average(g" & j - 3 & ":" & "g" & j - 1 & ")"
          .Range("g" & j).Copy Destination:=.Range("g" & j & ":" & "EV" & j)
```

```
            .Rows(j).Copy
            Sheets(Flatmeans).Select
            Rows(ctr).Select
            Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, _
        SkipBlanks:=False, Transpose:=False
            Sheets(Nm).Select
            ctr = ctr + 1

        End If
    Next j

    'some formatting
    Sheets(Flatmeans).Select
    Rows(1).Insert
    Rows(1).Insert
    Rows(1).Insert
    Sheets(Nm).Select
    Range("G8:EV10").Select

    Application.CutCopyMode = False
    Selection.Copy
    Sheets(Flatmeans).Select
    Range("G1:EV3").Select

    ActiveSheet.Paste
    Selection.Font.Bold = True

    'move to a single file
    Sheets(Flatmeans).Select
    '
    'Sheets(Flatmeans).Move Workbooks("alldays.xls").End
    Sheets(Flatmeans).Move before:=Workbooks("alldays.xls").Sheets("First")


    'Sheets("Sheet1").Delete

End With

End Sub
```

(2) Alldays.xls to aggregate data for all days during each experiment

```
Sub Aggregate()
'
' Created 3/21/2003 by Mahesh Rao, modified by zhiming on May30,03
' code aggregates the daily average measurements along with the indices to a sheet
named "Alldays"
' run this code after you have calculated the daily mean measurements (using the
Calculate code)
' make sure "Alldays" worksheet does not exist in you alldays.xls workbook before
running this code.
'   Sheets(1).Select
   Sheets.Add
   ActiveSheet.Name = "AllDays"
   Sheets("First").Delete

   ctr = 1
   Sheets(2).Select
   For i = 2 To Sheets.Count
      If i = 2 Then
         Sheets(i).Select
         r = ActiveSheet.UsedRange.Rows.Count
         Rows("1:" & r).Select

         Application.CutCopyMode = False
         Selection.Copy
         Sheets("AllDays").Select
         Rows(ctr).Select

         ActiveSheet.Paste
         ctr = ActiveSheet.UsedRange.Rows.Count
         ctr = ctr + 1
      ElseIf i > 2 Then
      Sheets(i).Select
      nRows = ActiveSheet.UsedRange.Rows.Count
      Rows("4:" & nRows).Select 'Rows("4:25").Select
      Selection.Copy
      Sheets("AllDays").Select
      Rows(ctr).Select
      ActiveSheet.Paste
      ctr = ActiveSheet.UsedRange.Rows.Count
      ctr = ctr + 1
      End If
   Next i
   Range("A2").Select
   ActiveCell.FormulaR1C1 = "Date"
```

```
    Range("B2").Select
    ActiveCell.FormulaR1C1 = "Time"
    Range("e2").Select
    ActiveCell.FormulaR1C1 = "Trt"
    rws = ActiveSheet.UsedRange.Rows.Count
    Range("G4:EU" & rws).Select

Selection.NumberFormat = "0.0000"
End Sub
```

B. SAS programs

(1)TEMPLATE_RTF_ARIAL.SAS

```
PROC TEMPLATE;
 DEFINE STYLE RTFArial;
 PARENT=Styles.RTF;
  REPLACE fonts /
    'TitleFont2' = ("Arial",10pt,Bold Italic)
    'TitleFont' = ("Arial",10pt,Bold Italic)
    'StrongFont' = ("Arial",10pt,Bold)
    'EmphasisFont' = ("Arial",10pt,Italic)
    'FixedEmphasisFont' = ("Arial, Helvetica",9pt,Italic)
    'FixedStrongFont' = ("Arial, Helvetica",9pt,Bold)
    'FixedHeadingFont' = ("Arial, Helvetica",9pt,Bold)
    'BatchFixedFont' = ("SAS Monospace, Courier",6.7pt)
    'FixedFont' = ("Arial, Helvetica",9pt)
    'headingEmphasisFont' = ("Arial",10pt,Bold Italic)
    'headingFont' = ("Arial",10pt)
    'docFont' = ("Arial",10pt);
  END;

RUN;
```

(2) MIXED_CALL.SAS

```
LIBNAME A 'H:\crop603';
OPTIONS PAGENO=1 NODATE;
data A.TRT; set A.MEASURE;
 FORMAT DATE MMDDYY10.;

%MACRO MIXED02(VAR_FIT,COVAR) ;
PROC MIXED DATA=A.TRT;
 CLASS TREATMENT PLOT DATE;
 MODEL &VAR_FIT = TREATMENT DATE TREATMENT*DATE /
DDFM=KENWARDROGER;
 REPEATED / TYPE=&COVAR SUBJECT=PLOT(TREATMENT);
 LSMEANS TREATMENT DATE TREATMENT*DATE;
 LSMEANS TREATMENT*DATE / SLICE=DATE;

  TITLE "&VAR_FIT";
  RUN;
%MEND;

%LET FIT_VAR=BAND450;      %INCLUDE 'H:\sas04\MIXED_MACRO.SAS';
%LET FIT_VAR=BAND485;      %INCLUDE 'H:\sas04\MIXED_MACRO.SAS';
```

```
DATA A;
 SET BAND450
    BAND485
         ;
 ABS_VALUE=ABS(VALUE);
 AICC=ABS_VALUE;

PROC SORT DATA=A; BY VAR_FIT;

PROC MEANS DATA=A NOPRINT; BY VAR_FIT; VAR ABS_VALUE; OUTPUT
OUT=MIN_FIT MIN=AICC;

DATA MIN_FIT; SET MIN_FIT; MARK='*';

PROC SORT DATA=A; BY VAR_FIT AICC;
PROC SORT DATA=MIN_FIT; BY VAR_FIT AICC;

DATA A.MIN_FIT; MERGE MIN_FIT A; BY VAR_FIT AICC; IF MARK='*';
 DROP _TYPE_ _FREQ_ MARK AICC;

ods rtf file='H:\sas04\slices.rtf' STYLE=RTFArial;
ods NOPTITLE;
ods select slices(persist);
DATA _NULL_; SET A.MIN_FIT;
 CALL EXECUTE ('%MIXED02('||VAR_FIT||','||COVAR||')') ;
run;
ods rtf close;

RUN; QUIT;
```

(3)MIXED_MACRO.SAS

```
ODS LISTING CLOSE;
ODS OUTPUT FITSTATISTICS=VC;

PROC MIXED DATA=A.TRT;
 *PROC MIXED DATA=A.MEASURE;
 CLASS TREATMENT PLOT DATE;
 *MODEL &FIT_VAR = TREATMENT DATE / E3;
 *MODEL &FIT_VAR = TREATMENT DATE / DDFM=KENWARDROGER;
 MODEL &FIT_VAR = TREATMENT DATE TREATMENT*DATE /
DDFM=KENWARDROGER;
 REPEATED / TYPE=VC SUBJECT=PLOT(TREATMENT) R RCORR;

 RUN;
```

```
ODS OUTPUT CLOSE;

DATA VC; SET VC; LENGTH COVAR $ 5; COVAR='VC'; IF DESCR='AICC
(smaller is better)';

ODS OUTPUT FITSTATISTICS=AR;
PROC MIXED DATA=A.TRT;
 *PROC MIXED DATA=A.MEASURE;
 CLASS TREATMENT PLOT DATE;
 *MODEL &FIT_VAR = TREATMENT DATE / E3;
 *MODEL &FIT_VAR = TREATMENT SDATE/ DDFM=KENWARDROGER;
 MODEL &FIT_VAR = TREATMENT DATE TREATMENT*DATE /
DDFM=KENWARDROGER;
 REPEATED / TYPE=AR(1) SUBJECT=PLOT(TREATMENT) R RCORR;
 RUN;

ODS OUTPUT CLOSE;

DATA AR; SET AR; LENGTH COVAR $ 5; COVAR='AR(1)'; IF DESCR='AICC
(smaller is better)';

ODS OUTPUT FITSTATISTICS=CS;
PROC MIXED DATA=A.TRT;
 *PROC MIXED DATA=A.MEASURE;
 CLASS TREATMENT PLOT DATE;
 *MODEL &FIT_VAR = TREATMENT DATE / E3;
 *MODEL &FIT_VAR = TREATMENT SDATE / DDFM=KENWARDROGER;
 MODEL &FIT_VAR = TREATMENT DATE TREATMENT*DATE /
DDFM=KENWARDROGER;
 REPEATED / TYPE=CS SUBJECT=PLOT(TREATMENT) R RCORR;
 RUN;

ODS OUTPUT CLOSE;

DATA CS; SET CS; LENGTH COVAR $ 5; COVAR='CS'; IF DESCR='AICC (smaller
is better)';

DATA &FIT_VAR; SET VC AR CS; LENGTH VAR_FIT $ 14;
VAR_FIT="&FIT_VAR"; DROP DESCR;

ODS LISTING;

RUN; QUIT;
```

C. SAS PROC MIXED outputs

See following example pages

ARVI

Tests of Effect Slices

Effect	DATE	Num DF	Den DF	F Value	Pr > F
TREATMENT*DATE	02/01/02	1	160	1.74	0.1887
TREATMENT*DATE	02/02/02	1	160	1.51	0.2215
TREATMENT*DATE	02/03/02	1	160	3.22	0.0744
TREATMENT*DATE	02/04/02	1	160	6.12	0.0144
TREATMENT*DATE	02/05/02	1	160	13.89	0.0003
TREATMENT*DATE	02/06/02	1	160	4.32	0.0392
TREATMENT*DATE	02/07/02	1	160	5.77	0.0175
TREATMENT*DATE	02/08/02	1	160	2.93	0.0892
TREATMENT*DATE	02/09/02	1	160	4.97	0.0273
TREATMENT*DATE	02/10/02	1	160	6.01	0.0153
TREATMENT*DATE	02/11/02	1	160	4.09	0.0448
TREATMENT*DATE	02/12/02	1	160	3.34	0.0694
TREATMENT*DATE	02/13/02	1	160	4.11	0.0442
TREATMENT*DATE	02/14/02	1	160	9.14	0.0029
TREATMENT*DATE	02/15/02	1	160	4.56	0.0342
TREATMENT*DATE	02/16/02	1	160	6.86	0.0096
TREATMENT*DATE	02/17/02	1	160	6.43	0.0122
TREATMENT*DATE	02/18/02	1	160	1.34	0.2485
TREATMENT*DATE	02/19/02	1	160	3.00	0.0852
TREATMENT*DATE	02/20/02	1	160	3.89	0.0502
TREATMENT*DATE	02/21/02	1	160	5.96	0.0157
TREATMENT*DATE	02/22/02	1	160	1.74	0.1891
TREATMENT*DATE	02/23/02	1	160	2.20	0.1400
TREATMENT*DATE	02/24/02	1	160	5.68	0.0183
TREATMENT*DATE	02/25/02	1	160	6.32	0.0129
TREATMENT*DATE	02/26/02	1	160	6.92	0.0093
TREATMENT*DATE	02/27/02	1	160	13.76	0.0003
TREATMENT*DATE	02/28/02	1	160	20.37	<.0001
TREATMENT*DATE	03/01/02	1	160	31.42	<.0001
TREATMENT*DATE	03/02/02	1	160	30.46	<.0001
TREATMENT*DATE	03/03/02	1	160	20.88	<.0001
TREATMENT*DATE	03/04/02	1	160	26.76	<.0001
TREATMENT*DATE	03/05/02	1	160	36.63	<.0001
TREATMENT*DATE	03/06/02	1	160	31.69	<.0001
TREATMENT*DATE	03/07/02	1	160	41.14	<.0001
TREATMENT*DATE	03/08/02	1	160	49.81	<.0001
TREATMENT*DATE	03/09/02	1	160	94.33	<.0001
TREATMENT*DATE	03/10/02	1	160	140.07	<.0001
TREATMENT*DATE	03/11/02	1	160	185.04	<.0001
TREATMENT*DATE	03/12/02	1	160	231.89	<.0001

BAND1480nm

Tests of Effect Slices

Effect	DATE	Num DF	Den DF	F Value	Pr > F
TREATMENT*DATE	02/01/02	1	113	12.19	0.0007
TREATMENT*DATE	02/02/02	1	113	77.84	<.0001
TREATMENT*DATE	02/03/02	1	113	17.28	<.0001
TREATMENT*DATE	02/05/02	1	113	0.65	0.4217
TREATMENT*DATE	02/06/02	1	113	0.83	0.3631
TREATMENT*DATE	02/07/02	1	113	22.89	<.0001
TREATMENT*DATE	02/08/02	1	113	0.59	0.4440
TREATMENT*DATE	02/09/02	1	113	19.21	<.0001
TREATMENT*DATE	02/10/02	1	113	4.76	0.0312
TREATMENT*DATE	02/11/02	1	113	2.96	0.0881
TREATMENT*DATE	02/12/02	1	113	0.48	0.4918
TREATMENT*DATE	02/13/02	1	113	11.35	0.0010
TREATMENT*DATE	02/14/02	1	113	0.36	0.5497
TREATMENT*DATE	02/15/02	1	113	6.53	0.0119
TREATMENT*DATE	02/16/02	1	113	3.73	0.0561
TREATMENT*DATE	02/17/02	1	113	0.64	0.4252
TREATMENT*DATE	02/18/02	0	.	.	.
TREATMENT*DATE	02/19/02	1	113	1.08	0.3005
TREATMENT*DATE	02/20/02	1	113	1.72	0.1919
TREATMENT*DATE	02/21/02	1	113	1.69	0.1956
TREATMENT*DATE	02/22/02	1	113	0.91	0.3414
TREATMENT*DATE	02/23/02	1	113	0.75	0.3884
TREATMENT*DATE	02/24/02	1	113	0.23	0.6320
TREATMENT*DATE	02/26/02	1	113	0.11	0.7464
TREATMENT*DATE	02/27/02	1	113	16.34	<.0001
TREATMENT*DATE	02/28/02	1	113	0.78	0.3797
TREATMENT*DATE	03/01/02	1	144	0.40	0.5293
TREATMENT*DATE	03/02/02	1	113	0.92	0.3404
TREATMENT*DATE	03/03/02	1	113	19.00	<.0001
TREATMENT*DATE	03/04/02	1	113	2.51	0.1161
TREATMENT*DATE	03/05/02	1	113	1.85	0.1768
TREATMENT*DATE	03/06/02	1	113	4.62	0.0338
TREATMENT*DATE	03/07/02	1	113	2.79	0.0976
TREATMENT*DATE	03/08/02	1	128	10.93	0.0012
TREATMENT*DATE	03/09/02	1	113	15.85	0.0001
TREATMENT*DATE	03/10/02	1	113	8.57	0.0041
TREATMENT*DATE	03/11/02	1	113	32.20	<.0001
TREATMENT*DATE	03/12/02	1	113	12.04	0.0007

Vita

Zhiming Yang

Candidate for the Degree of Doctor of Philosophy

DISSERTATION: DETECTION OF GREENBUG INFESTATION USING GROUND-BASED RADIOMETRY

EDUCATION:

M.S., Environmental Science, August 2000
The Ohio State University, Columbus, OH
B.S., Environmental Chemistry, July 1986
Jilin University, Changchun, P.R.China

RELEVANT EXPERIENCE:

Oklahoma State University, Oklahoma

- Detection of Greenbug infestation using a field radiometer (April 01- Present)

Ohio Supercomputer Center, Columbus, Ohio

- Management of web site (May 00 – Aug 00)

Chinese Research Academy of Environmental Science

- Program manager, Center for Environmental Assessment & Planning (March, 1994 - August, 1998)
- Researcher, Atmosphere Environment Institute (July, 1986 - March, 1991 and March, 1992 - March, 1994)

Research fields or activities: Environmental pollution control, Acid Rain and effect, Environmental management, Environmental impact assessment, Environmental monitoring and Chemistry analysis, Environmental planning and remedy and etc.

Chinese National Environmental Protection Bureau

- Office Assistant (March, 1991 - March, 1992)

Varied administrative tasks

RESEARCH PUBLICATIONS:

- Published six articles on environmental management, acid rain, environmental impact assessment and remote sensing
- Co-authored two books on environmental management and traffic pollution;
- Author or co-author of more than 20 scientific reports.

PROFESSIONAL AFFILIATIONS

Association of American Geographers

Association of Chinese Environmental Science

Name: Zhiming Yang Date of Degree: May, 2005

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: DETECTION OF GREENBUG INFESTATION ON WHEAT USING GROUND-BASED RADIOMETRY

Pages in Study: 131 Candidate for Degree of Doctor of Philosophy

Major Field: Environmental Science

Scope of Methods of Study: The purpose of this greenhouse study was to characterize stress in wheat caused by greenbugs using ground-based radiometry. Experiments were conducted to (a) identify spectral bands and vegetation indices sensitive to greenbug infestation; (b) differentiate stress caused due to greenbugs from water stress; (c) examine the impacts of plant growth stage on detection of greenbug infestation; and (d) compare infestations due to greenbug and Russian wheat aphid. Wheat (variety-TAM 107) was planted (seed spacing 1 in. x 3 in.) in plastic flats with dimension 24 in. x 16 in. x 8.75 in. Fifteen days after sowing, wheat seedlings were infested with greenbugs (biotype-E). Nadir measurement of canopy reflectance started the day after infestation and lasted until most infested plants were dead. Using a 16-band Cropscan radiometer, spectral reflectance data were collected daily (between 13:00-14:00 hours) and 128 vegetation indices were derived in addition to greenbug counts per tiller. Using SAS PROC MIXED, sensitivity of band and vegetation indices was identified based on Threshold Day. Subsequent to Threshold Day there was a consistent significant spectral difference between control and infested plants. Sensitivity of band and vegetation indices was further examined using correlation and relative sensitivity analyses.

Findings and Conclusions: Results show that it is possible to detect greenbug-induced stress on wheat using hand-held radiometers, such as Cropscan. Band 694 nm and the ratio-based vegetation index (RVI) derived from the band 694 nm and 800 nm were identified as most sensitive to greenbug infestation. Landsat TM bands and their derived vegetation indices also show potential for detecting wheat stress caused by greenbug infestation. Also, RVIs particularly derived using spectral band 694 nm and 800 nm were found useful in differentiating greenbug infestation from water stress. Furthermore, vegetation indices such as Normalized total Pigment to Chlorophyll Index (NPCI) could be used to distinguish greenbug infestation and infestation caused by Russian wheat aphid. Finally, stress was detected in a shorter time interval when wheat plants were infested with greenbugs at two-leaf stage than wheat plants infested at tillering stage. This study demonstrated the utility of adopting remote sensing techniques for detecting greenbug infestation on wheat. Further field-based studies are suggested to apply the technology that has great potential for integrated pest management.

ADVISOR'S APPROVAL: Mahesh Rao