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Authors
Reisig, D
Godfrey, L

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Dominic D. Reisig
Department of Entomology
University of California, Davis
One Shields Ave.
Davis, CA 95616
Tel: (530) 752-0488
Fax: (530) 752-1537
ddreisig@ucdavis.edu

Remote sensing for detection of cotton aphid (Homoptera: Aphididae) and spider mite- (Acari: Tetranychidae) infested cotton in the San Joaquin Valley

Dominic Reisig and Larry Godfrey

Department of Entomology, University of California, Davis, One Shields Ave., Davis, CA 95616

ABSTRACT. We explored remote sensing methods for their potential to distinguish aphid (*Aphis gossypii* Glover) and spider mite-infested (*Tetranychus* spp.) cotton (*Gossypium hirsutum* L.) from uninfested cotton. Field plots were established using selective and disruptive pesticides to establish a range of aphid and mite populations over 2 years. Aerial and satellite remote sensing data in 2003 and 2004 were supplemented with ground-based remote sensing data, in 2004, and by ground-truthing of arthropod populations in both years. Mite and aphid-infested cotton was detected using aerial data in the green and near-infrared (NIR) wavelengths in 2003, with sub-economic threshold aphid population levels. At the time aerial data were collected, mite populations peaked at 95% leaves infested and exceeded treatment threshold levels of 30-50% leaves infested. However, the number of mites per leaf in the treatments was low to moderate (32, 9, 4, 6 and 2 average mites/leaf). Moreover, cotton infested with cotton aphids above economic threshold levels was consistently detected using NIR wavelengths from the satellite data in 2004. Similarly, aphid-infested cotton was detected at both sub and supra-economic threshold aphid levels using NIR wavelengths from the ground-based remote sensing data. Finally, accumulated mite-days were linearly correlated with a canopy, false color, and a vegetation index using satellite data in 2004. Wavelengths in the NIR were fair to moderately accurate predictors of aphid and mite infested cotton.

KEY WORDS. Accumulated aphid-days, accumulated mite-days, Integrated Pest Management, near-infrared, remote sensing.

Introduction

Cotton aphids (*Aphis gossypii* Glover) and spider mites (*Tetranychus* spp.) are economically important pests of cotton (*Gossypium hirsutum* L.) in the San Joaquin Valley (SJV) of California. Cotton aphids feed by piercing the phloem, usually on the abaxial surface, and removing the assimilates. The carbohydrates from the phloem are metabolized by the aphids and are excreted, often deposited on the leaves of the cotton plant as a complex sticky substance referred to as honeydew. Honeydew on the leaves causes them to become glossy, as a result of the increase in light reflected off the honeydew, and may cause lint contamination, commonly called "sticky cotton". Spider mites feed on the abaxial surface of cotton leaves by piercing plant cells with their stylets and assimilating the contents. The chloroplasts are removed, leaving the dead cell, which appears brown. Damage proceeds from small yellowish to reddish spots on the leaves, to leaf bronzing, and, in the case of a serious infestation, complete defoliation.

Cotton aphid management is most critical after the open boll stage of cotton in order to protect the exposed lint. The economic threshold for aphids before the open boll stage is 50-75 aphids per leaf for at least 7-10 days (5^{th} mainstem node leaf from the top) (Godfrey et al. 2005a) and this threshold declines to 5 aphids per leaf after boll opening (Godfrey et al. 2004, 2005b). Although economic damage does not occur until 80% of the leaves are infested ($6\text{-}9^{th}$ mainstem node leaf from the top) (Wilson et al. 1991) with spider mites, the treatment threshold is set at 30-50% infested leaves (5^{th} mainstem node leaf from the top) to allow time for the acaricide to manage the infestation before economic loss (Godfrey et al. 2005a).

Remote sensing is a precision technology, with roots in the aerospace and defense sectors, and acquires information about objects without being in contact with the objects. Airborne sensors can be used in agriculture, by capitalizing on their ability to detect light reflected off of large areas of vegetation. Vegetation indices can be created from the data by combining spectral measurements from different wavelengths; these are useful because they convert multidimensional data into a single value.

Several studies in cotton have evaluated the potential of remote sensing methods to facilitate arthropod pest management (Everitt et al. 1994, 1996, Summy et al. 1997, Brewster et al. 1999, Fitzgerald et al. 1999, 2000, 2004, Willers et al. 1999, Riedel et al. 2001, Sudbrink et al. 2003). Several studies found the wavelengths in the NIR to be the best indicators of arthropod-damaged cotton (Everett et al. 1994, 1996, Summy et al. 1997, and Fitzgerald et al. 1999, 2000, 2004). Although the study done by Brewster et al. (1999) included a ground survey and classification of crop types most likely to be attacked by whiteflies (*Bemisia argentfolii* Bellows & Perring) and the study done by Sudbrink et al. (2003) included a visual rating of pest damage, only the studies done by Summy et al. (1997) and Willers et al. (1999) incorporated extensive ground-based insect monitoring (ground-truthing). For remote sensing to be a useful management tool for Integrated Pest Management (IPM), consideration must be given to threshold levels of arthropod infestations.

Many arthropod pests are distributed among patches within landscapes (Taylor 1984, Hughes 1996). Both spider mites and aphid infestations begin in spatially heterogeneous areas within fields (Hannah et al. 1996; L.D. Godfrey, unpublished data). In cotton, these infestations begin as small “hot spots” and grow into larger infestations (Steinkraus et al. 2003; L.D. Godfrey, unpublished data). Because of this spatial heterogeneity, the appropriate scale of detection must be applied to reveal the distribution pattern of the aphid or mite infestation within the field (Holland et al. 1999, Pearce and Zalucki 2006). Consequently, threshold levels of arthropod infestations must be considered with regard to the spatial scale of the remote sensor that is used.

The goal of this study was to incorporate ground-truthing with remote sensing methods and to explore the application of this technique for cotton aphid and spider mite monitoring in SJV cotton IPM. It was hypothesized that these arthropods, at sub-threshold levels, would change leaf reflectance and that this could be detected using remote sensing. Both of these pests occur in heterogeneous areas of the field, but current monitoring and treatment are done on an intra-field basis. Using remote sensing in combination with ground-truthing, it may be possible to shift these management efforts to an inter-field basis, which would potentially save resources and protect the environment by limiting whole-field pesticide applications.

Materials and Methods

Field preparation. Cotton was planted at ca.13 seeds/m on 5 May 2003 (Maxxa) and 26 April 2004 (NemX) at the University of California (UC) Shafter Research and Extension Center near Shafter, CA. Twenty plots (~15.2 m long x ~8.1 m wide [8 rows]) were arranged in a randomized complete block design (4 replications per treatment) with resident populations of cotton aphids (*Aphis gossypii* Glover) and spider mites (*Tetranychus* spp.). Spider mites are a perennial pest of cotton in the SJV and populations normally develop by July. In 2003, however, spider mite populations did not develop until mid-August, while spider mite populations developed in July 2004. Additionally, the spring in 2003 was unseasonably wet and the cotton was planted later than usual. By mid-July 2003, there was only >1 aphid per leaf (5^{th} mainstem node leaf from the top of the plant). In contrast, aphid populations were ca.12 aphids per leaf by mid-July 2004.

Cotton aphids have been a severe pest of the SJV during the last ten years. Because aphid populations are favored by high nitrogen levels (Cisneros and Godfrey 2001), all the plots were fertilized with 252 kg N/ha of ammonium sulfate (21-0-0) on 24 June and liquid urea (Un32) on 9 July in 2003 to favor population development (this amount is on the upper end used by growers). A more commonly used fertilizer regiment was employed in 2004, because aphids were more abundant than in 2003. Thus, the fields were fertilized according to UC recommendations and a nitrogen Un32 application was applied at 90 kg N/ha on 24 June 2004 (Basset et al. 1996). No potassium or phosphorus was applied to the field.

Weed control and furrow irrigation followed the recommendations of the UC (Bassett et al. 1996, Bell et al. 1996, Vargas and Wright 2005). No plant growth regulators were used on the tests in either year. Yields were assessed on 18 November 2003 and on 3 November 2004 by harvesting two rows per plot using a John Deere 9910 cotton picker (Deere, Moline, IL), which was adapted to pick into sacks. The sacks with cotton were weighed and seed cotton yields per acre were calculated.

Arthropod populations were monitored in 2003 from 23 June to 18 September and in 2004 from 16 July to 1 September. Whiteflies populations were well below treatment levels in 2003, but in 2004, all the plots were treated with buprofezin (Courier at 298.1 g [AI]/ha, Nichino America, Inc., Wilmington, DE) on 25 July as a prophylactic treatment; this eliminated any interference that they would have caused though honeydew production.

Differential population establishment. To establish differential arthropod populations, selective and disruptive pesticide treatments were applied at the onset of population build-up for both cotton aphids and spider mites (Leigh 1980, Lasota and Dybas 1991, James 1997, Slosser et al. 2001). Five treatments were established on 11 August 2003; Acetamiprid (Assail 70WP at

53.9 g [AI]/ha, Cerexagri, Inc., King of Prussia, PA) and abamectin (Zephyr 0.15EC at 0.32 g [AI]/ha, Syngenta Crop Protection, Inc. Greensboro, NC) were applied to eliminate aphid and spider mite populations in one treatment. Additionally, bifenthrin (Capture 2EC at 16.9 g [AI]/ha, FMC Corp., Philadelphia, PA) was used to flare aphids in one treatment. Acephate (Orthene 75S at 577.9 g [AI]/ha, Valent U.S.A. Corp. Walnut Creek, CA) and abamectin were used to flare mite populations and eliminate aphids in another treatment. Finally, there was only treatment where populations were untreated.

Differential populations were also established in plots on 25 July 2004. Acetamiprid (Assail 70WP at 53.9 g [AI]/ha) and abamectin (Zephyr 0.15EC at 0.32 g [AI]/ha) were applied to eliminate aphid and spider mite populations in one treatment. Lambda-cyhalothrin (Warrior at 3.8 g [AI]/ha, Syngenta Crop Protection, Inc. Greensboro, NC) was used to flare aphids in another treatment. Acephate (Orthene 97 at 815.4 g [AI]/ha, Valent U.S.A. Corp. Walnut Creek, CA) and abamectin were used to flare mite populations and eliminate aphids in another treatment. In addition, acephate (Orthene 97 at 815.4 g [AI]/ha) was applied a second time on 5 August 2004 to the plots previously treated with Orthene 97, because spider mite populations were slow to build. Acetamiprid and abamectin were used to eliminate both aphids and mites in another treatment. Finally, there was only treatment where populations were untreated. Lambda-cyhalothrin was substituted for bifenthrin in 2004 to increase aphid populations to a greater degree than the previous year (Kerns and Stewart 2000, Slosser et al. 2001), although aphid populations were much higher overall in 2004 than 2003.

Sampling. Ground-truthing data were collected by sampling for aphids and mites at weekly intervals (approximate) within the plots. Both cotton aphids and spider mites were sampled in 2003 by collecting 10-leaf samples (5th mainstem node leaf from the top of the plant) per plot and counting the individuals in the laboratory under 50x magnification. Twenty-leaf samples (5th mainstem node leaf from the top) were collected in 2004, making the analysis more robust by increasing the power of obtaining a true measurement of population density. Aphids were counted first and the leaves were soaked for 20 minutes in a ~0.5% bleach solution, with a drop of liquid detergent. The leaves were then washed onto a 40 mesh, followed by a 100 mesh screen, and the retained material was back-washed onto filter paper for storage and later quantification of spider mite number. From the aphid and mite numbers, accumulated aphid-days and accumulated mite-days were calculated for the period after treatment (Ruppel 1983).

Remote sensing platforms. *2003*. Flight data, provided by Opto-Knowledge Systems, Inc. (OKSI, Torrance, CA) through the USDA-ARS Western Integrated Cropping Systems Research Unit, were collected on 20 August and 11 September 2003. The flight data from 20 August were used to correspond with a range of arthropod populations that included levels above and below economic thresholds. The airplane was equipped with both a multispectral, Shafter Airborne Multispectral Remote Sensing System (SAMRSS), and hyperspectral, Airborne Visible Near Infrared (AVNIR), camera system. The SAMRSS system consisted of three 1024 x 1024 charged-coupled device cameras with filters that collected ~0.6 m resolution imagery, in four bands: green (~550 nm, 10 nm bandwidth), red (~675 nm, 10 nm bandwidth), NIR (~850 nm, 40 nm bandwidth), and thermal (~8-12 μm). Regions of interest (ROI) from these images were ~20 m^2 (55 pixels) for each plot. The AVNIR was a pushbroom hyperspectral system that collected images in 60 bands ranging from ~430 to 1,012 nm in wavelength, at a 10 nm bandwidth, with a 1.6 m spatial resolution. ROI from these images were ~13 m^2 (40 pixels) for each plot. These images were calibrated to ground-based reflectance and georectified by OKSI. The software ENVI (Research Systems Inc., Boulder, CO) was used for visualization.

2004. An airplane was also flown on 3 August 2004 before aphid and mite population levels had built in the field. This imagery was provided by InTime, Inc. (Cleveland, MS), whose airplane was equipped with a proprietary multispectral camera system that was similar to the SAMRSS system used in 2003. Spatial resolution was 1 m and ROI from these images ranged from ~78 to ~84 m^2 (78-84 pixels) for each plot. The fields were uniformly dry when all the aerial imagery was collected.

QuickBird (DigitalGlobe, Inc., Longmont, CO) satellite imagery was also acquired in 2004. QuickBird was equipped with a multispectral system that detected 3 bands, at a spatial resolution of 2.8 m, and a panchromatic sensor with a spatial resolution of 0.6 m. The images provided by DigitalGlobe, through AgriDataSensing, Inc. (Fresno, CA), were calibrated to reflectance factor at the earth's surface and were collected on 25 August 2004, 30 days after treatment. The fields were uniformly wet from flood irrigation the morning the images were taken. The images that were received were representative of information in the red, green, blue, and infrared (IR) bands; a panchromatic image was also received. Data products were provided from DigitalGlobe, which included the following images: canopy closure, green vegetation index (GVI) (Kauth and Thomas 1976), adjusted vegetation index, and a vegetation adjusted soil index. These data products were created by DigitalGlobe by processing the data through a proprietary vegetation index-type algorithm, an advanced derivative of the TSAVI model (Baret et al. 1989, Baret and Guyot 1991). All images were subjected to the same analysis in ENVI as the aerial data. ROI for the panchromatic images ranged from ~54 to 67 m^2 (170-208 pixels) for each plot, while they were ~50 m^2 (18 pixels) for each plot in the other images. More dates were not available, because of the high cost of the data collection methods and the availability of acceptable conditions for data collection (i.e. windless days for flight data, positioning of the satellite, and cloudless days for both types of data).

The flight information was supplemented with measurements on 28 July, 4, 11, 18 and 26 August 2004 using a backpack spectrometer in combination with a hand-held contact probe [FieldSpec® Pro FR (ASD), Analytical Spectral Devices, Inc., Boulder, CO]. Measurements of reflectance were made, using the spectrometer, on the adaxial surface of five random leaves in each plot. Several indices and narrow bands were analyzed (Table 1). In addition, the adaxial surface of the same leaves was scanned in five equidistant locations around the leaf edges using a Minolta Chlorophyll SPAD 502 meter (Konica Minolta, Osaka, Japan) (chlorophyll meter); this measured the relative amount of chlorophyll in the leaf using the absorbance of a wavelength in the red and NIR (exact wavelength not specified by manufacturer).

Statistical analyses. The calculated indices and representative reflectance values from the airplane data, were each, individually, analyzed using two-way ANOVA ($P<0.05$). Likewise, every band from each image in the QuickBird satellite data was subjected to a separate two-way ANOVA ($P<0.05$). A two-way ANOVA ($P<0.05$) was also performed using the yield data in 2003 and 2004. Finally, the hyperspectral ground data in 2004 were subjected to repeated measures ANOVA ($P<0.05$), using each day that measurements were taken, for both field trials. The split-plot conservative approach was taken, for the repeated measures ANOVA, by using the interaction between the block and the treatment.

Tukey's HSD procedure was used for mean separation in most of the above analyses. However, in the event that no factors were significantly different by Tukey's HSD procedure, the *P* values for the differences among means were used for mean separation (Fisher's protected LSD procedure). These results were considered marginally significant, since Fisher's protected

LSD is prone to Type I errors (Carmer and Swanson 1973). Finally, orthogonal contrasts were used to test the null hypothesis that arthropod-infested plots were significantly different than non-arthropod infested plots, when the interaction of day of measurement*treatment was significant in repeated measures ANOVA.

Data that violated the assumptions of ANOVA were transformed or, in the case that this failed for satisfying the assumption homoscedasticity, were subjected to a weighted ANOVA ($P<0.05$). Data that violated the assumptions of normality (Shapiro-Wilk value <0.95) and could not be successfully transformed using parametric transformations were subjected to non-parametric ranked ANOVA. Data presented herein are untransformed arithmetic means and standard errors.

For each treatment, the accumulated aphid-days, accumulated mite-days and yield were correlated to the index and reflectance values from the spectrometer, airborne and satellite data using Spearman rank-order correlation. Slopes were only presented if the correlations had *P* values greater than 0.05.

Error, or confusion matrices, are often used to establish the accuracy (sensitivity) and precision (specificity) of the classification model (Congalton 1991, Richards 1993, Brewster et al. 1999). Cohen's kappa (κ) was developed to solve the problem of accounting for measurements that may have been correct or incorrect due to chance (Cohen 1960, Hudson and Ramm 1987, Congalton 1991, Richards 1993, Varbyla 1995, Brewster et al. 1999). The κ statistic is expressed from -1 to 1 (if $\kappa<0$, the classification is worse than random, if $\kappa=0$ the classification scheme is no better than a random classification, and if $\kappa>0$, the classification is better than random). Generally a Cohen's kappa value of <0.2 represents a slightly accurate assessment, 0.21-0.40 a fairly accurate assessment, 0.41-0.60 a moderately accurate assessment, 0.61-0.80 a substantially accurate assessment, and 0.81-1.00 an almost perfectly accurate assessment (Groote et al. 2000, Kalra et al. 2003). Cohen's kappa does not assess accuracy perfectly and is a conservative assessment. The kappa coefficient tends to overestimate the agreement between classification sets that is due to chance, while underestimating the overall classification accuracy (Foody 1992, Lo and Yeung 2002).

Utility of the green band (~550 nm), NIR band (~850 nm), narrow band wavelengths at ~579 and ~880 nm, and the NDVI and GNDVI were assessed using Cohen's kappa coefficient (κ) (Cohen 1960), using the data from 2003. Bands from the images that were significant by ANOVA (P<0.05) were also assessed for their utility using Cohen's kappa coefficient (κ) in 2004.

When using Cohen's kappa, the cutoff value for classification was the median of the difference between values of the treatments. For example, in the 2004 canopy image, the lambda-cyhalothrin treatment had an average value of 110.68, the acetamiprid treatment an average value of 58.97, the untreated plots an average value 54.53, and the acetamiprid + abamectin treatment an average value of 52.27. The values that were between 84.825 and 56.75 were predicted to be part of the acetamiprid treatment.

Results

2003. The pesticides helped manipulate mite levels among treatments and mite populations in the treatments with the highest levels continued to build until the 4th week of the study. Cotton aphid populations were also manipulated by the pesticides and they increased until the 3rd week of the study, without much population increase after this point (Fig. 1). Nonetheless, there were a range of aphid populations among the treatments when the remote sensing data were collected (August 20, 2003) (Fig. 1). These numbers represent populations that were below the economic threshold levels for aphids and above the treatment threshold level for mites. Treatment thresholds for spider mites are set by the percentage of leaves infested. Although there were a high percentage of leaves infested, actual mite numbers were low and the infestation was still in an early stage when the remote sensing data were collected.

None of the yields among treatments were significantly different (F = 0.82; df = 4, 12; *P* = 0.5352). There was an average of 15764, 15519, 15212, 14207 and 14079 kg/ha (seed cotton) in the untreated, abamectin, acetamiprid + acephate, bifenthrin, and acetamiprid + abamectin-treated plots, respectively.

Multispectral data. Treatments differed significantly in the green band (~550 nm) (F = 6.16; df = 4, 12; P = 0.0062) and in the NIR band (~850 nm) (F = 9.27; df = 4, 12; P = 0.0012) (Fig. 2). In the green band, the average reflectance values for the acetamiprid + abamectin and bifenthrin treatment were significantly higher than the abamectin treatment. Acetamiprid + acephate and untreated plots had intermediate reflectance values and did not differ significantly from the other values. In contrast, in the NIR band, the bifenthrin treatment had significantly higher average reflectance values than the acetamiprid + abamectin and the abamectin treatments. As in the green band, acetamiprid + acephate and untreated plots had moderate average reflectance and did not differ significantly from the other values.

Although there were significant differences among the treatments in the green and NIR bands, there were no correlations for the bands or vegetation indices between accumulated mite-days or accumulated aphid-days. Some of the vegetation indices and bands were correlated with yield (Table 2).

The Cohen's kappa value was 0 for the reflectance values in the green band (~550 nm). Thus, the predictive quality of the reflectance values in the green band, in this case, was no better than random. The Cohen's kappa value was the 0.313 for the NIR band (~850 nm). Interestingly, although no significance was shown among the treatments for the NDVI ($F = 1.30$; df = 4, 12; $P = 0.3230$) and GNDVI ($F = 1.18$; df = 4, 12; $P = 0.9355$), they both had a Cohen's kappa value of 0.125.

Hyperspectral data. Treatments differed significantly in one of the wavelengths in the green area tested (~579 nm) ($F = 3.69$; df = 4, 12; $P = 0.0351$) (Fig. 2). The average reflectance values at ~579 nm for the acetamiprid + abamectin treatment were significantly higher than the abamectin-treated plots; values for the other treatments were intermediate.

There were no correlations among any of the indices or narrow bands with accumulated mite-days. There were weak correlations at ~569 nm and ~579 nm with accumulated aphid-days (slope = 0.37; $P = 0.037$ and slope = -0.50; $P = 0.022$). There was weak correlation with yield among some of the indices and narrow bands (Table 2).

The Cohen's kappa value was 0.25 for the reflectance values at ~579 nm. Analogous to the multispectral data, although they did not significantly differentiate any of the treatments from each other, the NDVI ($F = 1.65$; df = 4, 12; $P = 0.2265$), the GNDVI ($F = 1.57$; df = 4, 12; $P = 0.2460$), the green peak (~550 nm) ($F = 1.98$; df = 4, 12; $P = 0.1618$), and the NIR band (~880 nm) ($F = 0.27$; df = 4, 12; $P = 0.8942$) all had Cohen's kappa values of 0.188.

2004. When the QuickBird data was collected, there was an excellent array of aphid populations among the treatments ranging from 39 to 1510 accumulated aphid-days (Fig. 3). Spider mite populations increased more slowly than the aphid populations, but slightly exceeded the treatment threshold during weeks 3 through 5 of the study (Fig. 3). As in 2003, although there were a high percentage of leaves infested, actual mite numbers were low and the infestation was still in an early stage when the remote sensing data were collected. All the treatments exceeded mite treatment thresholds by the 6th week.

There were no significant differences in yield among the treatments (F = 1.23; df = 4, 12; P = 0.3508). There was an average of 9905, 8951, 8286, 7939 and 7807 kg/ha (seed cotton) in the plots treated with the acetamiprid + abamectin, untreated, acephate, abamectin, and lambda-cyhalothrin-treated plots, respectively.

Ground (hyperspectral spectrometer) data. No significant differences were found among treatments using the spectrometer on any given date. Additionally, the chlorophyll meter measurements were the only dependent variable that was significant for time (day of measurements) by treatment interaction (Table 3). Plots with natural infestations of aphids and spider mites had chlorophyll meter values that were significantly lower over time than acetamiprid + abamectin-treated plots. The response was quadratic, rather than linear (F = 9.76, P = 0.0028). Moreover, all the narrow band and index values tested changed significantly over time (day of measurements) (Table 3). There were no correlations among accumulated aphid-days, mite-days calculated up to the 28 July, with yield, which was collected 3 November.

On 11 August, although there were no significant differences among treatments for any of the variables tested by ANOVA, the DVI and NIR (~880 nm) were negatively linearly correlated with accumulated aphid-days (Table 4). There were no correlations among any of the indices or narrow bands with yield.

Like the previous week, on 18 August there were no correlations with accumulated mite-days or yield. Furthermore, although there were no significant differences among treatments by ANOVA, the narrow band at in the NIR wavelength (~880 nm) was negatively linearly correlated with accumulated aphid-days (Table 4). There were no correlations among any of the indices or narrow bands with yield.

On 26 August, there were correlations among various vegetation indices and narrow bands vs. accumulated aphid-days (Table 4). Finally, there were no correlations among any of the indices or narrow bands with yield.

Airborne (multispectral) data. Using the airborne data provided by InTime, none of treatments were significantly different in any of the narrow bands or indices tested. Additionally, there were no correlations among accumulated mite, accumulated aphid-days, or yield with any of the bands or indices tested.

*Satellite (multispectral) data***.** The lambda-cyhalothrin treatment was significantly different from the other treatments in the canopy image, three of the four color infrared images, the false color image, and one of the vegetation images (Table 5). None of the treatments were significantly different using the panchromatic image, one of the color infrared images, the soil/vegetation image, or the GVI image. Additionally, although treatments in the false color image and one the vegetation images were significant by ANOVA, the Tukey groupings failed to differentiate among the treatments (Fig. 4); accordingly, the letter groupings in the preceding figure represents the *P* values for Fisher's LSD procedure.

Three images were significantly linearly correlated with accumulated mite-days, while two images were significantly linearly correlated with accumulated aphid-days (Table 5). None of the images were significantly correlated with yield. Furthermore, the Cohen's kappa values for the significant image bands were 0.19 for the canopy image, 0.5 for the color infrared image 1, 0.44 for the color infrared image 2, 0.13 for the color infrared image 2, 0 for the false color image and 0.06 for the vegetation index 1 image. The Cohen's kappa values for the treatments that showed no significant differences were 0.25 for the panchromatic image and 0.46 for the GVI image.

Discussion

In 2003, aphids were well below threshold levels throughout the study and, although spider mite levels had exceeded threshold levels by August 20, the population levels were still low. A similar phenomenon was observed in 2004, with spider mite levels above threshold levels, but with low numbers. Albeit aphid levels were higher in 2004, the accumulated mite and aphid-days were low enough that the arthropods had no significant on the yield in both years.

Although, the growth stage of the cotton in these experiments was consistent with the normal occurrence of these pests in SJV cotton, these exploratory experiments were performed in a manipulated controlled environment. Intrafield variation that is detected with remote sensing methods alone is not adequate for prescribing a treatment regime against spider mite and aphid pests. For example, an area of cotton that has few naturally occurring arthropod pests will have variation that is attributable to factors such as plant growth stage, irrigation status, soil condition, nutrient status and injury from other pest classes (e.g. weeds, nematodes, fungi). However, arthropod-infested cotton was successfully detected over a two year period in this study. In addition, aphids and spider mites were detected in fields that had dry soil in 2003 and in fields that had wet soil in 2004. Finally, the field characteristics and the amount of nitrogen applied to the plants were different both years, but both spider mites and aphids were still detected. Even though arthropod-damaged cotton was detected over a range of conditions, each field must be ground-truthed to demonstrate that an arthropod infestation is present and at what level it is present.

In 2003, cotton with mite and aphid infestations in the early stages could be detected in the green peak areas, using airborne imagery. Treatments with spider mites were detected using bands in the green peak in both multispectral and hyperspectral data. However, spider mites were only detected in NIR bands using multispectral (SAMRSS) data. Because treatment decisions are based on percent infested leaves, mite numbers were above the treatment threshold levels (30-50% infested mite leaves), but were only present in low numbers (2 to 31 average mites/leaf). Thus, the infestations were detected at a stage that was early enough for a grower to make a treatment decision. The presence of aphids lowered the reflectance values in the abamectin-treated plots, while the presence of mites and aphids lowered the reflectance values in the acetamiprid + abamectin treated plots.

Using the multispectral data from 2003, it is possible that plots with high numbers of aphids, but low numbers of mites, and plots with low number of aphids, but low numbers of mites (i.e. the untreated and acetamiprid + acephate-treated plots), were statistically similar because the accumulated-mite and aphid-days offset one another. Moreover, aphid damage was clearly detected in the green band (acetamiprid + abamectin plot values were significantly higher than abamectin-treated plots), although untreated plots had accumulated mite and aphid-days that were similar to abamectin-treated plots. Finally, the Cohen's kappa values calculated indicate that the NDVI, GNDVI and the NIR band were better predictors of aphid and spider mite infestations than the green band, with the NIR band being the best predictor of aphid and spider mite infestations that was tested.

Using the hyperspectral data from 2003, it is conceivable that the cotton with few accumulated aphid and mite-days (i.e. acetamiprid + abamectin-treated plots) had a higher reflectance value at ~579 nm in the plots because it had less aphid and mite pressure. Also, plots with high accumulated aphid-days, but few accumulated mite-days, had lower average reflectance values at ~579 nm. This is similar to the findings in the green band using the multispectral data.

The narrow band at ~579 nm had a Cohen's kappa value of 0.25. Thus, the predictive quality of the reflectance values at ~579 nm, in this case, was better than random, but not extremely accurate. Nonetheless, the Cohen's kappa values calculated indicate that the narrow band ~579 nm (in the green wavelengths) was the best predictor of spider mites and aphid-infested cotton, using the hyperspectral imagery. The NNIR, NR, OSAVI, MCARI, GDVI, RVI_1, HM, YI and narrow bands at ~569 nm ~802 nm were not useful to detect aphid or mite-infested cotton in both the 2003 multispectral and hyperspectral images.

Aphids were detected with the ground-based spectrometer measurements before they reached economically damaging levels in the mite and aphid experiment in 2004. Again, wavelengths in the NIR were correlated with aphid pressure and there was a relationship among decreasing reflectance values and increasing accumulated aphid-days (Table 5). Based on these correlations, the NIR wavelengths were the first to significantly distinguish aphid-infested plots well below economic threshold levels. Treatments with higher aphid and mite pressure had significantly lower chlorophyll levels over time, using the chlorophyll meter data. Finally, aphid-infested cotton was detected using the satellite imagery from 2004, although the aphid infested cotton had received a high amount of aphid pressure by the time the imagery was collected. Because these images were correlated with accumulated aphid-days and not accumulated mite-days, we used the images to differentiate the lambda-cyhalothrin treatment based on aphid damage, rather than mite damage. Although the acetamiprid + acephate and the untreated plots had more accumulated aphid and mite-days than the abamectin treatment (Fig. 3), they were not significantly different from each other in any of the images received.

Spider mite damaged cotton was not detected with the ground-based spectrometer measurements in 2004, although the chlorophyll meter detected lower chlorophyll levels in plots with higher aphid and mite pressure. Spider mite infested cotton could be detected with airborne imagery in 2003, and accumulated mite-days were linearly correlated with decreasing reflectance, using airborne images in 2004. Mite damage above treatment threshold levels, but with low mite numbers, could be detected in 2003 and 2004. Three images had values that were linearly correlated with accumulated mite-days, using the QuickBird airborne data in 2004.

Airborne methods are different than ground based methods because they are subject to sources of variation such as anisotropy, variable illumination, and water vapor, and aerosol particles in the air. Many of the spectrometer measurements were made in conditions >38°C, although the ASD FieldSpec® Pro is designed to function in temperatures <38°C. Airborne methods way have been able to detect canopy differences in spider mite damaged cotton that the spectrometer was not able to detect, because the contact probe used with the spectrometer samples a small portion of the leaf and only 5 leaves per plot were sampled. Spider mite damaged cotton may more seriously affect the canopy before affecting the reflectance of the leaves, perhaps by eliciting a host response in the cotton, such as leaf curl or drooping. With remote sensing technology, this could only be detected with canopy methods.

Unfortunately, in the mite and aphid test in 2004, there were no aerial or satellite data in the time period between 8 days after treatment, when there were few aphids, and 30 days after treatment, when the aphids had reached economic threshold levels. Aphid damaged cotton was correlated with accumulated aphid-days using the spectrometer ground-based measurements in the mite and aphid test. Nevertheless, it would be beneficial to have aerial or satellite data on an intermediate number of aphids to determine if they could be detected with such data when the plants were stressed, before yield loss occurred, and when the economic threshold was reached. Aphid-infested cotton was detected using satellite data at levels well below the economic thresholds in a separate test (unpublished data).

Some residue from the lambda-cyhalothrin treatment was visible on the leaves until approximately 2 weeks after treatment in 2004. Also, some insecticides, such as acephate, can change cotton plant physiology to indirectly facilitate mite infestations (Leigh 1980, Maggi and Leigh, 1983, Beasley et al. 1996) and it is feasible that this physiological change could be detected using remote sensing. However, the aerial remote sensing data taken 9 days after the pesticide applications showed no significant differences among treatments. Additionally, the spectrometer data were not significant or correlated with accumulated aphid-days until the aphid pressure was high. Consequently, it is unlikely that the differences in reflectance were due to the direct or indirect effects of the chemicals on the cotton. Rather, wavelengths in the NIR were the most robust, in comparison with other indices and images tested in 2003 and 2004, when used to distinguish aphid or mite damaged cotton from other cotton.

In 2003, the presence of low aphid numbers decreased reflectance values when compared with uninfested cotton. Additionally, aphids with higher population levels also decreased reflectance values in 2004. Both spider mite and aphid-infested cotton leaves decreased in the NIR reflectance values over time. However, the NIR wavelengths alone cannot be used to distinguish infested cotton. For example, the decrease in the values of the NIR wavelength is consistent with a general decline in canopy cover (more bare soil exposed and more shadows) or a senescing plant, because healthier plants reflect more light in the NIR (Richardson et al. 1975, Summy et al. 1997, Brewster et al. 1999). Because both spider mite and aphids were detected by a decrease in NIR wavelength values, monitoring the field populations is crucial to parse their presence from other factors in the field that may cause similar damage. Once an infestation of aphids or mites is discovered, the extent of the infestation can be monitored by comparison of high aphid and/or spider mite populations in cotton to cotton with low aphid and/or spider mite infestation levels; the highly-infested cotton should have a lower NIR wavelength value than the cotton with low aphid populations. Cohen's kappa values from multispectral data in 2003 and 2004 indicate that fairly (0.21-0.40) to moderately accurate (0.41-0.60) predictions (Groote et al. 2000, Kalra et al. 2003) can be made using the NIR wavelengths for predicting areas of cotton that are infested with a range of cotton aphid and spider mite populations.

Ground-truthing and remote sensing methods must be amalgamated for remote sensing to be useful for the accurate identification of spider mite and cotton aphid infestations. The ground-based information must confirm the dominant arthropod problem that is present. The remote sensing imagery can assist, using supervised classification, to prescribe and appropriate management strategy.

Because spider mites and aphids occur in heterogeneous areas of the fields, it is possible that these "hot spots" can be differentiated from other sources of variation, using the wavelengths in the NIR. The sensors that we tested had resolutions ranging from 0.6 - 2.8 m, with ROI from 13-84 m^2. Hence, we have shown that remote sensing can detect spider mite and aphid infestations in small areas. It must be demonstrated that this is possible outside of a controlled experiment and that the costs associated with ground-truthing, processing of remote sensing images, and variable rate pesticide applications are less than traditional sampling methods and traditional pesticide applications. Thus, the results presented herein are exploratory and represent one step in the process of integrating remote sensing techniques into the IPM management practices of SJV cotton growers.

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Table 1.

Vegetation Index		Equation	Reference
Normalized Difference Vegetation Index (NDVI)	NDVI =	$\frac{(R_{NIR} - R_{RED})}{(R_{NIR} + R_{RED})}$	(Rouse et al. 1974)
Normalized Near Infrared (NNIR)	NNIR =	$\frac{(R_{NIR})}{(R_{NIR} + R_{RED} + R_{GREEN})}$	(Ojala unpublished)
Normalized Red (NR)	NR =	$\frac{(R_{RED})}{(R_{NIR} + R_{RED} + R_{GREEN})}$	(Ojala unpublished)
Optimized Soil Adjusted Index (modified) (OSAVI)	OSAVI =	$\frac{(R_{NIR} - R_{RED})}{(R_{NIR} + R_{RED} + 0.16)}$	(Rondeaux et al. 1998, Ojala unpublished)
Modified Chlorophyll Absorption in Reflectance Index (MCARI)	MCARI =	$[(R_{770} - R_{670}) - 0.2 * (R_{770} - R_{550})] * (R_{770} - R_{670})$	(Daughtrey et al. 2000)
Green Differential Vegetation Index (GDVI)	GDVI =	$R_{GREEN} - R_{RED}$	(Ojala unpublished)
Ratio Vegetation Index (RVI_1) [or Simple Ratio (SR_1)]	RVI or SR =	$\frac{(R_{NIR})}{(R_{RED})}$	(Jordan 1969)
Ratio Vegetation Index (RVI_2) [or Simple Ratio (SR_2)] ^{x}	RVI or SR =	$\frac{(R_{RED})}{(R_{GREEN})}$	(Jordan 1969)
Green Vegetation Index (GNDVI) ^{y}	GNDVI =	$\frac{(R_{NIR} - R_{GREEN})}{(R_{NIR} + R_{GREEN})}$	(Gitelson and Merzlyak 1998)
Difference Vegetation Index (DVI) ^{x}	DVI =	$(R_{NIR} - R_{RED})$	(Tucker 1979)
Visible Atmospherically Resistant Index ($VARI_{GREEN}$) ^{x}	$VARI_{GREEN}$ =	$\frac{(R_{GREEN} - R_{RED})}{(R_{GREEN} + R_{RED} - R_{450})}$	(Gitelson et al. 2002)
Half Max (HM) ^{z}	HM =	$R_{675} + \frac{(R_{760} - R_{675})}{2}$	(Ojala unpublished)
Photochemical Reflectance Index (PRI) ^{z}	PRI =	$\frac{(R_{520} - R_{580})}{(R_{520} + R_{580})}$	(Gamon et al. 1992)
Yellowness Index (YI) ^{z}	YI ≈	$\frac{(R(\lambda_1) - 2R(\lambda_0) + R(\lambda_{+1}))}{\Delta\lambda^2}$	(Adams et al. 1999)
Narrow Bands	~550 nm^y =	$\sim R_{550}$	
	~553 nm =	$\sim R_{553}$	
	~569 nm^z =	R_{569}	
	~579 nm^y =	R_{579}	
	~802 nm^z =	R_{800}	
	~850 nm^x =	R_{850}	
	~880 nm =	$\sim R_{880}$	

x: Only tested these in 2004, hyperspectral spectrometer data.

y: Only tested these in 2003, hyperspectral data and 2004 hyperspectral spectrometer data.

z: Only tested these in 2003, hyperspectral data.

Table 2. Spearman correlations for the indices and narrow bands versus yield, 2003.

	Index or Band	Slope	*P*
Multispectral	NDVI	0.73	0.0002***
	NNIR	0.72	0.0004***
	RVI_1	0.49	0.0287*
	GNDVI	0.82	<0.0001***
	RVI_1	0.49	0.0287*
Hyperspectral	NNIR	0.52	0.0197*
	NR	-0.49	0.0265*
	OSAVI	0.49	0.0298
	RVI_1	0.54	0.0141*
	GNDVI	0.52	0.0188*
	~550 nm	-0.75	0.0001***
	~569 nm	-0.78	<0.0001***
	~579 nm	-0.76	0.0001***

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

Table 3. Results from repeated measures ANOVA. Day of measurement represents the weekly hyperspectral spectrometer measurements on 28 July, 4, 11, 18, and 26 August 2004. chloro. meter = chlorophyll meter.

Index or Band	Treatment[x]		Day measured [y]		Day measured*Treatment [z]	
	F	*P*	*F*	*P*	*F*	*P*
NDVI	2.23	0.1273	101.73	<0.0001***	1.14	0.3406
NNIR	1.26	0.3368	66.86	<0.0001***	1.07	0.4010
NR	2.32	0.1158	124.05	<0.0001***	1.00	0.4706
OSAVI	0.86	0.5147	81.31	<0.0001***	1.40	0.1731
MCARI	0.45	0.9623	25.00	<0.0001***	0.77	0.6823
GDVI	0.63	0.6490	59.75	<0.0001***	1.59	0.0989
RVI_1	1.81	0.1926	109.25	<0.0001***	0.91	0.5616
RVI_2	0.49	0.7437	286.05	<0.0001***	1.06	0.4146
GNDVI	0.47	0.7601	115.64	<0.0001***	1.16	0.3239
DVI	0.30	0.8725	58.53	<0.0001***	0.86	0.6148
$VARI_{GREEN}$	2.39	0.1092	10129.2	<0.0001***	1.27	0.2472
~553 nm	0.27	0.8924	10.07	<0.0001***	1.30	0.2284
~579 nm	0.41	0.7894	31.44	<0.0001***	0.70	0.7860
~880 nm	1.00	0.4466	4.03	0.0059**	1.40	0.1731
chloro. meter	1.33	0.3159	7.57	<0.0001***	1.99	0.0310*

x: Corrected df = 4,12.

y: Corrected df = 4,59.

z: Corrected df = 16,59.

* *P* < 0.05.

** *P* < 0.01.

*** *P* < 0.001.

Table 4. Spearman correlations for hyperspectral spectrometer indices and narrow bands vs. accumulated aphid-days.

Date	Index or Band	Slope	*P*
11 August 2004	~880 nm	-0.57	0.0082**
18 August 2004	GDVI	-0.48	0.0307*
	RVI_2	0.49	0.0276*
	$VARI_{GREEN}$	-0.52	0.0180*
	~880 nm	-0.46	0.0422*
26 August 2004	NR	0.64	0.0025**
	OSAVI	-0.63	0.0026**
	GDVI	-0.69	0.0008***
	RVI_1	-0.61	0.0041**
	RVI_2	0.68	0.0010**
	DVI	-0.74	0.0002***
	$VARI_{GREEN}$	-0.58	0.0072**
	~553 nm	-0.49	0.0279*
	~880 nm	-0.62	0.0035**

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

Table 5. Images provided by DigitalGlobe, Inc. that were able to significantly distinguish aphid infested cotton (lambda-cyhalothrin treatment) from other cotton. 25 August 2004- 31 days after treatment.

Index or Band	Lambda-cyhalothrin treated plots vs. other plots[z]		Images correlated with accumulated mite-days		Images correlated with accumulated aphid-days	
	F	*P*	Slope	*P*	Slope	*P*
Canopy	7.4	0.0030**	0.59	0.0059**	0.46	0.0396*
Color Infrared 1	6.72	0.0045**	-0.40	0.0797	-0.75	0.0001***
Color Infrared 2	6.61	0.0048**	-0.38	0.0949	-0.77	<0.0001***
Color Infrared 3	6.71	0.0045**	-0.39	0.0870	-0.79	<0.0001***
False Color	3.41	0.0439*	0.67	0.0011**	0.28	0.2399
Veg. Index 1	3.38	0.0452*	0.68	0.0010**	0.27	0.2521

z: Corrected df = 4,12.

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

Figure Legends

Fig. 1. Average accumulated aphid and mite-days calculated after treatment, over time, 2003. Arrow denotes the date that airborne data were collected. ad: acetamiprid; an: abamectin; u: untreated; ae: acephate; bn: bifenthrin

Fig. 2. Average reflectance values of multispectral data (~550 and ~850 nm) and hyperspectral data (~579 nm), 2003. Letters represent mean separation by Tukey's HSD procedure. ad: acetamiprid; an: abamectin; bn: bifenthrin; ae: acephate; u:untreated

Fig. 3. Average accumulated aphid and mite-days calculated after treatment, over time, 2004. Arrow denotes the date that airborne data were collected. ad: acetamiprid; an: abamectin; u: untreated; ae: acephate; ln: lambda-cyhalothrin

Fig. 4. Average QuickBird (satellite) false color image and vegetation image values (+SE) among treatments. Letter groupings represent *P* values obtained from Fisher's LSD procedure. Groupings represent marginal significance. ad: acetamiprid; an: abamectin; ln: lambda-cyhalothrin; ae: acephate; u: untreated

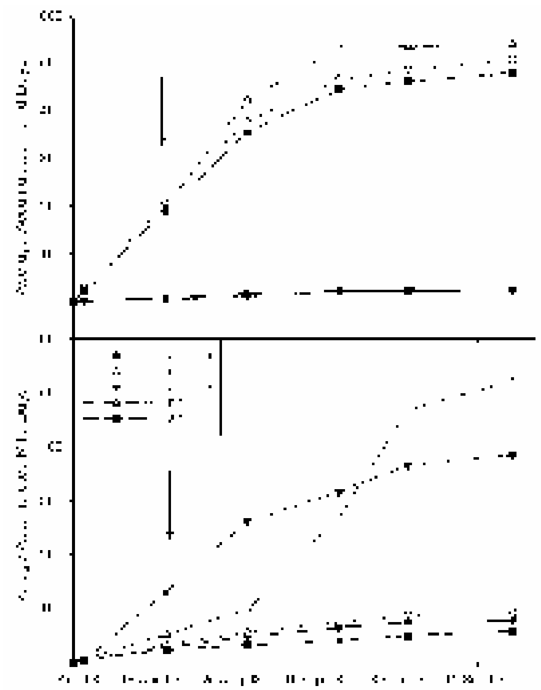

Figure 1; Reisig and Godfrey.

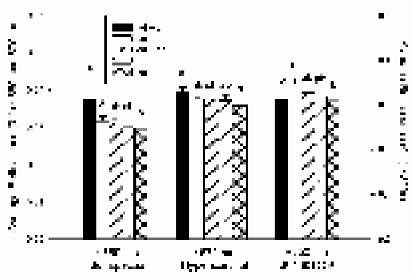

Figure 2; Reisig and Godfrey.

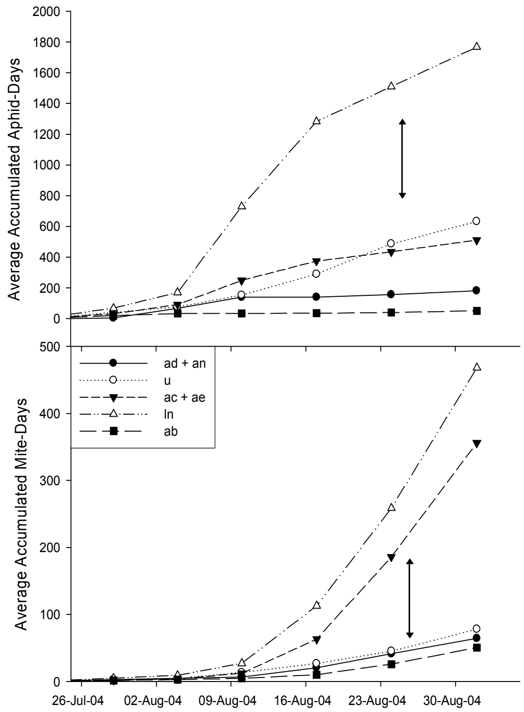

Figure 3; Reisig and Godfrey.

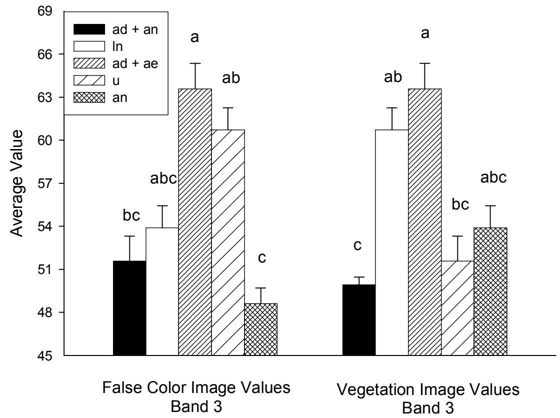

Figure 4; Reisig and Godfrey.