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An Overview of Aircraft Remote Sensing in Integrated Pest Management

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ABSTRACT

This paper presents four exemplary applications of aerial photography and videography, global positioning system (GPS), and geographic information system (GIS) technologies for detecting, monitoring, and mapping insect infestations in agriculture, forestry, and rangeland areas. Applications demonstrated include detecting and mapping: (1) citrus blackfly (*Aleurocanthus woglumi* Ashby) infestations in citrus orchards; (2) silverleaf whitefly (*Bemisia argentifolii* Bellows and Perring) infestations in cotton; (3) harvester ant (*Pogonomyrmex barbatus* F. Smith) infestations on rangelands; and (4) western pine beetle (*Dendroctonus brevicomis* LeConte) infestations in a forested area. The integration of a GPS with the video imagery permitted latitude and longitude coordinates of insect infestations to be recorded on each image. The GPS coordinates were entered into a GIS to map insect infestations on a regional scale. The integration of remote sensing, GPS, and GIS provide valuable tools that can enable resource managers to develop maps showing the distribution of insect infestations over large areas. The digital imagery can serve as a permanent geographically located image data base for monitoring future contraction or spread of insect infestations over time.

RESUMEN

En este artículo se presentan cuatro ejemplos de las aplicaciones de las tecnologías de fotografía y videografía aéreas, el sistema de posición global (GPS), y del sistema de información geográfica (GIS) para la detección, monitoreo, y mapeo de infestaciones de insectos en áreas agrícolas, forestales y en pastizales. Las aplicaciones demonstradas incluyeron la detección y el mapeo de (1) infestaciones por la mosca negra de los cítricos (*Aleurocanthus woglumi* Ashby) en huertas de cítricos; (2) mosquita blanca (*Bemisia argentifolii* Bellows and Perring) en algodón; (3) hormiga cosechadora (*Pogonomyrex barbatus* F. Smith) en pastizales; y (4) escarabajo del pino del oeste (*Dendroctonus brevicomis* Le Conte) en una área forestal. La integración del sistema de GPS con las imágenes de video permitió registrar las coordenadas de longitud y latitud en cada imagen. Las coordenadas de cada imagen se incorporaron en un mapa de GIS para crear un mapa de las infestaciones de insectos a una escala regional. La integración de un sistema de detección a distancia, GPS, and GIS brinda herramientas valiosas para permitir a los supervisores de recursos desarrollar mapas que muestren la distribución de infestaciones de insectos en áreas extensas. El sistema de imágenes digital puede servir como una base permanente de datos localizados geográficamente para el monitoreo de futuras concentraciones o dispersiones de plagas de insectos a lo largo del tiempo.

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Aerial imaging systems have been used extensively for detecting and monitoring insect infestations in both agricultural and noncultivated environments (Myers et al. 1983; Aldrich et al., 1983; Riley, 1989; Lund, 1997). These systems allow rapid acquisition of data with short turn-around time, overhead imaging of entire areas at one time, and a procedure that is considerably less costly than ground surveys (Tueller, 1982; Hart et al., 1988). Aerial photography is often used for detecting insect infestations because of its high spatial resolution (Myers et al. 1983; Riley, 1989) and aerial videography has potential for entomological applications (Hart et al., 1988).

Aerial videography and global positioning system (GPS) technology have been integrated and shown to be useful tools for detecting and monitoring insect activity over forested areas (Bobbe and Ishikawa, 1992; Myhre, 1992). The latitude and longitude data provided by the GPS were entered into a geographic information system (GIS) to geographically reference forest pest problems (Myhre, 1992). Richardson et al. (1993) entered aerially obtained GPS coordinates into a GIS to map the distribution of cotton (*Gossypium hirsutum* L.) fields in a regional boll weevil (*Anthonomus grandis* Boheman) management program in south Texas (Summy and King, 1992).

Scientists at the United States Department of Agriculture

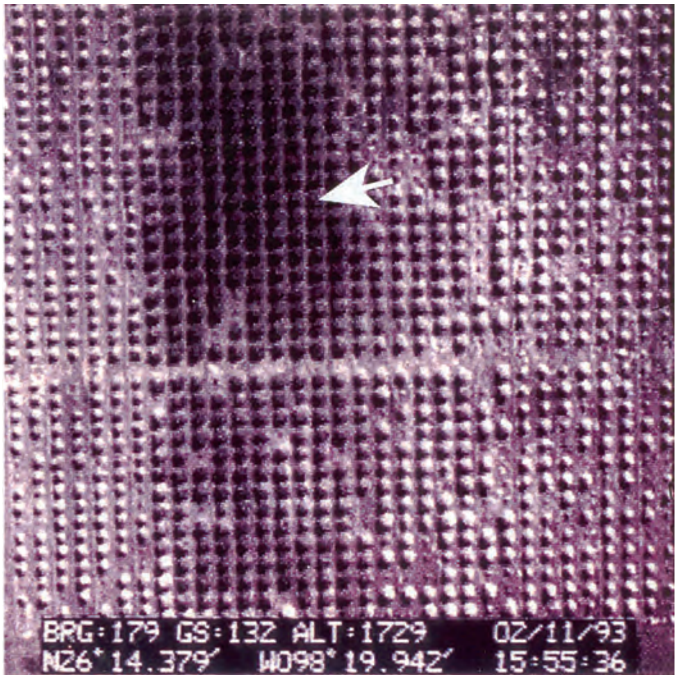

Fig. 1. Black-and-white near-infrared narrowband video image of a citrus orchard near Mission, TX, infested with citrus blackfly. The image was obtained at an altitude above ground level of 525 m in February 1993. The arrow on the print points to the dark tonal response of trees infested with citrus blackfly. The GPS data shown at the bottom of the image includes the bearing (direction), ground speed, altitude, date, north latitude, west longitude, and time.

(USDA), Agricultural Research Service (ARS), Kika de la Garza Subtropical Agricultural Research Center, Weslaco, Texas, have conducted research using aerial imaging systems for pest management studies for over two decades. This paper presents an overview of four pest management studies using aerial photography and videography, GPS, and GIS technologies for entomological applications.

Citrus Blackfly. The citrus blackfly (*Aleurocanthus woglumi* Ashby), an exotic pest of citrus indigenous to the Asian tropics, can cause extensive damage to citrus foliage (Hart, 1978; Summy et al., 1983) by feeding injury and physiological damage caused by a sooty mold fungus (*Capnodium citri* B. & D.) that develops on the honey dew excreted by the developing insect (Hart et al., 1976). When sooty mold deposits become heavy, reception of sunlight reduces the trees' ability to carry on photosynthesis, resulting in lower fruit production. Hart et al. (1973) used aerial CIR photography to detect the presence of sooty mold deposits caused by citrus blackfly in citrus foliage.

More recently, Everitt et al. (1994) used aerial multispectral videography, GPS, and GIS technologies to detect and map citrus blackfly infestations in citrus orchards in the Lower Rio Grande Valley of southern Texas. The darker infested trees were easily distinguished from the typical white-gray tone of noninfested trees (Fig. 1). Trees with the heaviest sooty mold deposits had the darkest image tones.

Analysis of the video imagery of the citrus growing areas of the Lower Rio Grande Valley showed that 27 orchards were infested with blackflies. Ground verification showed that the imagery was 93% accurate. The remaining two orchards that were not infested with citrus blackfly were infested with brown soft scale (*Coccus hesperidum* L.), which also produces sooty mold deposits on the foliage. Most of the blackfly infestations could be detected from fixed-wing aircraft at an altitude of 1,675 m, which had a resolution of 1.8 m. However, infestations on some replacement trees in mature orchards and newly planted orchards with individual trees less than 2 m in diameter, were not detected at this altitude because of small canopies and greater exposure of soil background. Infestations on some trees were detected at an altitude of 525 m with a resolution of 0.6 m (Fig. 1).

The GPS latitude and longitude data were used with GIS technology to georeference citrus blackfly-infested orchards in a three-county (Cameron, Hidalgo, and Willacy) region. The merger of the GPS data with a GIS is shown in Figure 2-A. The dots on the map represent citrus orchards infested with blackfly. The map also shows primary roads and the approximate locations of towns. A more detailed GIS map shows the locations of blackfly-infested orchards in Hidalgo County (Fig. 2-B). With this map one can begin to associate general streets and roads with the GPS marked location of each orchard where citrus blackfly infestations occur. A local site

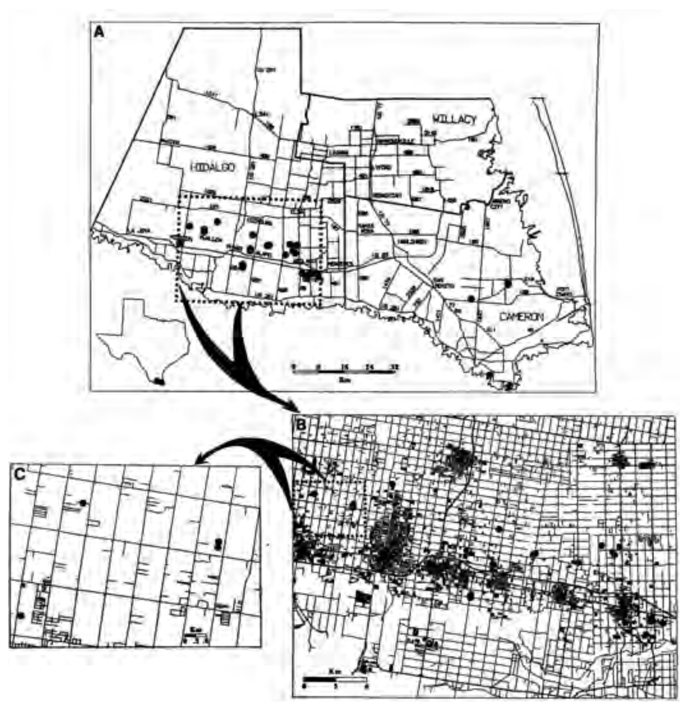

Fig. 2. Regional GIS map (A) of the three-county citrus growing area of the Lower Rio Grande Valley of Texas depicting GPS locations (dots) of citrus orchards infested with citrus blackfly. The specific locations were obtained from GPS latitude and longitude data collected in aerial videographic surveys. Print B shows a more detailed map showing the locations of citrus blackfly-infested orchards in Hidalgo County. Print C shows a local site map showing even greater detail on the location of selected orchards in Hidalgo County.

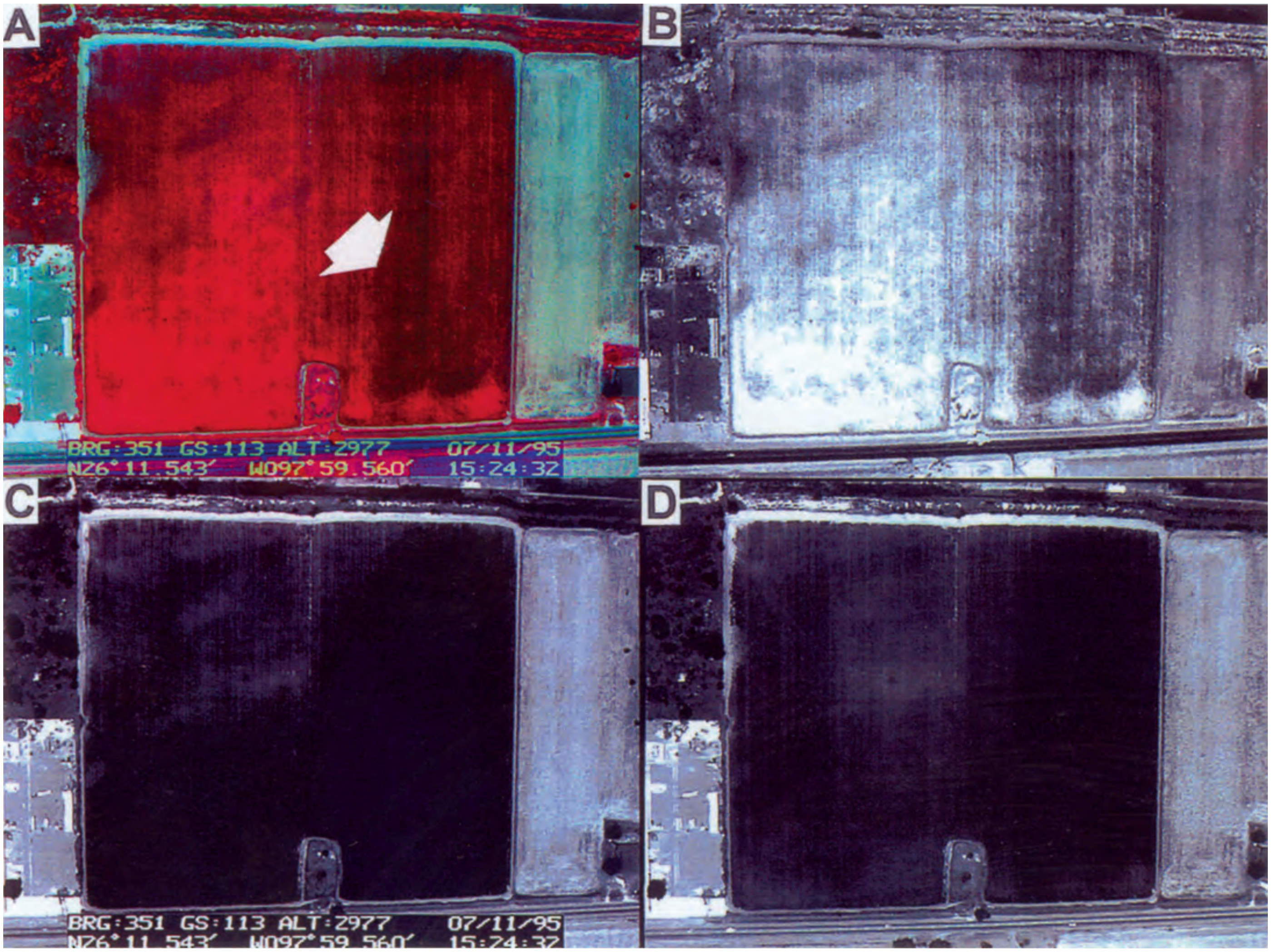

Fig. 3. Color-infrared (CIR) composite (A), and near-infrared (B), red (C), and yellow-green (D) black-and-white narrowband digital video images of a cotton field near Weslaco, TX. The imagery was obtained at altitude above ground level of 960 m in July 1995. The arrow on the CIR composite points to the dark gray to gray-black image response of high levels of sooty mold fungus on the cotton foliage caused by whitefly infestation. The infested area is also delineated in the near-infrared image.

map showing even greater detail on the location of the selected orchards is illustrated in Figure 2-C.

Whitefly. The silverleaf whitefly (*Bemisia argentifolii* Bellows and Perring) is a pest of cotton, vegetables, and numerous ornamental plants. Whitefly outbreaks have occurred in several areas of the United States resulting in heavy economic losses to producers (Norman et al., 1992; Summy et al., 1996; Norman et al., 1996). For example, a severe whitefly outbreak in 1991 caused an estimated $200 million in losses nationwide (Henneberry, 1993).

Damage caused by whiteflies of the *Bemesia* species complex can damage crops in several ways, including transmission of several important plant pathogens (Brown and Bird, 1992) and a general reduction in plant vigor by feeding (Byrne et al., 1990). Moreover, feeding nymphs excrete copious quantities of honeydew which may contaminate cotton lint and, like the citrus blackfly, promote the growth of sooty mold fungi (Hendrix and Wei, 1992). Heavy sooty mold deposits on the plant foliage, while detrimental in the sense that they impede photosynthesis, are highly visible and distinct.

Aerial multispectral videography, GPS, and GIS technologies were used to detect and map whitefly infestations in cotton in the Lower Rio Grande Valley of Texas (Everitt et al., 1996). Mean canopy reflectance values of cotton plants with no sooty mold deposits on the foliage, those with low to moderate levels, and those with heavy levels for two cotton fields are given in Table 1. For field 1, plants with low to moderate and high levels of sooty mold had lower visible green reflectance values than those with no sooty mold. At the visible red wavelength, plants with low to moderate levels of sooty mold had lower reflectance than those with no sooty mold. However, the visible red reflectance of cotton plants with high levels of sooty mold did not differ from that of plants with no sooty mold deposits. The inability to distinguish high sooty mold levels from those with no sooty mold was attributed to soil background reflectance which increased their red reflectance (Richardson et al. 1975, Everitt et al. 1986). At the NIR wavelength, cotton plants with low to moderate levels of sooty mold deposits had lower reflectance than plants with no sooty mold deposits. Plants with high levels of sooty mold had lower

Table 1. Canopy reflectance of noninfested and whitefly-infested cotton (as determined by deposits of sooty mold fungus on the foliage) at the green, red, and near-infrared wavelengths. Measurements were made in two cotton fields near Weslaco, Texas, in July 1995.

Site and Date	Sooty Mold Level	Canopy reflectance(%) for three wavelengths		
		Green[z]	Red	Near infrared
Field 1	None	4.7a	2.9a	36.5a
12 July 1995	Low-Moderate	3.2b	2.2b	16.9b
	High	2.8b	2.5ab	9.0c
Field 2	None	5.6a	3.0a	34.5a
20 July 1995	Low-Moderate	3.0b	2.1b	17.1b
	High	2.3c	2.0b	9.1c

[z]Means within a column at each date followed by the same letter do not differ significantly at the 0.05 probability level, according to Duncan's multiple range test.

NIR reflectance than those with light to moderate levels or those with no sooty mold deposits. The reflectance data obtained from field 2 followed a similar pattern to that shown for field 1, but there was a better separation among the visible reflectance values. The lower visible and NIR reflectance of cotton plants with sooty mold deposits on their leaves was attributed to the dark sooty mold fungus which absorbed a large percentage of the visible and NIR radiation (Gausman, 1985).

Figures 3-A, B, C, and D show CIR composite and NIR, red, and yellow-green narrowband black-and-white digital video images, respectively, of a cotton field near Weslaco, Texas, infested with whiteflies. High levels of sooty mold fungus on the cotton foliage can be distinguished by their dark gray to gray-black tonal response on the CIR composite image. Some of the gray-black image was attributed to in-canopy shadowing caused by loss of leaves due to whitefly devastation. Cotton plants with low to moderate levels of sooty mold fungus have a dull magenta to gray-brown response, while plants with no sooty mold deposits have a bright red tone. Sparsely vegetated and essentially bare soil areas have a green to light gray image. Most of the whitefly-infested plants can also be distinguished in the NIR black-and-white image. The sooty mold deposits generally could not be detected in the red and yellow-green images. Analysis of the video imagery of the study area identified approximately 65 locations thought to be infested by whitefly. In several instances more than one infestation was recorded within large cotton fields. Ground reconnaissance of the study area verified the presence of whiteflies at all locations.

The superiority of the NIR image over the yellow-green and red images for distinguishing sooty mold deposits

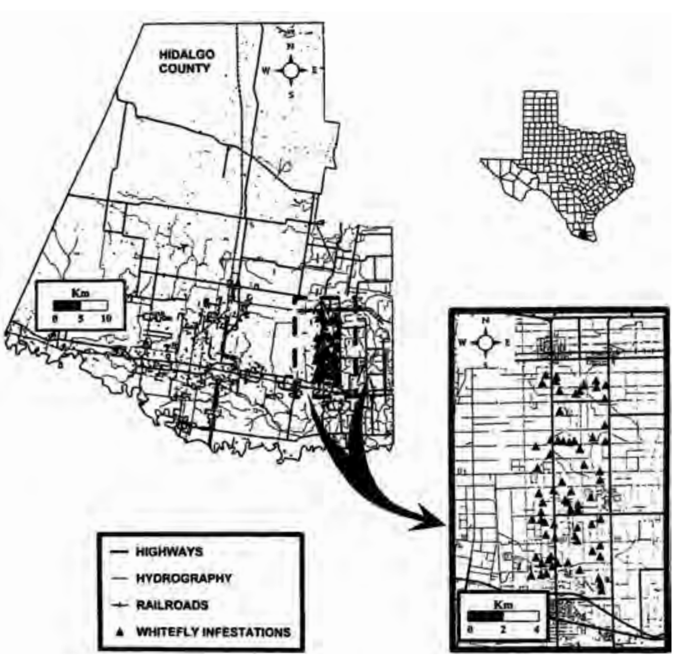

Fig. 4. GIS map (upper left) of Hidalgo County with the whitefly experimental site denoted in the lower right portion of the map. The symbols (triangles) within the study area represent GPS latitude and longitude coordinates of whitefly infestations in cotton fields. A detailed GIS map (lower right) clearly depicts the locations of the whitefly infestations.

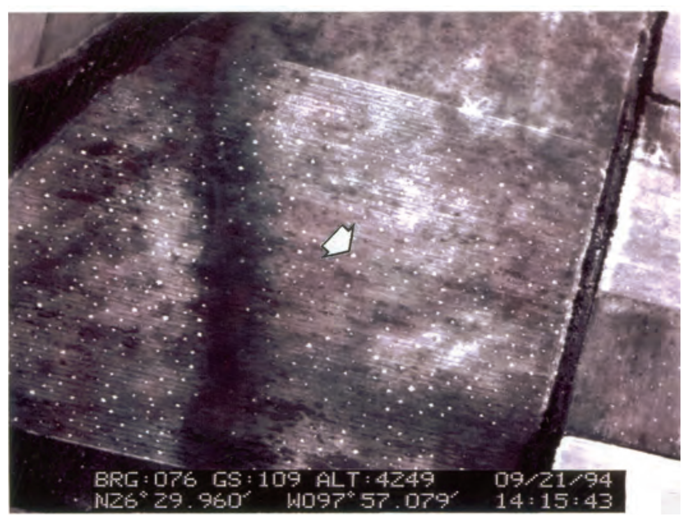

Fig. 5. Black-and-white red narrowband video image of a pasture near Elsa, TX, infested with harvester ants. The arrow on the print points to the light gray-white response of a harvester ant mound. The image was obtained at an altitude above ground level of 1380 m. The GPS data is shown at the bottom of the image.

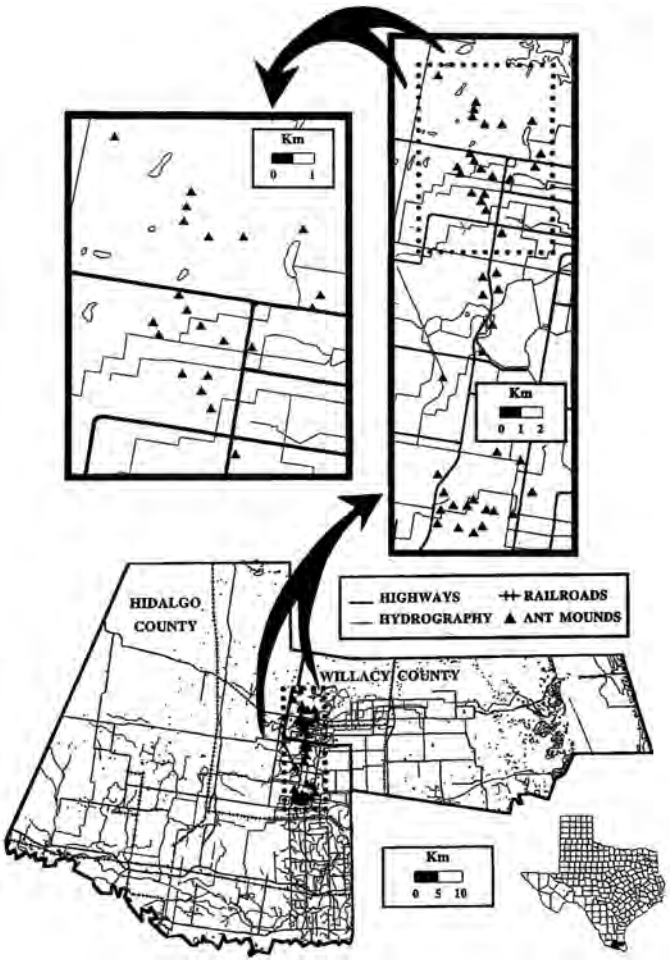

Fig. 6. GIS map (lower) of Hidalgo and Willacy counties with the harvester ant study area delineated with a dotted boundary. The symbols (triangles) within the experimental site represent GPS latitude and longitude coordinates where harvester ant infestations occurred. Each symbol represents a single pasture with a harvester ant infestation. A detailed GIS map (upper right) clearly depicts the locations of the harvester ant infestations within the study area. The upper left map shows even greater detail of a portion of the study area.

generally agrees with the canopy reflectance data, where the best differences among cotton plants with and without sooty mold deposits on the foliage occurred at the NIR wavelength interval (Table 1). These findings also concur with previous research on using videography for detecting citrus blackfly infestations (Everitt et al., 1994). Although the red and yellow-green canopy reflectance data showed potential for spectrally separating cotton plants with and without sooty mold deposits, these differences apparently were not great enough to be distinguished in the red and yellow-green video images.

The GPS data displayed at the bottom of the CIR and red video images of the whitefly-infested cotton field are useful to locate infestations and can be entered into a GIS. The GPS latitude and longitude data were used with GIS technology to develop a map of Hidalgo County with the experimental site north of Weslaco denoted in the lower right portion of the map (Fig. 4 - left). A more detailed GIS map of the study area depicting the 65 locations (triangles) where whitefly infestations occurred is shown in the lower right part of the illustration.

Harvester Ant. The harvester ant (*Pogonomyrmex barbatus* F. Smith) is a pest affecting rangeland and pastures, other turf areas, and a variety of crop plants in the southwestern United States (Little, 1972). Harvester ants are particularly damaging to pastures where they turn up the soil in mound-building activities and feed heavily on grass seeds, thereby interfering with the reseeding of pastureland (Myers et al., 1983). Mound size can vary from approximately 1 to 5 m in diameter. In south Texas, many ranges and pastures have heavy infestations of harvester ants that reduce the carrying capacity of the land. Aerial CIR photography has been used successfully to detect harvester ant infestations (Hart et al., 1971; Myers et al., 1983).

Everitt et al. (1996) used multispectral videography, GPS, and GIS technologies to detect and map harvester ant infestations in pasture and rangelands in south Texas. Red narrowband black-and-white digital video imagery can be used to detect harvester ant infestations (Fig. 5). The generally circular shape of the ant mounds delineates them from the sparsely vegetated areas which have a similar image response. Grassland vegetation has a gray to dark gray response. The harvester ant mounds could also be easily detected in the CIR composite image and could generally be delineated in the yellow-green image, but they could not be distinguished in the NIR image (other images not shown). Analysis of the video imagery of a 220 km^2 study area showed what appeared to be 44 ant infestations. Ground surveys confirmed the presence of harvester ants at every location.

The GPS latitude and longitude data obtained from the video survey of harvester ant infestations was merged with a GIS to develop a map showing infestations (Fig. 6). The lower portion of the figure shows GIS maps of Hidalgo and Willacy Counties with the study area delineated by a dotted boundary. The southern part of the experimental site was in Hidalgo County, whereas the northern portion was in Willacy County. The symbols (triangles) within the experimental area represented GPS latitude and longitude coordinates where harvester ant infestations occurred. Many of the locations are overlapped because of the small map scale. A more detailed GIS map of the study area is shown in the upper right portion of the illustration. A local site map showing even greater detail on the location of selected harvester ant infestations is shown in the upper left portion of the figure.

Western Pine Beetle. The western pine beetle (*Dendroctonus brevicomis* LeConte) is a pest that can cause mass destruction of ponderosa pines (*Pinus ponderosa* Dougl. ex Laud.) in the southwestern United States and British Columbia. Infestations often occur when trees are weakened by drought stress (Cobb et al., 1974; Furniss and Carolin, 1977). Drought conditions have prevailed in the Davis Mountains of west Texas since 1992 and several western pine beetle infestations have been observed in ponderosa pines in this area.

Everitt et al. (1997a) completed a study evaluating aerial photography for detecting and monitoring a western pine beetle infestation in a ponderosa pine forest in west Texas. Figure 7 shows a composite of four CIR (left column) and conventional

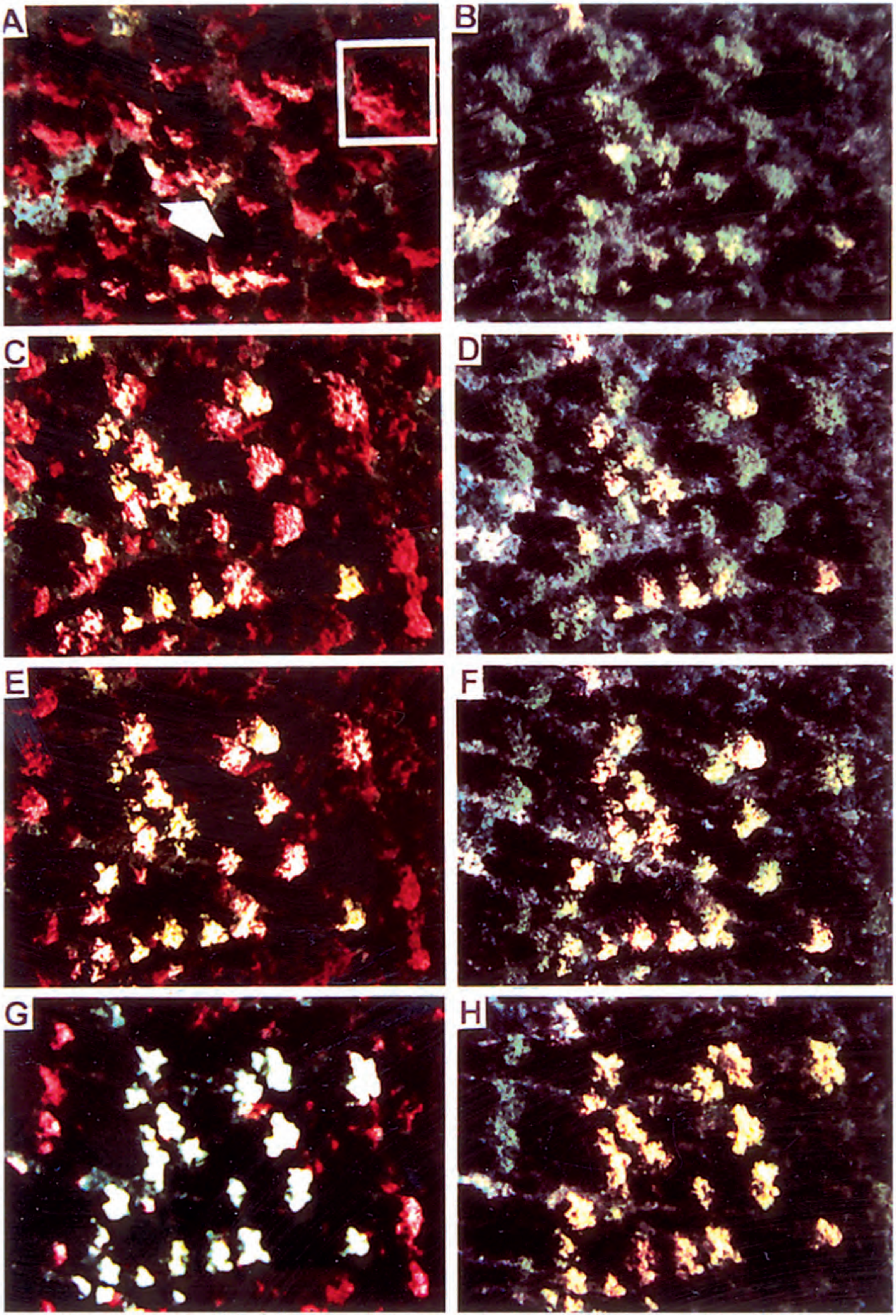

Fig. 7. Color-infrared (left column) and conventional color (right column) aerial photographs of ponderosa pine trees infested with western pine beetles in the Davis Mountains of west Texas. Imagery was acquired on 21 August (A and B), 9 September (C and D), 9 October (E and F), and 5 November (G and H), 1996. The arrow on print A points to a stressed tree, whereas the block denotes a tree showing no stress.

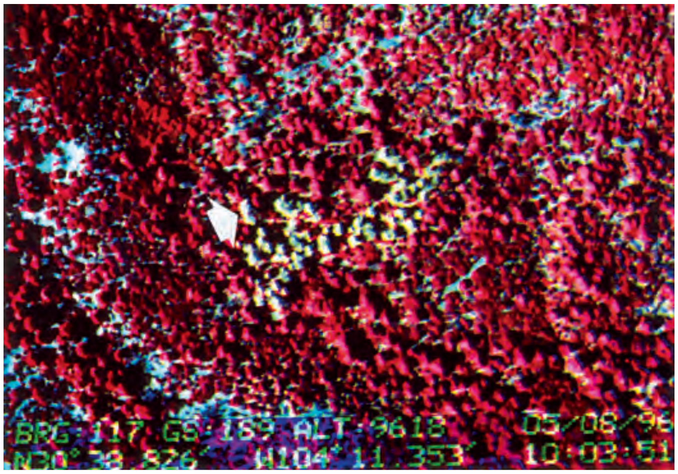

Fig. 8. Color-infrared digital video image of a stand of ponderosa pines killed by western pine beetles in the Davis Mountains of west Texas. The image was obtained on May 8, 1996 at an altitude above ground level of approximately 700 m. The arrow points to the yellowish-gray image response of infested trees. The GPS data are shown at the bottom of the scene.

color (right column) aerial photographs obtained of a stand of ponderosa pine trees infested with western pine beetles near Fort Davis, Texas. The photographs were obtained on four dates: August 21 (A and B), September 9 (C and D), October 9 (E and F), and November 5 (G and H), 1996. The arrow on the CIR print points to the pinkish-white hues of trees showing signs of stress by changes in foliage color. These trees exhibited a slight yellowing tinge (chlorosis) to the foliage. Other infested trees can be distinguished in the lower center and upper center of the photograph. Pine trees with the typical light green foliage have a magenta tone. Some of these trees showed evidence of beetle infestation, but had not shown a change in foliage color on August 21. The small block in the upper right portion of the photograph denotes one such tree. Other hard wood species (primarily oaks, *Quercus* spp.) have dark magenta to red image tones. In the conventional color photograph (B), the infested pine trees with yellow-tinged foliage have a slight greenish-white hue and can not be readily distinguished from the normal light green color of healthy pine trees. A single dead ponderosa pine tree (whitish response) can be seen on the upper top-left margin of both photos (A and B).

The western pine beetle infestation became more apparent in the photographs acquired on September 9 (Figs. 7C and 7D), than in the August 21 photos. Several of the infested trees whose foliage had not shown the effects of stress in August were exhibiting considerable yellowing of foliage by September. The trees that initially showed slight yellow-tinged foliage in August had a significant increase in discoloration by September with some leaves turning yellow-tan. The infested trees that had a whitish-pink response on CIR film in August had a more distinct whitish-tan CIR film response in September (Fig. 7C); pine trees showing only very faint or no stress in August had a whitish-pink CIR image tone in September. This change in CIR image response is evident by comparing the tree enclosed in the box in Figure 7A with the same tree in Figure 7C. The beetle-infested trees exhibiting stress symptoms were more distinguishable in the conventional color photograph (Fig. 7D) taken in September than in the August photograph (Fig. 7B); stressed trees had a whitish-green to whitish-tan image response in the September photograph.

The image responses of the stressed trees showed generally slight changes in both the CIR (Fig. 7E) and conventional color (Fig. 7F) photographs on October 9, as compared to the September 9 photographs. Ground surveys indicated that the trees had an increase in yellow and yellow-tan foliage over the one month period, but apparently this did not greatly affect their photographic responses.

Stressed ponderosa pines could be distinguished in both the CIR (Fig. 7G) and conventional color (Fig. 7H)

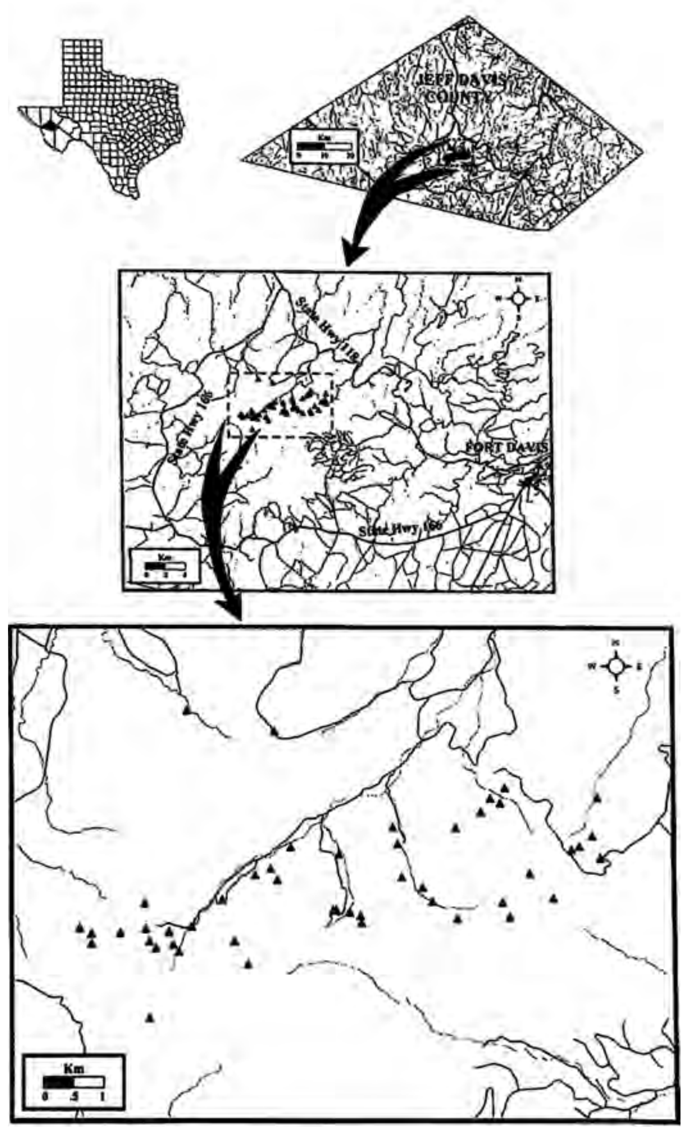

Fig. 9. GIS map (upper) of Jeff Davis County, TX, with the study site denoted in the lower center portion of the map. A large scale GIS map (center) of the study site showing the locations (triangles) where western pine beetle infestations occur. A large scale detailed GIS map (lower) of the study site depicting all 49 locations (triangles) where western pine beetle infestations occur.

photographs obtained on November 5. However, the stressed trees could be more clearly delineated in the CIR photograph where they have a conspicuous white image response. In the conventional color photograph the stressed trees have a whitish-tan tonal response. Ground surveys of the site showed that the majority of the needles on the stressed trees were a yellow-tan to yellow-red color, indicating that the trees were dying. By comparing the CIR image response of the tree enclosed in the box in Figure 7A across the four dates, the change in spectral response is conspicuous from that of a tree showing no stress to that of a dying tree in Figure 7G.

The CIR photographs were better than conventional color photographs for distinguishing western pine beetle infestations in ponderosa pines. This agrees with the findings of Ciesla et al. (1967) who used both types of film to detect southern pine beetle (*Dendroctonus frontalis* Zimmerman) infestations in the southeastern United States.

Everitt et al. (1997b) also conducted additional research using airborne videography with GPS and GIS technologies for detecting and mapping western pine beetle infestations in a 8x10 km study area in the Davis Mountains of west Texas.

The first phase of this study was to evaluate CIR videography for detecting western pine beetle infestations in ponderosa pines. Infested trees have a distinct yellow-gray image response in aerial CIR video imagery (Fig. 8). Healthy ponderosa pines and other tree species have various magenta and red image tones. The distinct signature of the dead ponderosa pine trees was due to their yellow-orange to orange-brown foliage color. Other stands of dead ponderosa pines infested with western pine beetles had a similar CIR video image to that shown in Figure 8 and could be readily distinguished from surrounding vegetation. Ponderosa pines under moderate stress from western pine beetle infestation could also be detected with the video imagery. These trees had a predominance of yellow to yellow-tan foliage (dying trees) and a pinkish-white CIR video image response (not shown). Analysis of the aerial video imagery identified what appeared to be 50 infestations of western pine beetles in ponderosa pines within the study site. Ground surveys confirmed the presence of western pine beetles in ponderosa pines at 49 of these locations. The remaining location was a stand of pinyon pines (*Pinus edulis* Engelm.) that were infested with a second species of pine beetle (*Ips confusus* LeConte). The dead pinyon pines had an orange-brown foliage color similar to that of the dead ponderosa pines and, consequently, had a video image response similar to that of the latter. A GPS was used in some of the ground surveys to help locate georeferenced coordinates of pine beetle infestations obtained from the aerial video imagery.

The GPS latitude and longitude data obtained from the video imagery were integrated with GIS technology to georeference western pine beetle infestations in ponderosa pines in the study site. Figure 9 (upper right) shows a GIS map of Jeff Davis County with the study site denoted in the lower center portion of the map. The triangles depict GPS latitude and longitude coordinates for western pine beetle infestations within the study site. The locations of infestations are overlapped because of the small map scale. Figure 9 (center) shows a more detailed GIS map of the study site depicting the locations (triangles) where western pine beetle infestations occurred. Many of the locations are overlapped due to the small map scale. However, this map is useful because one can associate general land use characteristics (i.e., hydrography, roads, towns) with the GPS marked locations where western pine beetle infestations occur. A detailed GIS map showing all of the locations where the 49 infestations occurred is shown in the lower portion of Figure 9. Dirt roads are represented by bold lines, while hydrographic features have finer lines.

CONCLUSIONS

Aerial photography and videography can be used successfully to detect insect infestations in both agricultural and natural environments. The fine resolution of aerial photography makes it particularly useful for both detecting early infestations and monitoring their spread.

The integration of videography, GPS, and GIS technologies provides valuable tools for detecting and mapping insect infestations. The video imagery can serve as a permanent geographically located image data base to monitor future contraction or spread of insect infestations. The joint use of these technologies provides previously unavailable information about the extent and spatial dynamics of insect infestations over large and often inaccessible areas such as rangeland and forested environments. The integration of these technologies can also be used for a variety of other natural resource management applications.

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