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Assessing Biological Control Damage of Giant Salvinia with Field Reflectance Measurements and Aerial Photography

J. H. EVERITT[1], D. FLORES[2], C. YANG[1], AND M. R. DAVIS[1]

ABSTRACT

A study was conducted on a small pond in southeast Texas to evaluate the potential for using remote sensing technology to assess feeding damage on giant salvinia (*Salvinia molesta* Mitchell) by the salvinia weevil (*Cyrtobagous salviniae* Calder and Sands). Field spectral measurements showed that moderately damaged and severely damaged plants had lower visible and near-infrared reflectance values than healthy plants. Healthy, moderately damaged, and severely damaged giant salvinia plants could be differentiated in an aerial color-infrared photograph of the study site. Computer analysis of the photograph showed that the three damage level classes could be quantified.

Key words: light reflectance, color-infrared photography, *Salvinia molesta*, *Cyrtobagous salviniae*, biocontrol.

INTRODUCTION

Giant salvinia is a rapidly proliferating, floating, aquatic fern native to southern Brazil that has spread to many other tropical countries around the world, as well as to Australia, New Guinea, New Zealand, South Africa and the United States (Forno et al. 1983, Nelson 1984, Barrett 1989, Chilton 1998). Giant salvinia develops dense mats that interfere with rice cultivation, clog fishing nets, and disrupt access to water for humans, livestock, and wildlife (Mitchell and Gopal 1991, Creigh 1991). It may damage aquatic ecosystems by overgrowing and replacing native plants that provide food and habitat for native animals and waterfowl (Mitchell 1978, Mitchell and Gopal 1991). Additionally, giant salvinia blocks out sunlight and decreases oxygen concentration to the detriment of fish and other aquatic species (Cook 1990, Mitchell and Gopal 1991). When plant masses die, decomposition lowers dissolved oxygen even further (Kannan 1979).

The use of biological control specifically with the salvinia weevil for management of giant salvinia is recognized as the leading and most widely used control strategy in all areas of the world due to its highly effective nature (Flores and Wendel 2001, Pieterse et al. 2003). The salvinia weevil is a small curculionid weevil that has been introduced to at least 12 countries. In all countries, giant salvinia has been completely and rapidly controlled, and reduced to less than 1% of its former infestation size. We know of no evidence of host switching in salvinia weevils, suggesting that non-target effects are unlikely. This has been evident in all areas of introduction (Forno et al. 1983, Thomas and Room 1986). In tropical areas, effect time has been measured in terms of months instead of years, as is the typical case with most insect biological control agents. Longer effect times are observed in cooler subtropical or warm temperate areas. It is highly cost-effective since the impact is realized for years without reintroduction.

Remote sensing is an important tool for wetland resource managers because of the inaccessibility and often large expanses of aquatic ecosystems (Carter 1982). Field reflectance measurements have been used to quantify the spectral characteristics of wetland plant species (Best et al. 1981, Everitt et al. 2000, Ulah et al. 2000) and aerial photography has been used successfully to remotely distinguish plant species and communities in wetland environments (Seher and Tueller 1973, Martyn 1985, Everitt et al. 2002). Remote sensing techniques have also been used successfully for detecting a variety of plant stresses, including those induced by insects (Murtha 1982, Myers et al. 1983, Lund 1997, Venugopal 1998).

Everitt et al. (2002) characterized the light spectra of giant salvinia and used color-infrared (CIR) aerial photography to distinguish infestations of this noxious weed from other associated vegetation. Little information is available on the use of remote sensing for assessing biological control of giant salvinia. The objectives of this study were: (1) to evaluate field reflectance measurements for distinguishing giant salvinia plants exhibiting feeding damage from the salvinia weevil; and (2) to determine the potential of CIR aerial photography for remotely detecting giant salvinia plants damaged by the salvinia weevil.

MATERIAL AND METHODS

This study was conducted on a 0.30 ha private pond located near Bridge City, Texas. This site was selected because it was infested with giant salvinia and was easily accessible. On November 7, 2001, giant salvinia plants containing all stages of the salvinia weevil were released into the pond for biologi-

[1]USDA/ARS, Integrated Farming and Natural Resources Unit, 2413 E. highway 83, Weslaco, TX 78596; e-mail: jeveritt@weslaco.ars.usda.gov; Phone: 956-969-4812, Fax: 956-969-4893.

[2]USDA/APHIS/PPQ/CPHST, Pest Detection, Diagnostics, & Management Laboratory, Moore Air Base, Building S- 6414, 22675 N. Moorefield Rd., Edinburg, TX 78541; e-mail: daniel.flores@aphis.usda.gov.

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cal control of this aquatic weed. The weevils were released from a road adjacent to the pond. The plant material and insects were reared in the USDA-APHIS laboratory facility in Edinburg, Texas. Since the initial release, an additional 16 releases have been made. The last release was on January 14, 2003. We estimate that approximately 199,000 salvinia weevils have been released at the pond. Releases were made into a floating 0.5 m^2 sampling square. Insect populations have continued to be sampled every 30-60 days through July 14, 2004.

On April 27 and July 14, 2004, giant salvinia plants were collected based on the visible damage level of plant material. Samples were collected from healthy (green) plant material, moderately damaged (green and brown) plant material, and severely damaged (predominantly brown) plant material. Six giant salvinia samples (2 from each damage level) were haphazardly collected from the study pond with the use of a 21.6-cm diameter strainer (9 × 9 cells per cm^2). All insect stages of the weevil are attached or imbedded in the plant eliminating the possibility of being lost through the strainer. The strainer was held below the mat of giant salvinia and in a vertical upward motion was pulled up with the sample of plant material. Each sample of plant material was then put into a 2-gallon freezer bag. All samples were labeled and placed into an ice chest and transported to the USDA laboratory in Edinburg where storage and scanning of the plant material occurred. At the laboratory, the bags of sampled material were removed from the ice chest and placed into a 0°C walk-in-freezer. Each sample was removed within 24 to 48 hours for further processing.

Five giant salvinia strands were removed from each sample and placed onto a dissecting table. When looking for eggs or larvae of the salvinia weevil, each frond was removed and split down the keel. After all the fronds were removed and bisected, the third submerged leaf (roots) was scanned for weevils at any life stage. The rhizome was also scanned with the aid of a scalpel. The scalpel was used to bisect the rhizome allowing for the viewing of weevil larvae or eggs. The adults can be easily detected on the plant while the fronds and roots are being removed. All numbers of eggs, larvae, pupae, and adults were recorded during the process. The entire process was repeated for each bagged sample after which all material was autoclaved and disposed.

Radiometric measurements, aerial photography, computer image analysis, and ground truth observations were also conducted for this study. Plant canopy radiometric reflectance measurements were made on the three damage levels of giant salvinia plants on May 5 and July 14, 2004. Reflectance measurements were made on ten haphazardly selected plant canopies of healthy, moderately damaged, and severely damaged giant salvinia on both dates with a Barnes[3] modular multispectral radiometer (Robinson et al. 1979). Measurements were made in the visible green (0.52 to 0.60 µm), visible red (0.63 to 0.69 µm), and near-infrared (NIR) (0.76 to 0.90 µm) spectral bands with a sensor that had a 15° field-of-view placed 1.0 to 1.5 m above each canopy. The ground area within the sensor field-of-view ranged from 0.26 to 0.39 m. Reflectance measurements were made between 1230 and 1500 h Central Standard Time under sunny conditions. Radiometric measurements were corrected to reflectance using a barium sulfate standard (Richardson 1981).

Green, red, and NIR reflectance data from the three classes of giant salvinia damage levels were analyzed using one-way analysis of variance. Spectral reflectance was the dependent variable and giant salvinia damage levels were the independent variable. Fisher's Protected Least Significant Difference (LSD) procedure was used to test statistical significance among the three classes at the 0.05 probability level (Steel and Torrie 1980).

Kodak Aerochrome CIR (0.50 to 0.90 µm) type 1443 film was used for acquiring the aerial photograph. Color-infrared film is sensitive in the visible green (0.50 to 0.60 µm), visible red (0.60 to 0.75 µm), and NIR (0.76 to 0.90 µm) spectral regions. The aerial photograph was obtained with a Fairchild type K-37 large format (23 cm × 23 cm) mapping camera. The camera was equipped with a 305-mm lens with an aperture setting of f11 at 1/250 sec. The photograph was obtained of the small pond on July 14, 2004 at an altitude above ground level of approximately 365 m (1:1,200 scale). A Cessna (model 404) airplane equipped with a camera port in the floor was used for obtaining the aerial photograph. The camera was maintained in a nadir position during acquisition. The aerial photograph was obtained of the study site at 1100 h Central Standard Time.

The aerial photographic transparency of the study area was scanned at 300 dots per inch (dpi). The area of interest (pond) within the photo was selected using the polygonal lasso tool of Adobe Photoshop (version 7.0). A new image of the area of interest was then created by masking out non-pond areas. An RGB (red-green-blue) image was converted to an index color image using the Mode function. The Mode function is the selection of color type from the image menu. The index color image is one of the options under the Mode function that consists of a color table that consists of up to 256 colors. Using the Image Mode function, three levels of giant salvinia plants were assigned to the pond. These included healthy plants, moderately damaged plants, and severely damaged plants. Each of these levels (areas) was quantified.

RESULTS AND DISCUSSION

Figure 1 shows a ground color photograph of a portion of the study site obtained July 14, 2004. Feeding damage by the salvinia weevil resulted in a color gradient in giant salvinia plants across the pond. Severely damaged plants have predominantly dark brown foliage with very few green fronds. Moderately damaged plants have an integrated mixture of brown and green foliage. Healthy plants appear green, but have a few brown fronds within the canopy.

Mean *Cyrtobagous salviniae*/salvinia strand found on three damage levels of giant salvinia plants in April and July 2004 are presented in Figure 2. In April, insect densities ranged from 0.7 insects/strand from severely damaged plants to 1.4 insects/strand from moderately damaged plants. Insect densities followed a similar pattern in July; however, mean values declined slightly within each damage category. The decline may have resulted from an increase in plant material. Although healthy plants showed little effects of feeding damage, they had higher densities of insects/strand than severely damaged plants.

Mean light percent reflectance measurements from healthy, moderately damaged, and severely damaged giant

Figure 1. Giant salvinia damage gradient across pond resulting from insect feeding damage. Healthy plants (H) appear green, moderately damaged plants (M) appear brownish-green, and severely damaged plants (S) appear dark brown.

salvinia plants at three wavelengths on two sampling dates are shown in Table 1. In both May and July 2004, healthy giant salvinia had higher visible green and red reflectance values than moderately and severely damaged plants. The green and red reflectance values of moderately and severely damaged plants could not be separated. The predominantly green foliage of healthy giant salvinia plants reflected more green and red light than the integrated brown and green color scheme of moderately damaged plants and predominantly brown color of severely damaged plants (Gausman 1985).

At the NIR wavelength the reflectance values of the three damage levels differed significantly in both May and July (Table 1). Healthy plants had the highest NIR reflectance, while severely damaged plants had the lowest. Previous work has shown that NIR reflectance in vegetation is highly correlated with plant density and vigor (Myers et al. 1983, Gausman 1985). An overhead vertical view of the canopies of the three damage levels in both May and July showed that healthy plants had greater vegetative density and less gaps in their canopies than the other damage levels. Conversely, severely damaged plants had more gaps and breaks in their canopies than moderately damaged and healthy plants. The brown foliage within the canopies of moderately damaged and severely damaged plants contributed greatly to their low NIR reflectance values (Myers et al. 1983).

Figure 3A shows an aerial CIR photograph of the general study area obtained July 14, 2004. The photo is a portion of a 23-cm photograph (1:1,200 scale). The pond study site is outlined in white. The pond is covered with a dense mat of giant salvinia. Arrow-1 points to the dark reddish-brown color of severely damaged giant salvinia plants, while arrow-2 points to the brownish-pink image response of moderately damaged plants. Healthy green plants (arrow-3) have a typical pink image response (Everitt et al. 2002). The visible green, visible red, and NIR spectral light from healthy giant salvinia highly affected the yellow, magenta, and cyan emulsion layers, respectively, of the CIR film The high NIR reflectivity of healthy giant salvinia eliminated most of the cyan layer, while

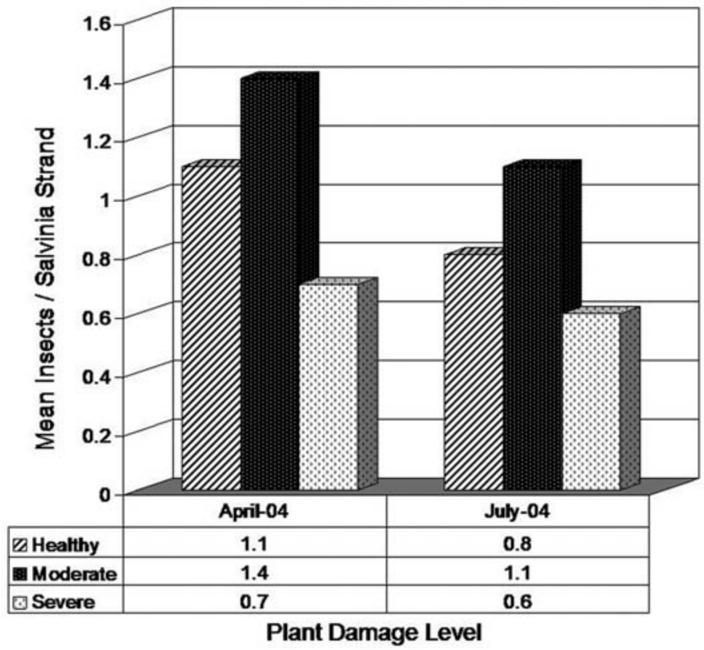


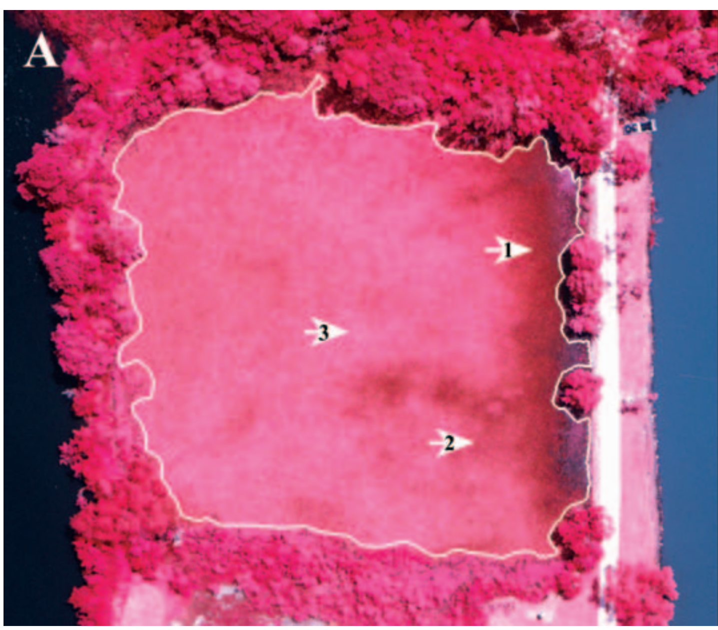
Figure 2. Mean *Cyrtobagous salviniae* per salvinia strand (± standard error) found on three damage levels [healthy, moderately damaged, and severely damaged] of giant salvinia plants in April and July 2004 (n = 10). Mean densities among samples did not differ significantly at the 0.05 probability level.

the moderately high green and red visible light reflectance significantly reduced the yellow and magenta emulsion layers, respectively, which combined to produce the pink image tonal response shown in the CIR photograph. The generally low reflectivity of moderately stressed and severely stressed

TABLE 1. MEAN LIGHT REFLECTANCE MEASUREMENTS OF HEALTHY (GREEN) GIANT SALVINIA PLANTS AND THOSE WITH MODERATE AND SEVERE FEEDING DAMAGE FROM SALVINIA WEEVILS. MEASUREMENTS WERE MADE NEAR BRIDGE CITY, TEXAS, IN MAY AND JULY 2004. MEANS WITHIN A COLUMN AT EACH SAMPLING DATE FOLLOWED BY THE SAME LETTER DO NOT DIFFER SIGNIFICANTLY AT THE 0.05 PROBABILITY LEVEL, ACCORDING TO FISHER'S PROTECTED LEAST SIGNIFICANT DIFFERENCE PROCEDURE FOLLOWING ANOVA FOR EACH SPECTRAL VARIABLE ON TWO DATES. THE STANDARD DEVIATIONS FOR EACH MEAN ARE GIVEN IN PARENTHESIS.

		Reflectance values for three wavelengths		
Date	Damage level	Green	Red	Near-infrared
May 2004	Healthy	7.0 a (± 0.4)	4.8 a (± 0.2)	38.3 a (± 2.6)
	Moderate	3.5 b (± 0.3)	3.2 b (± 0.2)	16.0 b (± 1.2)
	Severe	3.2 b (± 0.4)	2.9 b (± 0.6)	9.5 c (± 0.4)
July 2004	Healthy	6.5 a (± 0.6)	4.5 a (± 0.5)	35.7 a (± 2.6)
	Moderate	2.9 b (± 0.2)	2.6 b (± 0.2)	14.5 b (± 0.9)
	Severe	2.8 b (± 0.2)	2.4 b (± 0.1)	10.3 c (± 1.3)

May 2004
Treatment effect for green: n = 10, df = 2, f value = 276, $p < 0.0001$, LSD = 0.37.
Treatment effect for red: n = 10, df = 2, f value = 71, $p < 0.0001$, LSD = 0.35.
Treatment effect for near-infrared: n = 10, df = 2, f value = 809, $p < 0.0001$, LSD = 1.54.
July 2004
Treatment effect for green: n = 10, df = 2, f value = 317, $p < 0.0001$, LSD = 0.34.
Treatment effect for red: n = 10, df = 2, f value = 123, $p < 0.0001$, LSD = 0.31.
Treatment effect for near-infrared: n = 10, df = 2, f value = 583, $p < 0.0001$, LSD = 1.63.



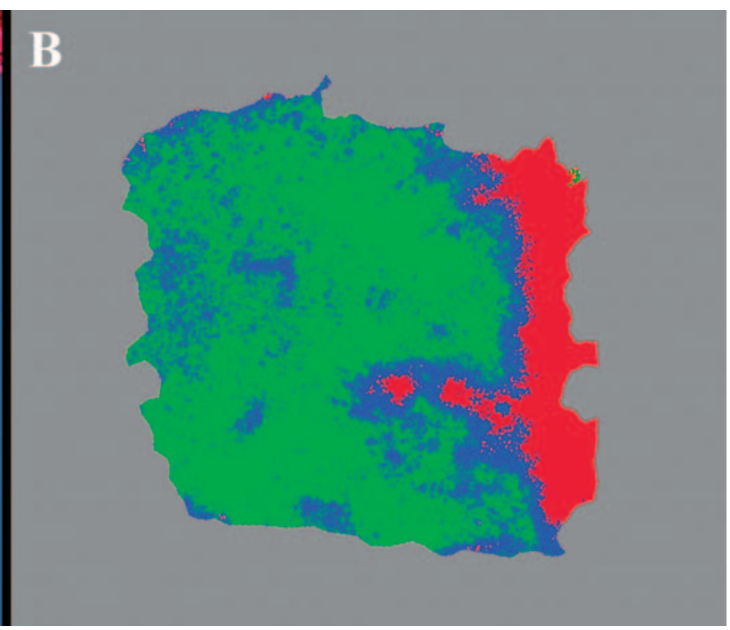


Figure 3. Aerial color-infrared photograph (A) of the pond infested with giant salvinia near Bridge City, Texas. The photograph (scale 1,200) was obtained July 14, 2004. The pond is outlined in white. Arrow-1 points to the dark reddish-brown color of severely damaged plants. Moderately damaged plants (arrow-2) have a brownish-pink color and healthy plants (arrow-3) have a pink image tone. Print B shows the computer-classified image of the pond. Color codes for the damage levels are: red = severely damaged plants, blue = moderately damaged plants, and green = healthy plants.

giant salvinia in the visible green, visible red, and NIR spectral regions did not markedly affect the CIR film emulsion layers. This caused the yellow, magenta, and cyan layers to become saturated in the film, thus producing the dark image tones of moderately stressed and severely stressed giant salvinia in the CIR photograph (Everitt et al. 2001) (Table 1).

Figure 3B shows the computer classification of the CIR photograph of the pond. Color codes and respective percentages for the three damage levels are: green = healthy giant salvinia (64.7%), blue = moderately damaged giant salvinia (21.7%), and red = severely damaged giant salvinia (13.6%). A qualitative comparison of the computer classification to the photograph indicates the image analysis technique did a good job in identifying the damage levels of giant salvinia. Ground surveys of the study site were in close agreement with the image classification map. A rigorous accuracy assessment was not performed on this map; this needs to be conducted in future work.

These results indicate that remote sensing techniques can be used successfully for assessing the effect of the salvinia weevil for controlling giant salvinia. The ability to distinguish feeding damaged giant salvinia plants on CIR aerial photography is useful because the film can be used for mapping and monitoring changes over time. This research was conducted in spring and early summer when giant salvinia plants are under optimum growing conditions and predominantly comprised of green foliage. Some giant salvinia populations undergo senescence in later summer and early fall where the foliage is predominantly brown. During this growth stage remote sensing techniques may be limited for differentiating feeding damaged plants from senesced plants (Everitt et al. 2002). Additional surveys need to be conducted to determine the potential of this technique later in the growing season.

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