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Remote Sensing of Giant Salvinia in Texas Waterways

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ABSTRACT

Giant salvinia (*Salvinia molesta* Mitchell) is an invasive aquatic fern that has been discovered at several locations in southeast Texas. Field reflectance measurements were made on two classes of giant salvinia [green giant salvinia (green foliage) and senesced giant salvinia (mixture of green and brown foliage)] and several associated species. Reflectance measurements showed that green giant salvinia could be best distinguished at the visible green wavelength, whereas senesced giant salvinia could generally be best separated at the near-infrared (NIR) wavelength. Green giant salvinia and senesced giant salvinia could be detected on color-infrared (CIR) aerial photographs where they had pink and grayish-pink or olive-green image responses, respectively. Both classes of giant salvinia could be distinguished in reflectance measurements made on multiple dates and at several locations in southeast Texas. Likewise, they could be detected in CIR photographs obtained on several dates and at widely separated locations. Computer analysis of a CIR photographic transparency showed that green giant salvinia and senesced giant salvinia populations could be quantified. An accuracy assessment performed on the classified image showed an overall accuracy of 87.0%.

Key words: Light reflectance, color-infrared photography, accuracy assessment, *Salvinia molesta.*

INTRODUCTION

The invasion and spread of noxious aquatic weeds in waterways present serious problems for wetland resource managers (Barrett 1989, Mitchell and Gopal 1991). The inaccessibility and often large expanses of many wetlands make ground inventory and assessment difficult, time consuming, expensive, and often inaccurate (Scarpace et al. 1981). Remote sensing techniques offer rapid acquisition of data with generally short turnaround time at costs lower than ground surveys (Tueller 1982, Everitt et al. 1992).

The value of remote sensing for wetland assessment is well established (Carter 1982, Tiner 1997). Plant canopy reflectance measurements have been used to spectrally differentiate among wetland plant species (Best et al. 1981, Everitt et al. 2000). Aerial photography and videography have been used extensively to remotely distinguish plant species and communities in wetland environments (Seher and Tueller 1973, Carter 1982, Martyn 1985, Mackey et al. 1987, Everitt et al. 1999).

Giant salvinia is a floating fern native to southern Brazil that has spread to many other warm freshwaters of the world (Barrett 1989). Categorized as an A2 weed, it ranks behind waterhyacinth [*Eichhornia crassipes* (Mort.) Solms] on the federal noxious aquatic weed list where it was placed in 1984 (Barrett 1989). 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). Additionally, giant salvinia will overgrow and replace native plants that provide food and habitat for wildlife, and it blocks out sunlight and decreases oxygen concentration to the detriment of fish and other aquatic species (Cook 1990, Mitchell and Gopal 1991). Giant salvinia has been found and eradicated in nurseries and ponds in the U.S. on several occasions (Nelson 1984). However, in September 1998, a major occurrence of giant salvinia was found in Toledo Bend Reservoir in east Texas (Chilton 1998). It has since spread to a number of private ponds and other waterways in east and southeast Texas.

Little information is available on the use of remote sensing technology for management of giant salvinia. The objectives of this study were: (1) to determine the plant canopy reflectance characteristics of giant salvinia and associated species to facilitate its detection on remotely sensed imagery; and (2) to evaluate color-infrared aerial photography for detecting giant salvinia infestations in southeast Texas waterways.

MATERIALS AND METHODS

This study was conducted on several waterways in southeast Texas. Study sites were located near Liberty, Bridge City, Mont Belvieu, Milam, and Raymondville. Aerial photography, radiometric reflectance measurements, computer image analysis, and ground truth observations were conducted for this study. Reflectance measurements were made to establish the spectral characteristics of giant salvinia and dominant associated plant species to help interpret aerial photographs. Aerial photographs and reflectance measurements were obtained on different dates and locations to study giant salvinia under various growing conditions.

Reflectance measurements were made on ten randomly selected plant canopies of each species with a Barnes[3] modular multispectral radiometer (Robinson et al. 1979). Measurements were made in the visible green (0.52 to 0.60 µm), visi-

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[3]Trade names are included for the benefit of the reader and do not imply endorsement of or a preference for the product listed by the United States Department of Agriculture.

ble 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-degree field-of-view placed 1.0 to 1.5 m above each plant canopy. The area within the sensor field-of-view ranged from 0.26 to 0.39 m. Reflectance measurements were made between 1100 and 1500 h Central Standard Time under sunny conditions. Radiometric measurements were corrected to reflectance using a barium sulfate standard (Richardson 1981). Overhead vertical photographs were obtained of the plant canopies measured with the radiometer to help interpret reflectance data.

Spectral measurements were made on May 27 and 31, 1999 near Liberty and Raymondville, respectively, and on July 1 and October 26, 1999 near Bridge City and Liberty, respectively. Additional reflectance measurements were made on March 29, 2000 near Liberty, May 24, 2000 near Tomball, and July 19, 2000 near Mont Belvieu. For the May 1999 period, reflectance measurements were made on giant salvinia and six additional common species known to grow in association with it. Although all of the species occur in various wetlands near Liberty and were surmised to grow in association with giant salvinia, some were not easily accessible. Thus, measurements were made at two different locations in May 1999. Reflectance measurements were made on giant salvinia, alligator weed [*Alternathera philoxeroides* (Mart.) Griseb.], smartweed (*Polygonum pensylvanicum* L.), and arrowhead (*Sagittaria latifolia* Willd.) near Liberty, while measurements on American lotus [*Nelumbo lutea* (Willd.) Pers.], waterhyacinth, and surfaced hydrilla [*Hydrilla verticillata* (L.F.) Royle] were made near Raymondville. Measurements were made on two classes of giant salvinia: plants with green foliage only and senesced plants with mixtures of green and brown foliage. Senesced giant salvinia occurred in areas where the plants had become extremely dense and available nutrients were probably limited. These two classes were often observed together in giant salvinia populations at other locations in southeast Texas. At some sites, however, only green or senesced giant salvinia plants occurred.

Measurements at the Bridge City site in July were made on green giant salvinia, alligator weed, smartweed, waterhyacinth, and pennywort (*Hydrocotyle verticillata* Thumb.). Spectral measurements at the Liberty site in October were made on senesced giant salvinia, alligator weed, arrowhead, smartweed, and waterhyacinth.

For March 2000 at Liberty, spectral measurements were made on green giant salvinia, senesced giant salvinia, alligator weed, arrowhead, and waterhyacinth. Measurements at the Tomball study site in May 2000 were made on green giant salvinia, smartweed, and waterhyacinth, while measurements at Mont Belvieu in July 2000 were made on green giant salvinia, senesced giant salvinia, waterhyacinth, and American buttonbush (*Cephalanthus occidentalis* L.).

Green, red and NIR reflectance data were analyzed using analysis of variance techniques. Duncan's multiple range test was used to test statistical significance at the 0.05 probability level among means (Steel and Torrie 1980).

Kodak Aerochrome color-infrared (CIR) (0.50 to 0.90 µm) type 2443 film was used for aerial photographs. 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. Photographs were 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. Photographs were obtained near Liberty and Bridge City on June 18, 1999, and near Liberty, Bridge City, and Milam on July 1, 1999. Additional photographs were obtained near Liberty on March 30, 2000 and near Mont Belvieu on June 7, 2000. Photographs were obtained at scales ranging from 1:1,500 to 1:8,500. A Cessna (model 404) airplane, equipped with a camera port in the floor, was used for obtaining aerial photography. The camera was maintained in a nadir position during image acquisition. Aerial photographs were acquired between 1130 and 1430 h Central Standard Time under sunny conditions. A CIR photographic transparency (1:8,500 scale) of a study site near Mont Belvieu obtained on June 7, 2000 was digitized to perform a computer classification and accuracy assessment on the photograph. A Trimble differential global positioning system (GPS) Pathfinder Pro XRS system that provided submeter accuracy was used in the field to establish control points on the digitized photographic transparency. The transparency was scanned at 600 dpi and had a pixel resolution of 0.6 m. Erdas Imagine software (Version 8.3) was used to georeference the transparency. The image was subjected to an Iterative Self-Organizing Data Analysis (ISODATA) which performs unsupervised classifications on the basis of specified iterations and recalculates statistics for each iteration (Erdas 1997). The ISODATA technique uses minimum spectral distance to assign a cluster for each selected pixel. It begins with arbitrary cluster means, and each time the clustering repeats, the means of these clusters are shifted. The new cluster means are used for the iteration. Each unsupervised classification completed in this study created five classes from the five data iterations at the 0.99% convergence threshold (the maximum percentage of pixels cluster assignments go unchanged between iterations). The classes consisted of water, woody plants, green giant salvinia, senesced giant salvinia, and waterhyacinth. For accuracy assessment, 100 points were assigned to the five classes in a stratified random pattern. The geographic coordinates of these points were determined and the GPS was used to navigate to the points in ground truthing. Both a producer's and user's accuracy were calculated. The producer's accuracy (measure of omission error) is the total number of correct points in a category divided by the total number of points of that category as derived from the reference data (ground truthing). The user's accuracy (measure of commission error) is the total number of correct points in a category divided by the total number of points of that category as derived from the classification data (map data).

RESULTS AND DISCUSSION

Reflectance Measurements

Mean light reflectance measurements of giant salvinia and associated plant species at three wavelengths from six sampling dates in southeast Texas are shown in Table 1. In May 1999 at Liberty/Raymondville, American lotus had higher visible green reflectance than the other species, whereas hydrilla had lower reflectance than the other species. Green giant salvinia had lower green reflectance than American lotus, but higher reflectance than the other species. The

TABLE 1. MEAN LIGHT REFLECTANCE MEASUREMENTS OF GIANT SALVINIA AND ASSOCIATED PLANT SPECIES AT FIVE SITES IN SOUTHEAST TEXAS ON SIX DATES. REFLECTANCE MEASUREMENTS WERE MADE AT THE VISIBLE GREEN, VISIBLE RED, AND NEAR-INFRARED WAVELENGTHS.

		Reflectance values[1] (%) for three wavelengths		
Location and date	Plant species	Green	Red	Near-infrared
May 1999 Liberty and Raymondville, TX	American lotus	9.3 a	3.7 b	46.0 a
	Giant salvinia—green	7.0 b	4.6 a	31.1 bc
	Alligator weed	5.6 c	3.0 c	34.8 b
	Giant salvinia—green and brown	5.3 c	4.6 a	25.3 d
	Smartweed	5.2 cd	2.5 d	33.7 bc
	Arrowhead	5.1 cd	2.3 d	28.9 c
	Waterhyacinth	4.4 d	1.7 e	43.3 a
	Hydrilla	2.9 e	1.8 e	13.1 e
July 1999 Bridge City, TX	Giant salvinia—green	7.5 a	4.4 a	42.0 a
	Alligator weed	5.4 b	2.6 b	36.8 b
	Smartweed	5.1 bc	2.3 b	41.6 a
	Pennywort	4.9 c	2.3 b	38.7 ab
	Waterhyacinth	3.8 d	1.6 c	41.8 a
October 1999 Liberty, TX	Giant salvinia—green and brown	5.4 a	3.7 a	26.2 b
	Arrowhead	4.3 b	2.8 b	23.0 c
	Smartweed	3.7 c	2.7 b	21.6 c
	Waterhyacinth	3.6 c	2.2 c	30.2 a
	Alligator weed	3.6 c	2.1 c	24.5 bc
March 2000 Liberty, TX	Giant salvinia—green	6.7 a	4.3 a	36.3 b
	Giant salvinia—green and brown	5.3 b	3.9 b	24.0 e
	Alligator weed	5.0 bc	2.4 c	33.0 c
	Arrowhead	4.9 c	2.5 c	30.4 d
	Waterhyacinth	3.8 d	1.9 d	41.0 a
May 2000 Tomball, TX	Giant salvinia—green	8.5 a	5.3 a	30.3 b
	Smartweed	5.1 b	2.9 b	30.7 b
	Waterhyacinth	3.4 c	1.9 c	39.1 a
July 2000 Mont Belvieu, TX	Giant salvinia—green	6.2 a	3.9 a	39.2 a
	Giant salvinia—green and brown	5.1 b	3.8 a	27.9 d
	American buttonbush	4.0 c	2.1 b	33.6 c
	Waterhyacinth	3.9 c	2.0 b	35.6 b

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

green light reflectance of senesced giant salvinia was similar to that of alligator weed, arrowhead, and smartweed. At the visible red wavelength, both green giant salvinia and senesced giant salvinia had higher reflectance than the associated species. Conversely, hydrilla and waterhyacinth had lower red reflectance than the other species. Visible reflectance in vegetation is primarily affected by plant pigments (Myers et al. 1983). The species varied in color from blue-green for American lotus to light green for green giant salvinia, to intermediate green for alligator weed, arrowhead, and smartweed, to dark green for waterhyacinth and hydrilla. Senesced giant salvinia had an integrated greenish-brown color scheme. The darker green foliage (higher chlorophyll concentration) of waterhyacinth and hydrilla reflected less green light and absorbed more red light than the lighter green, green and brown, and blue-green foliage (lower chlorophyll concentration) of green giant salvinia, senesced giant salvinia, and American lotus, respectively.

At the NIR wavelength, American lotus and waterhyacinth had higher reflectance than the other species, while hydrilla had lower reflectance than the other species. The NIR reflectance of green giant salvinia did not differ from that of alligator weed, arrowhead, and smartweed. However, the NIR reflectance of senesced giant salvinia differed from that of the other species. Near-infrared reflectance in vegetation is highly correlated with plant density and vigor (Myers et al. 1983, Everitt et al. 1986). An overhead view of the plant species showed that American lotus and waterhyacinth had greater leaf density and less gaps in their canopies than the other species, while hydrilla had more gaps and breaks in its canopy. The canopy of senesced giant salvinia had similar density to that of green giant salvinia, but its brown foliage gave it lower NIR reflectance (Myers et al. 1983). Although the low NIR reflectance of hydrilla was contributed to significantly by its open canopy, the integration of water with the canopy also absorbed a large percentage of the NIR light (Myers et al. 1983, Everitt et al. 1999).

In July 1999 at Bridge City, green giant salvinia had higher visible green and red reflectance than the associated species. Conversely, waterhyacinth had lower green and red reflectance than the associated species. The NIR reflectance of giant salvinia did not differ from that of three associated species.

Reflectance data for October 1999 at Liberty indicated that senesced giant salvinia had higher green and red reflectance than the four associated species. However, at the NIR wavelength giant salvinia had similar reflectance to that of alligator weed. No green giant salvinia plants occurred at the study site in October.

At Liberty in March 2000, green giant salvinia had higher green and red reflectance than senesced giant salvinia and three other associated species. Senesced giant salvinia had similar green reflectance to alligator weed, but its red reflectance differed from that of green giant salvinia and the associated species. Green giant salvinia had lower NIR reflectance than waterhyacinth and higher reflectance than the other two associated species and senesced giant salvinia.

Spectral measurements made at Tomball in May 2000 showed that green giant salvinia had higher green and red reflectance than smartweed and waterhyacinth. The NIR reflectance of giant salvinia did not differ from that of smartweed. Giant salvinia plants appeared to have lighter green foliage than green giant salvinia plants at other locations, which probably caused the slightly higher visible reflectance values.

In July 2000 at Mont Belvieu, green giant salvinia had higher green reflectance than senesced giant salvinia, American buttonbush, and waterhyacinth. At the red wavelength, green giant salvinia and senesced giant salvinia had similar reflectance values; however, their reflectance values were higher than those of American buttonbush and waterhyacinth. Green giant salvinia had higher NIR reflectance than the two associated species and senesced giant salvinia. Conversely, senesced giant salvinia had lower NIR reflectance than the two associated species and green giant salvinia.

Aerial Photography

Figure 1A shows a CIR positive photographic print obtained on June 7, 2000 of a small lake infested with giant salvinia near Mont Belvieu. The print is a portion of a 23 cm photograph (1:8,500 scale). Arrow-1 points to the pink image tone of green giant salvinia, while arrow-2 points to the grayish-pink image response of senesced giant salvinia. Both classes of giant salvinia can be readily distinguished throughout the lake. The small dark red clumps are American buttonbush and live oak (*Quercus virginiana* Mill.) trees on small islands, whereas the small lighter red clumps are waterhyacinth. Water has dark blue to black image tones. The lake is surrounded by a dense woodland. Fallow agricultural fields are located in the lower portions of the photograph, while another lake is located on the right side of the photo.

Green giant salvinia had a similar color tonal response to that shown in Figure 1A in additional CIR photographs obtained near Liberty, Bridge City, and Milam. The CIR image response of senesced giant salvinia varied from grayish-pink (Figure 1A) to olive-green. Some senesced giant salvinia populations near Liberty had both grayish-pink and olive-green CIR image responses. The darker image response of some senesced giant salvinia populations was attributed to a higher proportion of brown foliage in their canopies. Nonetheless, these populations could be differentiated qualitatively from other associated plant species. Both green giant salvinia and senesced giant salvinia could be distinguished in CIR photos obtained in June and July 1999, and in March and June 2000. Giant salvinia could be distinguished at photographic scales ranging from 1:1,500 to 1:8,500.

The unsupervised computer classification of the June CIR photograph (Figure 1A) is shown in Figure 1B. Color codes and respective areas/percentages for the various land-use types are: yellow = green giant salvinia (41.4%), orange = senesced giant salvinia (27.7%), aqua = woody plants (0.7%), magenta = waterhyacinth (1.4%), and dark blue = water (28.8%). American buttonbush and live oak were included in the woody plant class. A qualitative comparison of the computer classification to the photograph shows that the computer did a good job in identifying both classes of giant salvinia.

Table 2 shows an error matrix by comparison of the classified data with the ground data for the 100 observations within the study area. The overall classification accuracy was 87.0%, indicating that 87% of the category pixels in the image were correctly identified in the classification map. The producer's accuracy of individual categories ranged from 46.2% for waterhyacinth to 100% for water, whereas the user's accuracy ranged from 75% for both woody plants and waterhyacinth to 100% for water. Water was the easiest category to identify, while waterhyacinth was the most difficult to differentiate. Both the producer's accuracy and user's accuracy for giant salvinia were quite good. Green giant salvinia had 89.5% accuracy for both the producer's and user's accuracy, while senesced giant salvinia had a producer's accuracy of 94.7% and a user's accuracy of 78.3%. The errors in both giant salvinia classes were insignificant because they were primarily due to confusion between the two. This was attributed to grading between healthy plants with green foliage and senesced plants with mixtures of green and brown foliage. The low producer's accuracy of waterhyacinth was caused by confusion with woody plants and the two classes of giant salvinia. Some of the error was due to small clumps of waterhyacinth less than 1 m in diameter that were intermixed with the two classes of giant salvinia. The confusion of waterhyacinth with the woody plant category (American buttonbush and live oak) was attributed to the similar reflectance values of the plants (Table 1; Everitt et al. 1987). Another accuracy measure, the kappa estimate for this study, was 0.825, indicating the classification has achieved an accuracy that is 82.5% better than would be expected from random assignment of pixels to categories.

Field reflectance measurements made on several dates and at various locations in southeast Texas showed that both green giant salvinia and senesced giant salvinia could be distinguished spectrally from each other and from other associated plant species. The visible green wavelength was optimum for distinguishing green giant salvinia, whereas the NIR wavelength was generally best for separating senesced giant salvinia.

Giant salvinia could be remotely distinguished in CIR aerial photographs obtained on several dates at widely separated sites in southeast Texas. Green giant salvinia had a pink image response on CIR film, whereas senesced giant salvinia had a grayish-pink or olive-green image tone. Computer image anal-

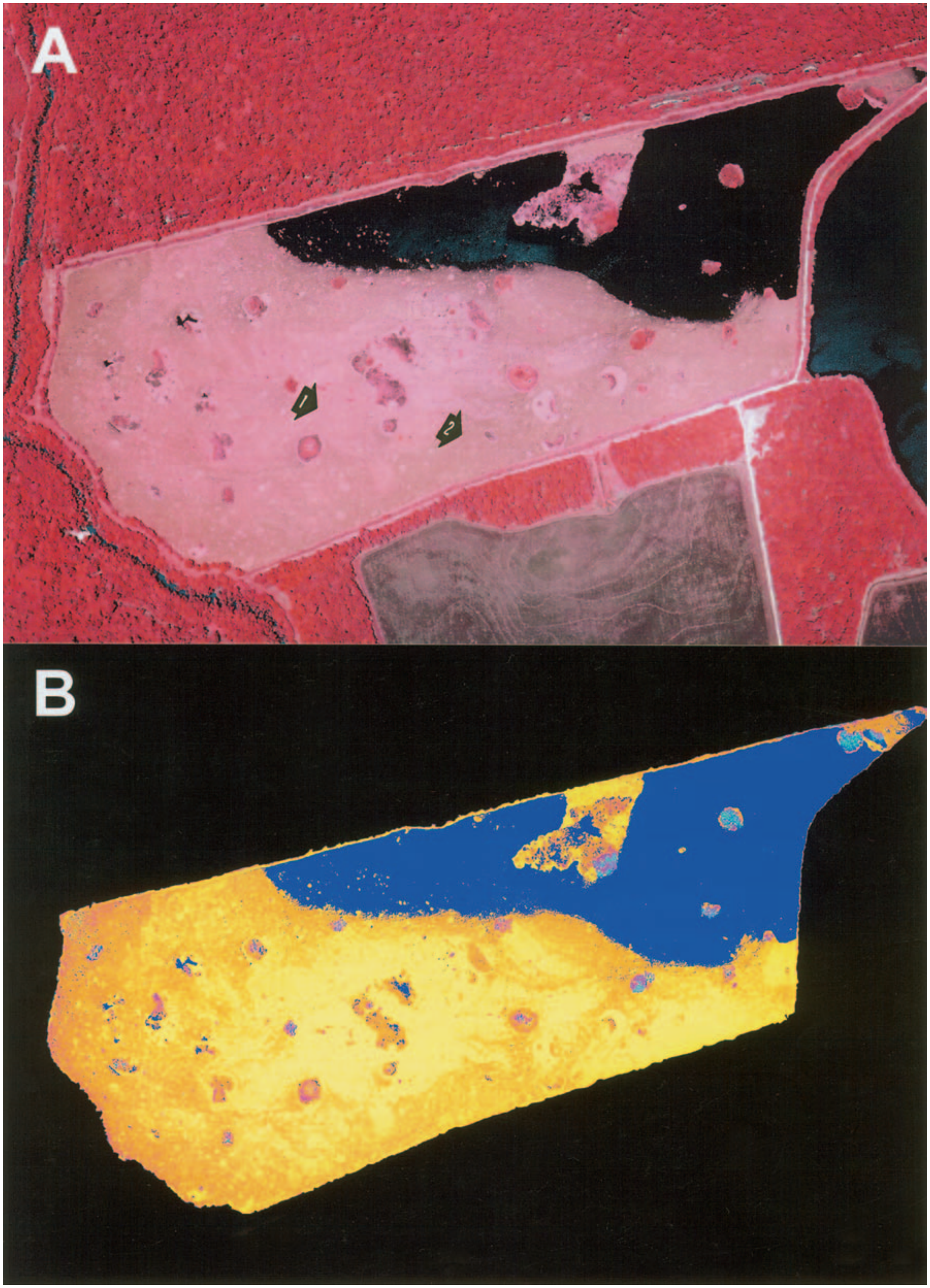

Figure 1. Color-infrared photographic print (A) obtained on June 7, 2000 of a small lake near Mont Belvieu, Texas infested with giant salvinia. Arrow 1 points to the pink image tone of green giant salvinia, whereas arrow 2 points to the grayish-pink response of senesced giant salvinia. The photograph had an original scale of 1:8,500. Unsupervised computer classification (B) of print A. Color codes for the various land-use types are yellow = green giant salvinia; orange = senesced giant salvinia; aqua = woody plants; magenta = waterhyacinth; and dark blue = water.

TABLE 2. AN ERROR MATRIX GENERATED FROM THE CLASSIFICATION DATA AND GROUND DATA FOR THE JUNE 7, 2000 COLOR-INFRARED PHOTOGRAPH OF THE MONT BELVIEU STUDY SITE.

	Actual Category						
Classified category	Water	Woody plants	Senesced GS	Waterhyacinth	Green GS	Total	Users's accuracy
Water	23	0	0	0	0	23	100%
Woody plants	0	6	0	2	0	8	75.0%
Senesced GS	0	0	18	2	3	23	78.3%
Waterhyacinth	0	1	0	6	1	8	75.0%
Green GS	0	0	1	3	34	38	89.5%
Total	23	7	19	13	38	100	
Producer's accuracy	100%	85.7%	94.7%	46.2%	89.5%		

Overall accuracy = 87.0%. Kappa = 0.825. GS - giant salvinia.

ysis of a CIR film transparency (1:8,500 scale) showed that green giant salvinia and senesced giant salvinia populations could be differentiated quantitatively from associated plant species and water. An accuracy assessment showed that the computer did a good job in identifying both classes of giant salvinia.

The capability to remotely distinguish giant salvinia infestations in southeast Texas waterways should be useful to wetland resource managers who are interested in controlling this invasive weed. Aerial photographs provide a record that can be stored and examined for comparative purposes at any point in time.

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