Using Remote Sensing and Spatial Information Technologies to Detect and Map Two Aquatic Macrophytes

J. H. EVERITT[1], C. YANG[1], D. E. ESCOBAR[1], C. F. WEBSTER[2], R. I. LONARD[3] AND M. R. DAVIS[1]

ABSTRACT

This paper describes the light reflectance characteristics of waterhyacinth [*Eichhornia crassipes* (Mort.) Solms] and hydrilla [*Hydrilla verticillata* (L. F.) Royle] and the application of airborne videography with global positioning system (GPS) and geographic information system (GIS) technologies for distinguishing and mapping the distribution of these two aquatic weeds in waterways of southern Texas. Field reflectance measurements made at several locations showed that waterhyacinth generally had higher near-infrared (NIR) reflectance than associated plant species and water. Hydrilla had lower NIR reflectance than associated plant species and higher NIR reflectance than water. Reflectance measurements made on hydrilla plants submerged below the water surface had similar spectral characteristics to water. Waterhyacinth and hydrilla could be distinguished in color-infrared (CIR) video imagery where they had bright orange-red and reddish-brown image responses, respectively. Computer analysis of the imagery showed that waterhyacinth and hydrilla infestations could be quantified. An accuracy assessment performed on the classified image showed an overall accuracy of 87.7%. Integration of the GPS with the video imagery permitted latitude/longitude coordinates of waterhyacinth and hydrilla infestations to be recorded on each image. A portion of the Rio Grande River in extreme southern Texas was flown with the video system to detect waterhyacinth and hyd-

[1]USDA/ARS Integrated Farming and Natural Resources Unit, 2413 E. Highway 83, Weslaco, TX 78596. E-mail:jeveritt@weslaco.ars.usda.gov

[2]Region 15 Water Program, Texas Natural Resource Conservation Commission, 1804 W. Jefferson, Harlingen, TX 78550

[3]Biology Department, University of Texas-Pan American, Edinburg, TX 78539. Received for publication February 2, 1999 and in revised form March 2, 2000.

[4]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.

rilla infestations. The GPS coordinates on the CIR video scenes depicting waterhyacinth and hydrilla infestations were entered into a GIS to map the distribution of these two noxious weeds in the Rio Grande River.

Key words: light reflectance, aerial videography, hydrilla, *Hydrilla verticillata*, waterhyacinth, *Eichhornia crassipes.*

INTRODUCTION

Aquatic macrophytes are important components of wetland communities because they play a crucial role in providing food and shelter for animals as well as regulating the chemistry of the open water (Mclaughlan 1974, Frodge et al. 1990). These plants may be free-floating or rooted in bottom sediment and may be submersed or protrude from the water (Patterson and Davis 1991). Although aquatic macrophytes are beneficial, some species can hinder human activity. They clog reservoirs, reducing water availability for human needs. Also, the proliferation of aquatic macrophytes affect recreational activities, obstructing boat navigation and reducing access to the shoreline, especially in protected areas such as coves (Narumalani et al. 1997).

Waterhyacinth and hydrilla are two exotic aquatic macrophytes that often invade and clog waterways. Waterhyacinth is a floating species that has been called the "world's worst weed" (Cook 1990). It is a native of South America that is now found in many tropical and subtropical areas of the world. Waterhyacinth is believed to have been introduced into the United States in the mid 1880s in Louisiana (Tabita and Woods 1962). It is now found from Virginia to Florida and west to Texas and Missouri; it also occurs in California (Correll and Correll 1972). Populations may double in size every 6 to18 days. Through the process of transpiration, the rate of water lost to the atmosphere in areas inundated with waterhyacinth may be 4 to 5 times that in areas with open water (Mitchell 1976).

Hydrilla is a submersed species that is probably native to the warm regions of Asia (Cook and Luond 1982). It is now a cosmopolitan species that occurs in many areas of the world, including Europe, Asia, Africa, Australia, South America, and North America (Langeland 1996). Hydrilla was first discovered in the United States in Florida in 1960 (Blackburn et al. 1969) and has since spread throughout the eastern seaboard states as well as California, Arizona, and Washington (Schmitz 1990, Langeland 1996). Once established in a system, hydrilla can alter the environment detrimentally by replacing native aquatic vegetation and affecting fish populations (Barnett and Schneider 1974, Colle and Shireman 1980, Langeland 1996). Hydrilla also interferes with movement of water for drainage and irrigation purposes and reduces boating access, thus reducing recreational use of the water body (Langeland 1996).

The value of remote sensing for assessing and managing wetlands is well established (Carter 1982, Tiner 1997). Plant canopy reflectance measurements have been used to differentiate among wetland plant species (Best et al. 1981) and aerial photography has been used extensively to remotely distinguish plant species and communities in wetland environments (Seher and Tueller 1973, Howland 1980, Carter 1982, Martyn 1985). More recently, airborne videography has also proven useful for assessing wetlands (Mackey et al. 1987, Sersland et al. 1995).

Aerial videography and global positioning system (GPS) technology have been integrated and shown to be useful tools for detecting and mapping weed species on rangelands and brush species in riparian areas (Everitt et al. 1994, 1996). Latitude/longitude data provided by the GPS were entered into a geographic information system (GIS) to map noxious plant populations over extensive areas.

Over the past few years hydrilla and waterhyacinth have increased in abundance in south Texas waterways, including the Rio Grande River. The objectives of this study were: (1) to determine the plant canopy light reflectance characteristics of hydrilla and waterhyacinth to facilitate their detection in aerial videography and (2) to demonstrate the effectiveness of airborne videography, GPS, and GIS technologies for detecting and mapping hydrilla and waterhyacinth infestations in waterways in southern Texas.

MATERIALS AND METHODS

This study was conducted on several waterways in southern Texas. Study sites included the Rio Grande River in the Lower Rio Grande Valley (LRGV), a pond near San Benito in the LRGV, the Frio River near Tilden, the Atascosa River near Pleasanton, and Lake Texana near Edna. Field reflectance measurements, aerial videography, and ground truth observations were conducted for this study.

Reflectance measurements were made at four sites: Brownsville, San Benito, Tilden, and Pleasanton, Texas. Measurements were made at the different sites on several dates during 1998 to characterize the spectral characteristics of the plant species over the summer growing season. Reflectance measurements were made on 10 randomly selected plant canopies of each species or species mixture and water surfaces with a Barnes[4] modular multispectral radiometer (Robinson et al. 1979). Measurements were made in the visible green (0.52-0.60 µm), visible red (0.63-0.69 µm), and near-infrared (NIR) (0.76-0.90 µm) spectral bands with a sensor that had a 15-degree field-of-view placed 1 to 1.5 m above each plant or water target. A small boat was used to approach those targets located in the water. Reflectance measurements were made between 1100 and 1500 hours central standard time under sunny conditions. Radiometric measurements were corrected to reflectance using a barium sulfate standard. Overhead photographs were obtained of plant canopies and water measured with the radiometer to help interpret reflectance data.

Reflectance measurements were made at a site on the Rio Grande near Brownsville on July 1 and September 14, 1998. Measurements were made on hydrilla, waterhyacinth, water stargrass [*Heteranthera dubia* (Jacq.) MacM.], guineagrass (*Panicum maximum* Jacq.), deep water (> 1.0 m), and shallow water (clear) (< 0.3 m). Water stargrass is an aquatic species that grows in association with hydrilla and waterhyacinth, whereas guineagrass is a common terrestrial species growing along the river bank. With the exception of water stargrass, measurements were made on these species on both dates. An insufficient number of water stargrass plants were available for measurements in September. For the July date, reflectance measurements were also made on totally submerged

hydrilla plants at three depths: 2.5 to 7.5 cm, 7.5 to 15.0 cm, and 15.0 to 30.0 cm. These criteria were selected based on observations of hydrilla growth status in the field. Hydrilla plants at depths greater than 30 cm were not taken into consideration because they generally were not discernible.

Spectral measurements were made on waterhyacinth, Bermudagrass [*Cynodon dactylon* (L.) Pers.], and water (turbid) at the San Benito study site on June 23, 1998. Measurements were made at the Pleasanton study site on June 24 and September 2, 1998. For the June date, measurements were made on waterhyacinth, Bermudagrass, black willow (*Salix nigra* Marsh.), and water (turbid). In September, measurements were made on waterhyacinth, Bermudagrass, black willow, mixed herbaceous species (grasses, sedges, and broad-leaved herbs), and water (turbid). Bermudagrass, black willow, and mixed herbaceous species were common terrestrial species at the respective study sites. Mixed herbaceous species were not available in June at Pleasanton due to drought conditions. No turbidity measurements were made on the water.

For the Tilden study site, reflectance measurements were made on June 24, 1998. Measurements were made on hydrilla (primarily on the surface), Bermudagrass, mixed herbaceous species, black willow, dryland willow (*Baccharis neglecta* Britt.), and water. Bermudagrass, mixed herbaceous species, black willow, and dryland willow were common terrestrial species at the Tilden site.

Aerial video imagery was taken with a three-camera multispectral digital video imaging system (Everitt et al. 1995) and a single camera color video system (Everitt et al. 1996). The multispectral system was comprised of three charge-coupled device (CCD) aligned cameras, a computer, a color encoder, and a super-VHS recorder. The cameras are visible/NIR (0.4-1.1 µm) light sensitive. Two of the cameras are equipped with visible yellow-green (0.555-0.565 µm) and red (0.623-0.635 µm) filters, respectively, while the third camera had a NIR (0.845-0.857 µm) filter. All of the cameras had fixed lenses with 17 mm focal lengths. The alignment of these cameras to acquire real-time registered CIR imagery has been previously described by Everitt et al. (1991).

The computer is a 486 DX 50 system that has an image grabbing board (640 × 480 pixel resolution) and a 1000-megabyte storage capacity hard drive. The NIR, red, and yellow-green image signals from the cameras are subjected to the RGB inputs, respectively, of the grabbing board in the computer and also the RGB inputs respectively, of the color encoder. This permits the simultaneous acquisition of both digital and analog real-time color-infrared (CIR) composite imagery. The digital imagery is stored in the computer hard drive, while the analog imagery is recorded on the super-VHS recorder. The hard drive can store 1000 CIR composite images. Multispectral imagery was acquired of the Rio Grande River from its mouth at Boca Chica to Falcon Dam near Roma, Texas on June 26 and August 25, 1998. Imagery was also acquired of the Edna and Tilden study sites on August 11, 1998, and the Pleasanton site on September 2, 1998. Additional imagery was also taken of an area near Brownsville on September 3, 1998. Imagery was acquired at altitudes above ground level ranging from 460 to 1525 m (0.35 to 1.20 m ground pixel sizes).

The color video system was comprised of a normal color camera and a super-VHS recorder. The camera was equipped with a fixed lens having a 17 mm focal length. Normal color video imagery was obtained of the Rio Grande from Boca Chica to Falcon Dam on August 26-27, 1998. Imagery was obtained at an altitude above ground level of 275 m and had a ground pixel size of 0.23 m.

A Cessna (model 404) airplane, equipped with a camera port in the floor, was used for obtaining the video imagery. All imagery was acquired between 1100 and 1530 hours under sunny conditions.

A CIR composite digital video image of a portion of the Rio Grande 13 km west of Brownsville infested with hydrilla and waterhyacinth was used for computer classification and accuracy assessment. The image was acquired on September 3, 1998. The image was subjected to pixel line correction and image to image registration using Adobe Photoshop and Image Pro Plus software, respectively. For the image registration process, the red band was used as the base image to rectify the other two bands. The image was also georeferenced using Erdas Imagine software (Version 8.3). The CIR composite 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, Inc. 1997). The ISODATA technique uses minimum spectral distance to assign a cluster for each selected pixel. With a specified number of arbitrary cluster means, the technique repetitively processes them in which new means shift toward the means of the clusters in the data. Each unsupervised classification completed in this study created four classes from four data iterations at a 0.99% convergence threshold (the maximum percentage of pixels cluster assignments go unchanged between iterations). The classes consisted of water, hydrilla, waterhyacinth, and riparian vegetation. For accuracy assessment of the classification, 65 points were assigned to the four classes in a stratified random pattern. The geographic coordinates of these points were determined and a Trimble GPS Pathfinder Pro XRS system was used to navigate to these 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 total number of points of that category as derived from the reference data (ground truth data). The user's accuracy (measure of commission error) is the total number of correct points in a category divided by total number of points of that category as derived from the classification data (map data).

An Omnistar (model 3000L) differential GPS and Horita (model GPT-50) real-time GPS video/digital captioner/interphaser was integrated with the video systems. The GPS acquired the latitude/longitude coordinate data of the aircraft location over the scene of interest, while the video interphaser transferred and superimposed the GPS data at the bottom of the video scene. The accuracy of the GPS was approximately ±20 m from the center coordinates of each video scene.

Personal computer MapInfo-GIS software was used to generate a regional map of the LRGV that included Cameron, Hidalgo, Starr, and Willacy Counties and a detail map of a portion of Cameron County. MapInfo uses StreetWorks which is a street display mapping product that provides coverage of U.S. streets, highways, city and town boundaries, area landmarks, point locations, and water features. StreetWorks

is based on U.S. Census Bureau TIGER (Topologically Integrated Geographic Encoding and Referencing) 95 data that includes street-level detail to the local level. The TIGER map-based system was constructed using USGS 1:100,000 scale digital line graph maps. These maps were produced to geographically map hydrilla and waterhyacinth infestations in the Rio Grande using the airborne video survey GPS data.

Ground truth surveys were conducted at sites where aerial videography was obtained. Observational data recorded were plant species, density, cover, soil type, and water condition. A small boat was used to conduct some of the ground surveys. Low altitude (75-150 m) aerial reconnaissance was also conducted at many sites to verify the presence of hydrilla and waterhyacinth.

Green, red, and NIR ground reflectance data for the plant species and water parameters from the various study sites were analyzed using analysis of variance techniques. Duncan's multiple range test was used to separate means at the 0.05 probability level (Steel and Torrie 1980).

RESULTS AND DISCUSSION

Reflectance measurements. At Brownsville in July 1998, water stargrass had higher reflectance than the other three plant species, deep water, and shallow water at the visible green wavelength (Table 1). It also had higher visible red reflectance than the other plant species and water. The green and red reflectance values of guineagrass were higher than those of waterhyacinth, hydrilla, and the two water parameters. The green reflectance value of waterhyacinth was significantly different (p = 0.05) than those of the other plant species and water parameters. Hydrilla, deep water, and shallow water had similar green reflectance values. At the red wavelength, hydrilla, waterhyacinth, and shallow water had similar reflectance values. Deep water had lower reflectance at the red wavelength than the plant species and shallow water. Visible reflectance in vegetation is primarily affected by plant pigments (Myers et al. 1983, Gausman 1985). Water stargrass had yellow-green leaves and guineagrass had light green leaves, whereas waterhyacinth and hydrilla had dark green and deep dark green leaves, respectively. The darker green foliage of waterhyacinth and hydrilla reflected less green light and absorbed more red light than the lighter green foliage of water stargrass and guineagrass (Gausman 1985). Chlorophyll in the water contributed to its dark color, thus causing lower visible reflectance values.

Waterhyacinth had higher NIR reflectance than the other plant species and water parameters at the Brownsville site in July 1998. Conversely, deep water had lower NIR reflectance than the four plant species and shallow water. Shallow water had higher NIR reflectance than deep water, but lower NIR reflectance than the plant species. Among the plant species, hydrilla had lower NIR reflectance than the other three species. Near-infrared reflectance in vegetation is highly correlated with plant density (Myers et al. 1983, Everitt et al. 1986). An overhead view of the plant species showed that waterhyacinth had greater leaf density and fewer gaps in its canopy than the other species, while hydrilla had more gaps and breaks in its canopy.

A large percentage of the hydrilla plant biomass is below the water surface and, therefore cannot be adequately measured with the radiometer sensor. The very low NIR reflectance of both shallow and deep water was attributed to their strong absorption of NIR light (Wiesnet et al. 1997). Although the low NIR reflectance of hydrilla was contributed to significantly by its open canopy, the integration of water with the canopy absorbed a large percentage of the NIR light (Myers et al. 1983, Everitt et al. 1989). Like hydrilla, water stargrass is also a submersed species with the majority of its biomass below the water surface. This characteristic contributed to the relatively low NIR reflectance of water stargrass.

Since hydrilla plants are mostly below the water surface, we further studied the reflectance of this aquatic weed at the Brownsville site (July 1998) at the surface and submerged at different depths (Table 1). Surfaced hydrilla plants and shallow water had higher visible green reflectance than hydrilla plants submerged at three depths and deep water. Hydrilla plants submerged at 2.5-7.5 cm, those submerged at 7.5-15.0 cm, and deep water had similar reflectance values at the green wavelength. Hydrilla submerged at 15.0-30.0 cm had lower green reflectance than the other hydrilla and water parameters. At the red wavelength, surfaced hydrilla had higher reflectance than submersed plants at all three depths. The red reflectance of shallow water did not differ from that of surfaced hydrilla and hydrilla submerged at 2.5-7.5 cm. Hydrilla submerged at 2.5-7.5 cm and that submerged at 7.5-15.0 cm had similar red reflectance values. The reflectance values of hydrilla submerged at 15.0-30.0 cm and deep water did not differ at the red wavelength. Submersed plants had a progressively darker color as their depth below the water surface increased which caused them to absorb more of the visible green and red light, thus giving them low reflectance values at these wavelengths (Carter 1982, Gausman 1985).

At the NIR wavelength, surfaced hydrilla plants had higher reflectance than plants submerged at three depths and the two water parameters (Table 1). Hydrilla submerged at 2.5-7.5 cm had lower NIR reflectance than surfaced hydrilla plants and higher NIR reflectance than plants submerged at 7.5-15.0 cm and 15.0-30.0 cm, and the two water parameters. The NIR reflectance of hydrilla submerged at 7.5-15.0 cm did not differ from that of shallow water. Hydrilla submerged at 15.0-30.0 cm and deep water had similar NIR reflectance values.

Visible and NIR reflectance values of guineagrass, hydrilla, waterhyacinth, and the two water parameters in September 1998 at Brownsville followed a similar trend to those in July (Table 1). The visible green reflectance of hydrilla differed from that of the other two species and water parameters. Waterhyacinth and shallow water had similar green reflectance values. The red reflectance values of hydrilla and waterhyacinth were similar, but they differed from those of guineagrass and the two water parameters At the NIR wavelength, waterhyacinth had higher reflectance than the other two species and water parameters. Hydrilla had lower NIR reflectance than waterhyacinth and guineagrass and higher NIR reflectance than the two water parameters. In June 1998 at San Benito, waterhyacinth had lower visible reflectance than water and Bermudagrass at both the green and red wavelengths (Table 1). At the NIR wavelength, waterhyacinth had higher reflectance than Bermudagrass and water. The water was turbid which probably caused it to have higher visible reflectance than the two plant species (Wiesnet et al.

TABLE 1. MEAN LIGHT REFLECTANCE OF HYDRILLA, WATERHYACINTH, ASSOCIATED PLANT SPECIES AND WATER AT THE GREEN, RED, AND NEAR-INFRARED WAVE-LENGTHS. MEASUREMENTS WERE MADE ON THE RIO GRANDE RIVER NEAR BROWNSVILLE, TEXAS, A POND NEAR SAN BENITO, TEXAS, THE FRIO RIVER NEAR TILDEN, TEXAS, AND THE ATASCOSA RIVER NEAR PLEASANTON, TEXAS. MEANS WITHIN A COLUMN AT EACH DATE OF SAMPLING FOLLOWED BY THE SAME LETTER DO NOT DIF-FER SIGNIFICANTLY AT THE 0.05 PROBABILITY LEVEL, ACCORDING TO DUNCAN'S MULTIPLE RANGE TEST.

Date	Plant species or water	Reflectance (%) for three wavelengths		
		Green	Red	Near infrared
July 1998	Guineagrass	5.9 b	3.8 b	31.8 b
Brownsville, TX	Hydrilla (surface)	3.5 d	2.1 c	16.2 d
	Water stargrass	7.3 a	5.9 a	20.0 c
	Waterhyacinth	4.9 c	2.3 c	43.2 a
	Deep water (>1.0 m)	2.0 d	0.8 d	0.5 f
	Shallow water(<0.3 m) (Clear)	3.2 d	1.8 c	2.3 e
July 1998	Hydrilla (surface)	3.5 a	2.1 a	16.2 a
Brownsville, TX	Hydrilla (submerged—2.5-7.5 cm)	2.3 b	1.5 bc	5.2 b
	Hydrilla (submerged—7.5-15.0 cm)	2.0 b	1.4 c	2.8 c
	Hydrilla (submerged—15.0-30.0 cm)	1.3 c	0.7 d	0.8 d
	Deep water (>1.0 m)	2.1 b	0.8 d	0.5 d
	Shallow water (<0.3 m) (Clear)	3.2 a	1.8 ab	2.3 c
September 1998	Guineagrass	6.1 a	4.0 a	30.4 b
Brownsville, TX	Hydrilla (surface)	3.0 c	2.1 c	17.9 c
	Waterhyacinth	4.0 b	1.7 c	40.6 a
	Deep water (>1.0 m)	1.2 d	0.6 d	0.4 d
	Shallow water (<0.3 m) (Clear)	4.3 b	3.2 b	1.5 d
June 1998	Bermudagrass	5.4 b	3.2 b	31.4 b
San Benito, TX	Waterhyacinth	5.1 c	2.4 c	41.7 a
	Water (turbid)	6.4 a	3.7 a	2.1 c
June 1998	Bermudagrass	6.2 b	3.5 a	43.0 a
Tilden, TX	Black willow	5.6 b	2.7 b	38.4 b
	Dryland willow	4.6 c	3.6 a	21.6 c
	Hydrilla (surface)	3.2 d	2.0 c	14.5 d
	Mixed herbaceous species	7.3 a	3.6 a	39.9 ab
	Water	3.2 d	1.9 c	0.8 e
June 1998	Bermudagrass	7.7 a	5.8 a	31.5 b
Pleasanton, TX	Black willow	6.2 b	4.0 b	43.5 a
	Waterhyacinth	5.5 b	2.4 c	47.0 a
	Water (turbid)	4.4 c	2.5 c	2.8 c
Sept. 1998	Bermudagrass	5.9 a	4.6 a	26.6 d
Pleasanton, TX	Black willow	6.0 a	3.0 c	38.3 b
	Waterhyacinth	5.0 b	2.0 d	43.1 a
	Mixed herbaceous species	6.2 a	3.8 b	32.7 c
	Water (turbid)	6.3 a	4.9 a	3.1 e

1997). Overhead views of the two plant species showed that waterhyacinth had greater vegetative density than Bermuda-grass. This characteristic probably had a significant influence on its high NIR reflectance (Myers et al. 1983).

At Tilden in June 1998, mixed herbaceous species had higher visible green reflectance than the other four species and water (Table 1). Conversely, hydrilla (surfaced) and wa-ter had lower green reflectance than the other three species and mixtures of species. At the red wavelength, Bermuda-grass, dryland willow, and mixed herbaceous species had higher reflectance than black willow, hydrilla, and water. Hy-drilla and water had lower reflectance at the red wavelength than the three associated species and mixtures of species. With the exception of mixed herbaceous species, Bermuda-grass had higher NIR reflectance than the associated plant species and water. Water had lower NIR reflectance than the associated plant species and mixtures of species. The NIR re-flectance of hydrilla was lower than that of three associated species and mixtures of species.

In June 1998 at Pleasanton, Bermudagrass had higher green and red reflectance than black willow, waterhyacinth, and water (Table 1). Waterhyacinth and black willow had similar green reflectance values. Water had lower green re-flectance than the three plant species. At the red wavelength, waterhyacinth and water had similar reflectance values. The NIR reflectance values of waterhyacinth and black willow did not differ.

At Pleasanton in September 1998, waterhyacinth had low-er green and red reflectance than Bermudagrass, black wil-low, mixed herbaceous species, and water. Conversely, waterhyacinth had higher NIR reflectance than the two asso-ciated plant species, mixtures of species, and water.
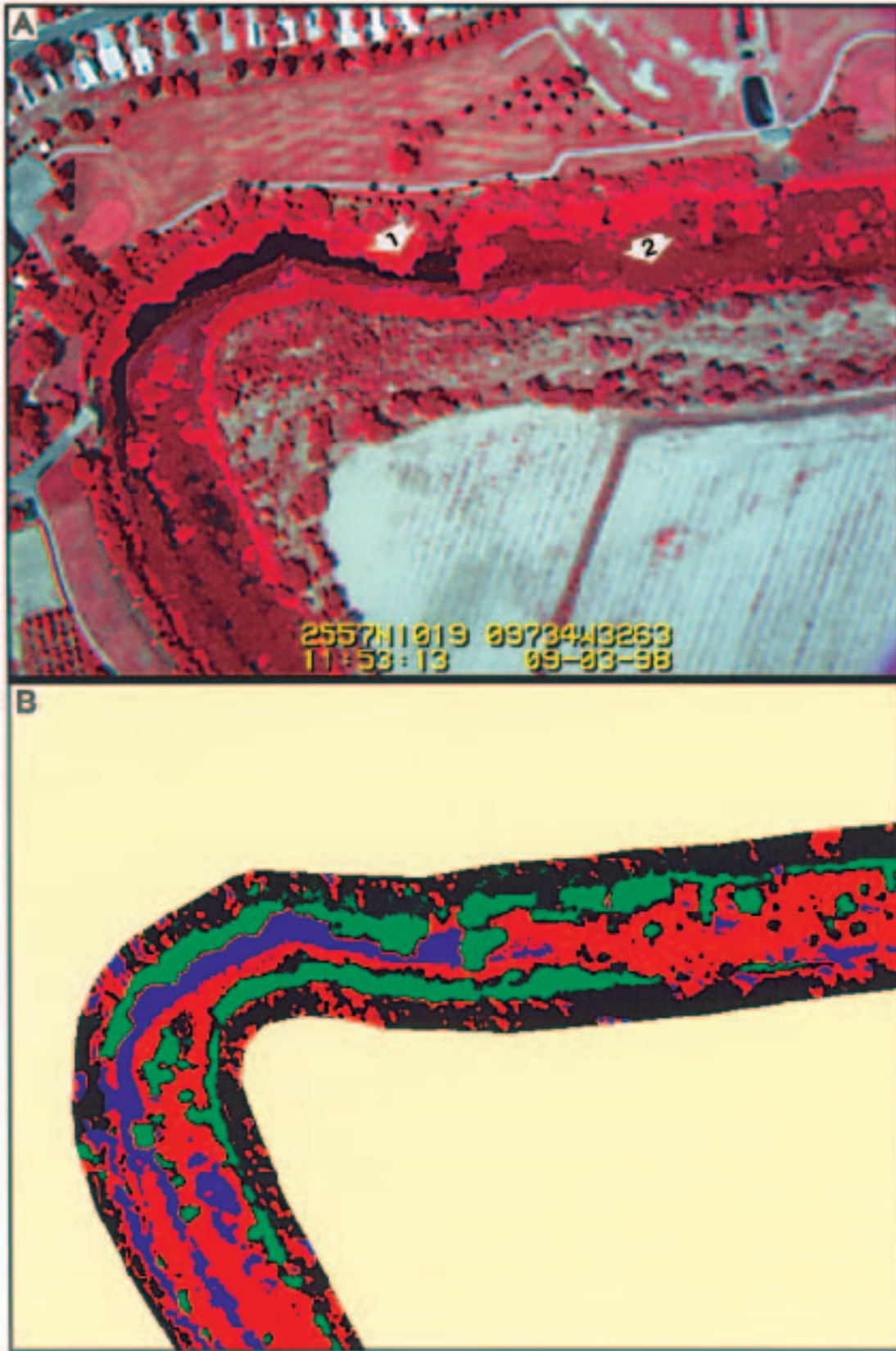
Figure 1. Color-infrared digital video image (A) of a portion of the Rio Grande River near Brownsville, Texas infested with waterhyacinth and hydrilla. Arrow 1 points to the conspicuous orange-red response of waterhyacinth, whereas arrow 2 points to the reddish-brown tonal response of hydrilla. The image was obtained on September 3, 1998. The GPS data are shown at the bottom of the image. Unsupervised computer classification (B) of the Rio Grande and its adjacent perimeter. Color codes for the various land-use types are: red: hydrilla; green: waterhyacinth; black: riparian vegetation; and blue: water.
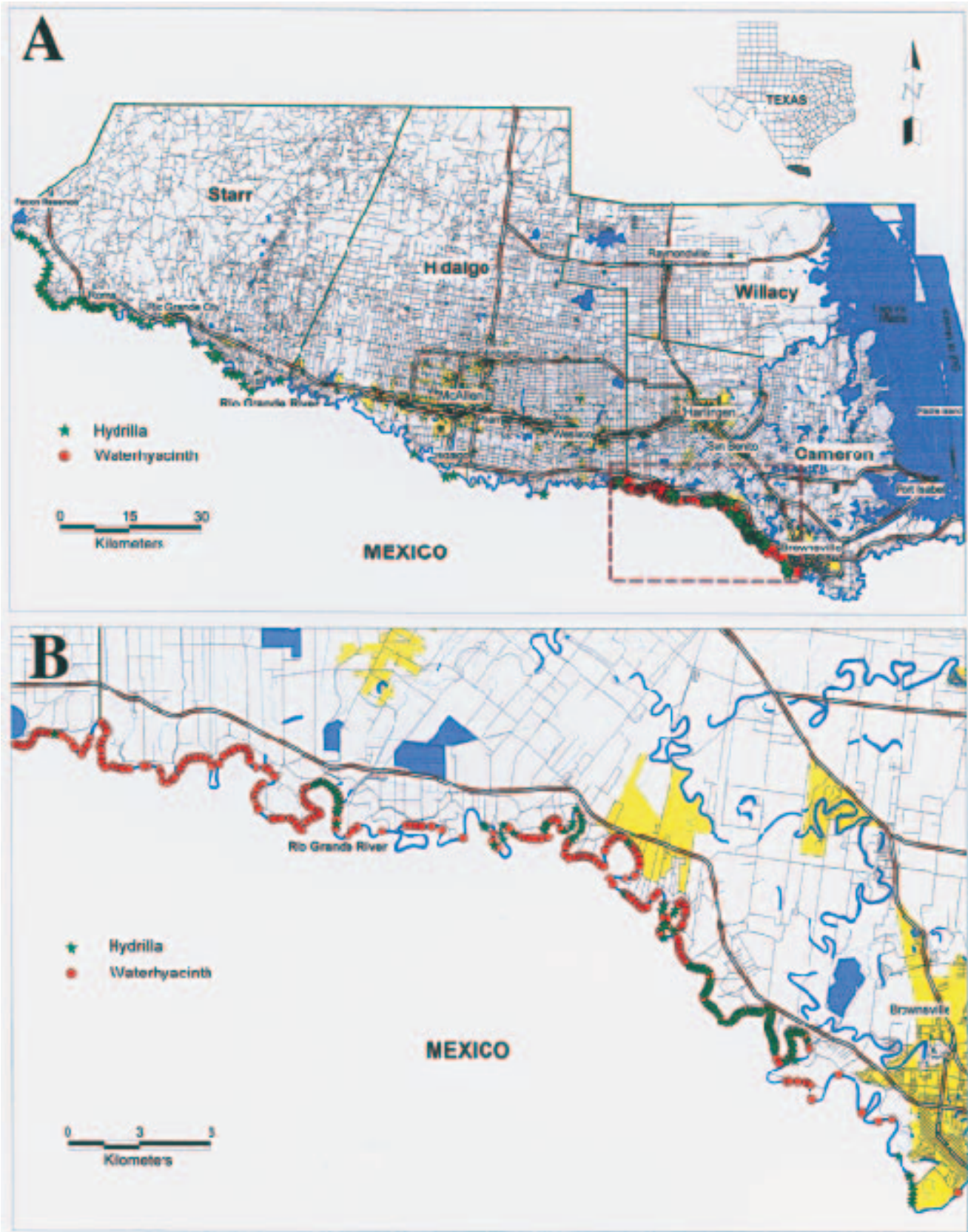
Figure 2. Regional GIS TIGER map (A) of Starr, Hidalgo, Cameron, and Willacy counties in the Lower Rio Grande Valley of south Texas. The Rio Grande River forms the lower boundary of the map with Mexico. Areas with green stars along the Rio Grande represent infestations of hydrilla, red dots represent waterhyacinth infestations. A detailed GIS map (B) of Cameron County depicting infestations of hydrilla and waterhyacinth along the Rio Grande.

Aerial videography, GPS, and GIS. Figure 1A shows a CIR digital video image acquired along the Rio Grande River near Brownsville, Texas on September 3, 1998. The image was obtained at an altitude above ground level of 460 m and has a ground pixel resolution of 0.35 m. Arrow 1 points to the conspicuous bright orange-red image response of waterhyacinth, whereas arrow 2 points to the reddish-brown image tone of surfaced hydrilla. Water has a black response, woody plants (shrubs and trees) and herbaceous vegetation adjacent to the river have various red and magenta tones. Bare soil, roads, and homesites have white to light gray tones. The GPS data are displayed at the bottom of the video image. Integration of longitude-latitude coordinates with the video imagery is useful to locate waterhyacinth and hydrilla populations over remote and inaccessible areas.

Waterhyacinth had a similar color tonal response to that shown in Figure 1A in additional CIR video imagery acquired at numerous other locations along the Rio Grande and at study sites near Edna and Pleasanton, and could be readily separated from other vegetation at all sites. Surfaced hydrilla had a similar response to that shown in Figure1A at a diversity of sites along the Rio Grande and at study sites near Edna and Tilden, and could be easily distinguished at all sites. However, hydrilla submerged 2.5-7.5 cm below the water surface had a dark brown to nearly black image that could not easily be differentiated from water. Hydrilla submerged at depths below 7.5 cm generally could not be distinguished in the video imagery. Ground truth confirmed that at some locations a large percentage of submersed hydrilla occurred below 7.5 cm that was not detectable in the imagery. The conspicuous orange-red image of waterhyacinth was primarily attributed to its high NIR reflectance, but visible green and red reflectance values contributed to its image response. The reddish-brown or dark brown to nearly black image tones of hydrilla were attributed to its low NIR, red and green reflectance (Table 1). The reddish-brown image response of surfaced hydrilla plants is in general agreement with the findings of Martyn (1985).

Waterhyacinth and hydrilla could also be distinguished in the low altitude normal color video imagery used in conjunction with the CIR imagery to survey the Rio Grande (imagery not shown). This imagery was primarily confined to the river and showed very little of the riparian areas adjacent to the river. Waterhyacinth had a dark green image tone with a smooth textured response in the normal color video imagery, whereas hydrilla had a very dark green to nearly black image response. Although both waterhyacinth and hydrilla could be distinguished in the normal color imagery, their false color image responses in the CIR imagery were more distinct. As with the CIR imagery, hydrilla below the water surface often could not be distinguished from water.

Figure 1B shows an unsupervised classification of the CIR video image of the Brownsville site (Figure 1A). Color codes and respective percent areas for the various land-use types are: red: hydrilla (34.8%); green: waterhyacinth (16.6%); black: riparian vegetation (36.6%); and blue: water (12.0%). A qualitative comparison of the computer classification to the video image shows that the computer generally identified most of the hydrilla and waterhyacinth and the other two parameters. Some areas within the riparian zone were misclassified as hydrilla, probably attributed to shadowing within the trees which had similar reflectivity to hydrilla. This technique can provide a means of quantifying hydrilla and waterhyacinth infestations in waterways.

Table 2 shows an error matrix by comparison of the classified data with the ground data for the 65 observations within the Brownsville study site. The overall classification accuracy was 87.7%, indicating that about 88% of category pixels in the image were correctly identified in the classification map. The producer's accuracy of individual categories ranged from 85% for water to 90% for hydrilla, whereas the user's accuracy ranged from 82% for hydrilla to 96% for riparian vegetation. Both producer's accuracy and user's accuracy for all four categories was quite good. The slightly lower producer's accuracy for waterhyacinth was probably due to the confusion among waterhyacinth, hydrilla, and riparian vegetation, while the slightly lower user's accuracy for hydrilla was due to the confusion between hydrilla and the other three categories The kappa estimate was 0.828, indicating the classification has achieved an accuracy that is 83% better than would be expected from random assignment of pixels to categories.

Figure 2A shows a regional GIS TIGER map of Starr, Hidalgo, Cameron, and Willacy counties in the LRGV of south Texas. The Rio Grande River forms the lower boundary of the map adjacent to Mexico. The map depicts the Rio Grande from its mouth in southeastern Cameron County to Falcon Dam in southwestern Starr County. The GPS latitude-longitude data provided on the aerial videograhic imagery of the Rio Grande from the June and August 1998 overflights have been integrated with the GIS to georeference infestations of hydrilla and waterhyacinth in the river. Areas with green stars represent infestations of hydrilla, whereas areas denoted with red dots are waterhyacinth infestations. The highest populations of aquatic weeds are located in Cameron County. The area was infested with both hydrilla and waterhyacinth. Due to the small scale of the map, many of the symbols are stacked on each other. Each symbol represents a composite from three to eight video scenes. Waterhyacinth was only found in Cameron County and extreme southeastern Hidalgo County. Isolated populations of hydrilla occur in central Hidalgo County, whereas numerous small infestations of hydrilla are found in Starr County.

A more detailed GIS map of the portion of the Rio Grande infested with hydrilla and waterhyacinth in Cameron County is shown in Figure 2B. This area corresponds to the enclosed box in Figure 2A. With this map one can associate general land-use characteristics (i.e., streets, roads) with the GPS locations where hydrilla and waterhyacinth occur.

Field reflectance measurements showed that waterhyacinth generally had higher NIR reflectance than associated vegetation and water. Hydrilla (surfaced) had lower NIR reflectance than associated vegetation and higher NIR reflectance than water. Reflectance measurements made on hydrilla plants below the water surface indicated that they generally had similar spectral characteristics to water.

Waterhyacinth and hydrilla (surfaced) could be remotely distinguished in CIR video imagery obtained on several dates at widely separated sites in south and southeast Texas where they had orange-red and reddish-brown image responses, respectively. Computer-based image analysis of a CIR video im-

TABLE 2. AN ERROR MATRIX GENERATED FROM IMAGE CLASSIFICATION DATA AND GROUND DATA FOR A SECTION OF THE RIO GRANDE RIVER. OVERALL ACCURACY = 87.7%. KAPPA = 0.828.

	Classified category					Producer's accuracy
Actual category	Water	Hydrilla	Waterhyacinth	Riparian	Total	
Water	7	1	0	0	8	87.5
Hydrilla	1	18	1	0	20	90.0
Waterhyacinth	0	1	11	1	13	84.6
Riparian	0	2	1	21	24	87.5
Total	8	22	13	22	65	
User's Accuracy	87.5	81.8	84.6	95.9		

age showed that waterhyacinth and hydrilla infestations could be differentiated quantitatively from associated vegetation and water. An accuracy assessment showed that the computer did an adequate job in identifying most of the waterhyacinth and hydrilla infestations. A study confined to the Rio Grande River showed that normal color video imagery could also be useful for detecting and surveying waterhyacinth and hydrilla.

Videography, GPS, and GIS technologies were integrated and used to map waterhyacinth and hydrilla infestations in a portion of the Rio Grande. The video imagery can provide a means of determining area estimates of waterhyacinth and hydrilla infestations and can serve as a permanent geographically located image database to monitor future contraction or spread of these aquatic weeds over time. The joint use of these technologies provides previously unavailable information on the distribution of these two species in the lower Rio Grande. It is anticipated that the integration of these technologies can also be used for a variety of other natural resource management applications.

ACKNOWLEDGMENTS

LITERATURE CITED

Barnett, B. S. and R. W. Schneider. 1974. Fish populations in dense, submersed plant communities. Hyacinth Control J. 12: 12-14.

Best, R. G., M. E. Wehde and R. W. Linder. 1981. Spectral reflectance of hydrophytes. Remote Sens. Environ. 11: 27-35.

Blackburn, R. D., L. W. Weldon, R. R. Yoo, and T. M. Taylor. 1969. Identification and distribution of certain similar-appearing submersed aquatic weeds in Florida. Hyacinth Control J. 8: 17-23.

Carter, V. 1982. Applications of remote sensing to wetlands. In: C. J. Johannsen and J. L. Sanders (eds.). Remote Sensing in Resource Management. Soil Conser. Soc. Am., Ankeny, IA. pp. 284-300.

Colle, D. E. and J. E. Shireman. 1980. Coefficients of condition for largemouth bass, bluegill, and redear sunfish in hydrilla-infested lakes. Trans. Amer. Fish Soc. 109: 521-531.

Cook, C. D. K. 1990. Origin, autecology, and spread of some of the world's most troublesome aquatic weeds. In: A. H. Pieterse and K. J. Murphy (eds.). Aquatic Weeds. Oxford University Press, Cary, NC. pp. 31-73.

Cook, C. D. K. and R. Luond. 1982. A revision of the genus *Hydrilla* (Hydrocharitaceae). Aquat. Bot. 13: 485-504.

Correll, D. S. and H. B. Correll. 1972. Aquatic and wetland plants of the southwestern United States. Water Pollution Control Research Series 16030. U.S. Government Printing Office. Washington, D.C. 1777 pp.

Everitt, J. H., D. E. Escobar, M. A. Alaniz and M. R. Davis. 1989. Using multispectral video imagery for detecting soil surface conditions. Photogramm. Eng. Remote Sens. 55: 467-471.

Everitt, J. H., D. E. Escobar M. A. Alaniz, M. R. Davis and J. V. Richerson. 1996. Using spatial information technologies to map Chinese tamarisk (*Tamarix chinensis*) infestations. Weed Sci. 44: 194-201.

Everitt, J. H., D. E. Escobar, I. Cavazos J. R. Noriega and M. R. Davis. 1995. A three-camera multispectral digital video imaging system. Remote Sens. Environ. 54:333-337.

Everitt, J. H., D. E. Escobar and J. R. Noriega. 1991. A high resolution multispectral video system. Geocarto Int. 6(4): 45-51.

Everitt, J. H., J. V. Richerson, M. A. Alaniz, D. E. Escobar, R. Villarreal and M. R. Davis. 1994. Light reflectance and remote sensing of Big Bend loco (*Astragalus mollissimus* var. *earlei*) and wooton loco (*Astragalus wootonii*). Weed Sci. 42: 115-122.

Everitt, J. H., A. J. Richardson and P. R. Nixon. 1986. Canopy reflectance characteristics of succulent and nonsucculent rangeland plant species. Photogramm. Eng. Remote Sens. 52: 1891-1897.

Erdas, Inc. 1997. Erdas-Imagine V8.3 tour guide. Erdas, Inc., Atlanta, GA. 454 pp.

Frodge, J. D., G. L. Thomas and G. B. Pauley. 1990. Effects of canopy formation by floating and submergent aquatic macrophytes on water quality of two shallow Pacific Northwest Lakes. Aquat. Bot. 38: 231-248.

Gausman, H. W. 1985. Plant leaf optical properties in visible and near-infrared light. Graduate Studies Texas Tech University, No. 29. Texas Tech Univ. Press, Lubbock. 78 pp.

Howland, W. G. 1980. Multispectral aerial photography for wetland vegetation mapping. Photogramm. Eng. Remote Sens. 46: 87-99.

Langeland, K. A. 1996. *Hydrilla verticillata* (L. F.) Royle (Hydrocharitaceae), "The Perfect Aquatic Weed". Castanea 61: 293-304.

Mackey, H. E., Jr., J. R. Jensen, M. E. Hodgson and K. W. O'Cuilinn. 1987. Color-infrared video mapping of upland and wetland communities. Proc. 11th Biennial Workshop on Color Aerial Photography and Videography in the Plant Sciences. Amer. Soc. Photogramm. and Remote Sens. Falls Church, VA. pp. 252-260.

Martyn, R. D. 1985. Color-infrared photography for determining the efficacy of grass carp in aquatic weed control. Proc. Southern Weed Sci. Soc. 38: 381-390.

McLaughlan, A. J. 1974. Recovery of mud substrate and its associated fauna following a dry phase in a tropical lake. Limnol. Oceanogr. 19: 74-83.

Mitchell, D. S. 1976. The growth and management of *Eichhornia crassipes* and *Salvina* spp. in their native environment and in alien situations. In: C. K. Varshncy and J. Rzoska (eds.). Aquatic Weeds in Southeast Asia. Dr. W. Junk Publisher. The Hague, Netherlands. pp. 167-175.

Myers, V. I., M. E. Bauer, H. W. Gausman, W. G. Hart, J. L. Heilman, R. B. McDonald, A. B. Park, R. A. Ryerson, T. J. Schmugge and F. C. Westin. 1983. Remote sensing in agriculture. In: R. N. Colwell (ed.). Manual of Remote Sensing. Amer. Soc. Photogramm., Falls Church, VA. pp. 2111-2228.

Narumalani, S. J., R. Jensen, J. D. Althausen, S. Burkhalter and H. E. Mackey, Jr. 1997. Aquatic macrophyte modeling using GIS and logistic multiple regression. Photogramm. Eng. Remote Sens. 63: 41-49.

Patterson, G. G. and B. A. Davis. 1991. Distribution of aquatic macrophytes in 15 lakes and streams in South Carolina. U.S. Geological Survey, Washington, D.C., Publ. 89-4132. 58 pp.

Robinson, B. F., M. E. Bauer, D. P. DeWitt, L. F. Silva and V. C. Vanderbilt. 1979. Multiband radiometer for field use. Measurements of Optical Radiations, SPIE Vol. 196, SPIE, Bellingham, WA. pp. 8-15.

Schmitz, D. C. 1990. The invasion of exotic aquatic and wetland plants into Florida: History and efforts to prevent new introductions. Aquatics 12(3): 6-24.

Seher, J. S. and P. T. Tueller. 1973. Color aerial photos for marshland. Photogramm. Eng. 39: 489-499.

Sersland, C. A., C. A. Johnston and J. Bonde. 1995. Assessing wetland vegetation with GIS-linked color video image mosaics. Proc. 15th Biennial Workshop on Videography and Color Photography in Resource Assessment. Amer. Soc. Photogramm. and Remote Sens. Bethesda, MD. pp. 53-62.

Steel, R. G. D. and J. H. Torrie. 1980. Principles and procedures of statistics. McGraw-Hill, New York. 481 pp.

Tabita, A. and J. W. Woods. 1962. History of waterhyacinth control in Florida. Hyacinth Control J. 1: 19-23.

Tiner, R. W. 1997. Wetlands. In: W. R. Philipson (ed.). Manual of Photographic Interpretation. Amer. Soc. Photogramm. and Remote Sens. Bethesda, MD. pp. 475-494.

Wiesnet, D. R., C. R. Wagner and W. D. Philpot. 1997. Water, snow, and ice. In: W. R. Philipson (ed.). Manual of Photographic Interpretation, 2nd Edition, Amer. Soc. Photogramm. and Remote Sens. Bethesda, MD. pp. 257-267.