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Using Remote Sensing to Detect and Map Invasive Plant Species

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Abstract: Invasive exotic plant species present a serious problem to natural resource managers in the United States. This paper presents an overview on the application of aerial photography and airborne videography for detecting invasive plant species in terrestrial and aquatic environments in the United States. Ground reflectance measurements have been used in conjunction with the studies to help determine the spectral characteristics of the plants. Season is an important variable for detecting some species because their reflectance varies at different times of the year and many species are distinguishable only when in a specific phenological stage. Computer analysis of aerial images are used to quantify weed infestations. Video imagery is integrated with global positioning system and geographic information system technologies to map noxious weed infestations. Plant species addressed include leafy spurge (*Euphorbia esula* L.), saltcedar (*Tamarix chinensis* Lour.), waterhyacinth (*Eichhornia crassipes* [Mort.] Solms), hydrilla (*Hydrilla verticillata* [L.F.] Royle), giant salvinia (*Salvinia molesta* Mitchell), and giant reed (*Arundo donax* L.).

Key words: Remote sesning, invasive plants, spectral characteristics, weed infestation, GIS.

The National Invasive Species Act of 1996 recognized the importance and impact of invasive plants and animals in United States ecosystems. The Invasive Species Council established in 1999 by Presidential Executive Order 13112, defines an invasive species as any plant, animal, or organism that is not native to the ecosystem under consideration and whose introduction is likely to cause harm to humans, health, environment, or the economy. It is estimated that invasive species in the United States cost its citizens over $100 billion annually (Faust, 2001).

Invasive plant species are an extremely big problem in the United States where they invade both terrestrial and aquatic ecosystems. Because these areas are often inaccessible, determining the extent of infestations or the botanical characteristics by ground surveys is difficult. More accurate measurements of area infested and canopy cover are essential to estimate the amount of damage and other ecological impact caused by invading brush and weeds. Remote sensing techniques offer rapid acquisition of data with generally short turn-around time at costs lower than ground surveys (Tueller, 1982; Everitt *et al*., 1992).

The value of remote sensing for distinguishing among plant species and communities is well established (Carter, 1982; Carneggie *et al*., 1983; Driscoll *et al*., 1997). Plant canopy reflectance measurements have been used to characterize the spectral characteristics of noxious plant species (Gausman *et al.*, 1977a; Everitt *et al.*, 1987; Lass and Callihan, 1997), and aerial photography, airborne electronic imagery (videography and digital), and satellite imagery have been used to remotely detect weedy species over large and inaccessible areas (Gausman *et al.*, 1977b; Richardson *et al.*, 1981; Tueller, 1989; Everitt *et al.*, 1995b; Lass *et al.*, 1996; Lass and Callihan, 1997; Anderson *et al.*, 1999).

Over the past decade, remote sensing, geographic information system (GIS), and global positioning system (GPS) technologies have been integrated for mapping the distribution of noxious plant species (Dewey *et al.*, 1991; Anderson *et al.*, 1993; Everitt *et al.*, 1999). Remote observations in georeferenced formats help to assess the extent of infestations, develop management strategies, and evaluate control measures on noxious plant populations.

Scientists at the United States Department of Agriculture (USDA), Agricultural Research Service (ARS) laboratory in Weslaco, Texas, have conducted extensive research on the utilization of remote sensing technology for distinguishing noxious plant species. Although there are many remote sensing techniques available for detecting weeds, USDA, ARS scientists have primarily worked with aerial photography and videography. In this paper the authors present an overview of their own research on using airborne remote sensing for detecting invasive exotic weeds that have invaded terrestrial (rangeland and wildland areas) and aquatic ecosystems in the United States.

General Procedures

With the exception of the progress report data on giant reed (*Arundo donax* L.), data presented in this paper have been published previously. Aerial imagery was obtained under sunny conditions with photographic and videographic systems mounted vertically in either a Cessna[1] 206T, Cessna 404, or Aero Commander aircraft. Geographic locations of images (and other pertinent information) presented here are given with the figure captions. Additional information on photographic and videographic systems, as well as the procedures used for image digitizing, processing and analyses, can be obtained from the literature citations.

Ground control data were collected for the research studies presented here. Field reflectance measurements were obtained for all studies. Other data included ground photographs, description of vegetation, plant cover, phytomass, soil types, and soil surface conditions. Standard statistical techniques (analysis of variance and Duncan's multiple range test) were used to analyze and interpret data (Steel and Torrie, 1980).

Results and Discussion

Leafy spurge

Leafy spurge (*Euphorbia esula* L.) is deep rooted, perennial troublesome weed that grows to 80 cm tall, which reproduces by both vegetative regrowth and by producing

[1] Mention of company name or trademark is included for the reader's benefit and does not constitute endorsement of a particular product by the US Department of Agriculture over others that may be commercially available.

large quantities of seeds (Stevens, 1963). Leafy spurge, a native of Eurasia, was first reported in the United States in Massachusetts in 1827 (Noble *et al.*, 1979). This weed is now most abundant in the Northern Great Plains of the United States and in the Prairie Provinces of Canada (Rees and Spencer, 1991). It often forms dense stands on rangelands and pastures, displacing useful forage plants and restricting grazing.

Everitt *et al.* (1995a) conducted a study to determine the feasibility of using remote sensing techniques to detect leafy spurge populations on Montana and North Dakota rangelands. They surmised that leafy spurge might be distinguishable on aerial photography in June, when it produces showy yellow bracts giving the plant a conspicuous appearance.

Field reflectance measurements for leafy spurge, nine associated plant species and mixtures of species, and soil at Medora, North Dakota are given in Table 1. Leafy spurge had lower visible reflectance than bare soil and clay rock, and higher visible reflectance than nine associated plant species and mixtures of species. The distinct visible reflectance of leafy spurge was attributed to its bright yellow-green bracts. The upper canopy of leafy spurge, which included a mass of bracts, absorbed less visible red light than the other species and mixtures which were primarily green foliage (Everitt and Villarreal, 1987). Although yellow sweetclover (*Melilotus officinalis* [L.] Lam.) and pinnate tansymustard (*Descurainia pinnata* [Walt.] Britt.) were in light and heavy flowering, respectively, their light yellow flowers apparently did

Table 1. Mean canopy reflectance of leafy spurge, nine associated plant species and mixtures of species, and soil for the visible (red) and near-infrared wavelengths. Reflectance measurements were made near Medora, North Dakota on June 17, 1993.

Site	Plant species, mixture, or soil	Canopy reflectance values*	
		Visible (red) 0.63-0.69µm	Near-infrared 0.76-0.90 µm
Medora, ND	Bare soil	12.4a	16.9de
	Clay rock	10.3b	17.4de
	Leafy spurge	3.7c	40.3ab
	Silver sagebrush	2.4d	19.0d
	Yellow sweetclover-light flowering	1.7d	24.9c
	Rocky Mountain Juniper	1.6d	18.3de
	Mixed herbaceous species	1.5d	20.5d
	Smooth brome	1.3d	15.0e
	Crested wheatgrass	1.3d	18.4de
	Creeping juniper	1.1d	17.2de
	Pinnate tansymustard-heavy flowering	1.1d	43.4a
	Western snowberry	1.0d	39.4b

* Values within a column followed by the same letter do not differ significantly at the 0.05 probability level; according to Duncan's multiple range test.

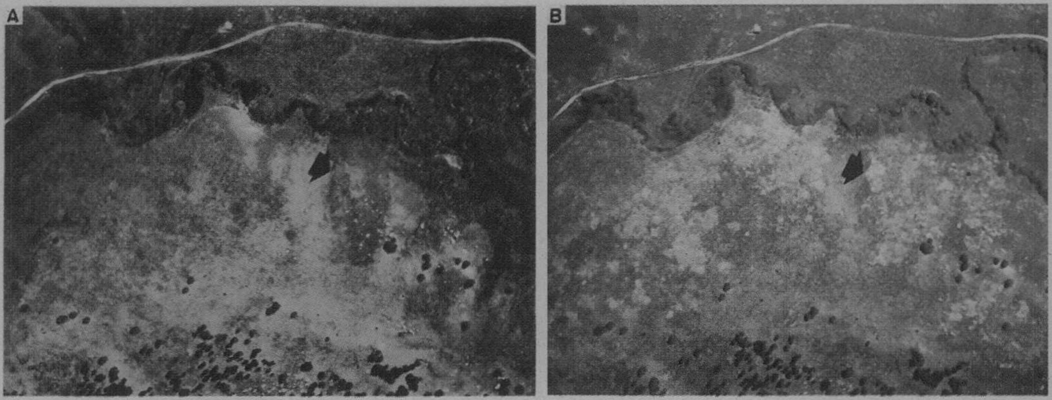

Fig. 1. Conventional color (A) and color-infrared (B) positive prints of a leafy spurge infestation near Lewistown, Montana, in June 1993. Arrows on the prints point to the yellow-green and pink image responses of leafy spurge on each respective film type. Both prints are 6X enlargements of portions of 70-mm photographs at an original scale of 1:15,000.

not contribute greatly to their visible reflectance. Pinnate tansymustard flowers are small and do not form a mass, thus its visible reflectance is primarily influenced by the leaves and stems. The near-infrared (NIR) reflectance of leafy spurge did not differ from that of pinnate tansymustard and western snowberry (*Symphoricarpos occidentalis* Hook.) Near-infrared reflectance in vegetation is highly correlated with plant density (Tucker, 1979).

An overhead view of the plant species and mixtures showed that leafy spurge, pinnate tansymustard, and western snowberry had similar vegetative densities and less gaps (sun flecks) than the other associated species and mixtures. The higher visible and low to moderate NIR reflectance of the soils agrees with other research findings (Bowers and Hanks, 1965; Skidmore *et al.*, 1975).

Figures 1A and 1B show conventional color and color-infrared (CIR) photographic positive prints of a rangeland area near Lewistown, Montana, infested with leafy spurge. The photography was obtained in June 1993. Leafy spurge has a conspicuous yellow-green image response in the conventional color photograph that can be easily distinguished from the dark gray-green image of mixed brush, light gray-green tone of mixed herbaceous species, light gray response of sparsely vegetated areas, and whitish response of bare soil and rocks (Fig. 1A). In the CIR photograph, leafy spurge has a pink image response that can be readily separated from the various red, dark magenta, and reddish-brown image responses of mixed brush, dull magenta to magenta response of mixed herbaceous species, light tan tone of sparsely vegetated areas, and whitish response of bare soil and rocks (Fig. 1B).

Leafy spurge had a similar image response in additional conventional color and CIR photographs acquired at several other scattered locations in Montana and North

Dakota and could be easily distinguished at all sites. The CIR image response of leafy spurge was attributed to its moderately high visible red and high NIR light reflectance (Table 1). Although the visible green reflectance was not obtained for this plant species, it can be visualized that the plants' yellow-green bracts would have caused a high green light reflectance (Gausman, 1985). Because spectral measurements were not made in the visible blue and green portions of the spectrum for leafy spurge, its image response in the conventional color photograph can not be adequately interpreted. A qualitative assessment of the conventional color and CIR photography showed that both types of film did a good job in distinguishing leafy spurge. This was confirmed by intense ground surveys of the study sites. Thus, both films were judged equal for detecting leafy spurge infestations.

Saltcedar

Saltcedar (*Tamarix chinensis* Lour.), also known as Chinese tamarisk, is a shrub introduced to the United States from Asia for use as an ornamental and for erosion prevention of streambanks (Baum, 1967). Saltcedar is an invader of riparian sites in the southwestern United States and northern Mexico where it forms dense, low thickets that displace native vegetation, impede water flow, increase sedimentation, use excessive water, and increase soil salinity (Horton and Campbell, 1974; Deloach, 1990). Saltcedar communities are also much less valuable for wildlife than are the native riparian communities they displace (Kerpez and Smith, 1989; Deloach, 1990). During late fall to early winter, the foliage of saltcedar turns a yellow-orange to orange-brown color prior to leaf drop. Previous research showed that saltcedar has higher visible light canopy reflectance than other associated plant species during this phenological stage, and subsequently, can be distinguished at this time on conventional color photography (Everitt and Deloach, 1990).

A project was conducted using conventional color videography, GPS, and GIS technologies to distinguish and map saltcedar infestations in riparian regions of the southwestern United States (Everitt *et al*., 1996). Study areas were along the Colorado River in southwestern Arizona and the Rio Grande and Pecos Rivers in west Texas. In this paper, only data obtained along the Rio Grande River will be presented.

Figure 2 shows a conventional color video image of a saltcedar infestation along the Rio Grande near Candellaria, Texas. Saltcedar has a conspicuous orange-brown image that is easily distinguished from other associated plant species, soil, and water. The distinct signature of saltcedar was due to the foliage turning a yellow-orange to orange-brown color. Saltcedar had an image tonal response similar to that shown in Fig. 2 at all locations along the Rio Grande and could be easily distinguished at every site.

Figure 3 (upper right) shows a regional GIS TIGER map of extreme west Texas. The bold symbols along the left margin of the map represent GPS latitude-longitude co-ordinates of saltcedar populations along a portion of the Rio Grande. Areas with stars represent high populations of saltcedar, those with triangles have medium populations, and those represented by a plus sign have low populations. Population

Fig. 2. Conventional color video image of a saltcedar infestation on the Rio Grande River near Candellaria, Texas. The image was obtained at an altitude above ground level of 1500 m in November 1994. Saltcedar has a conspicuous yellow-orange image tone.

levels were assigned after a qualitative analysis of the video imagery of the area. Criteria for population levels were: 50% cover, high; 25 to 50% cover, medium; and and <25% cover, low. Each symbol represents a composite of 2 to 3 video scenes because of the small map scale. A detailed GIS map of an area with several high saltcedar populations is shown in the center left portion of Fig. 3. The map in the lower left portion of Fig. 3 provides more details of roads and hydrography associated with the saltcedar populations.

Waterhyacinth and Hydrilla

Aquatic plants 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 open water (Mclaughlan, 1974). Although many aquatic plants are beneficial, some species can hinder human activity. They clog reservoirs, reducing water availability for human needs. Also, the proliferation of aquatic plants affect recreational activities, obstructing boat navigation and reducing access to shoreline, especially in protected

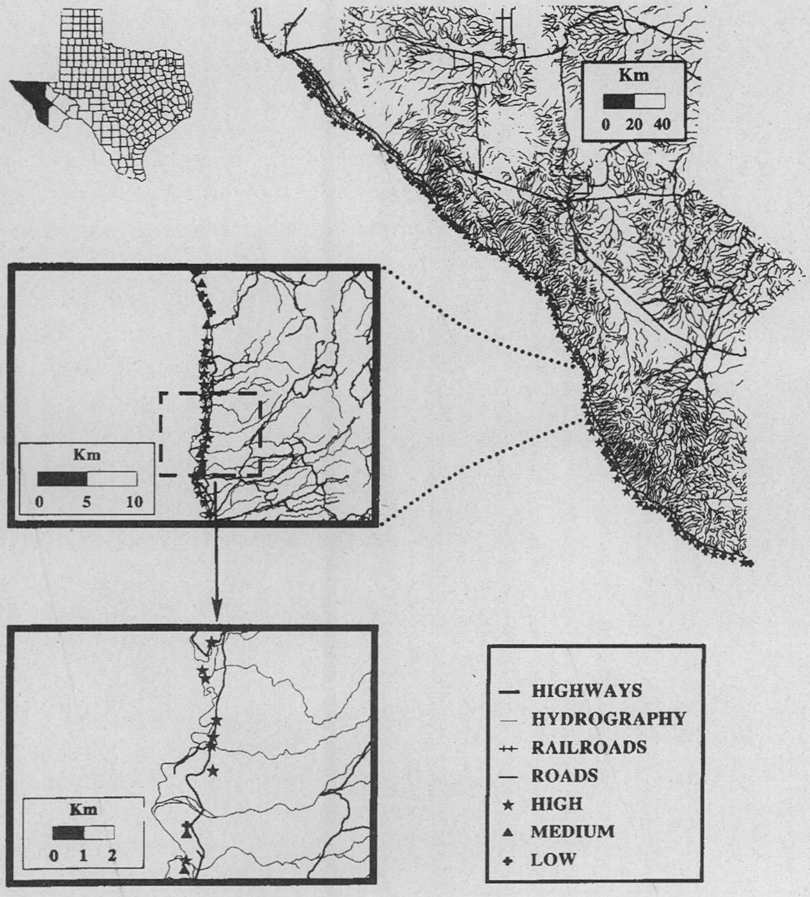

Fig. 3. Regional GIS TIGER map (upper right) of extreme west Texas depicting GPS locations where saltcedar infestations occur along a portion of the Rio Grande River. The stars represent high populations of saltcedar, triangles are medium populations, and plus signs have low populations. Each symbol represents a composite of 2-3 video scenes because of the small detail of the map. A detailed map (left center) depicts an area with generally high populations of saltcedar. The lower left map shows even greater detail of the highly populated area.

areas such as coves (Narumalani *et al*., 1997). Waterhyacinth [*Eichhornia crassipes* (Mort.) Solms] and hydrilla [*Hydrilla verticillata* (L.F.) Royle] are two exotic aquatic weeds 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 to the United States in the mid 1880's in Louisiana (Tabita and Woods, 1962). It is now found throughout the southeast United States and also occurs in California (Correll and Correll, 1972). Populations may double in size every 6 to 18 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 submerced 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 and may be the most invasive submerged species known (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). Because of its aggressive growth rate, hydrilla has established itself in a wide range of aquatic habitats. 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. By restricting flow, hydrilla can artificially raise water levels and cause increased water loss through bank absorption (Langeland, 1996).

Water shortages in the Rio Grande River in southern Texas have been significantly impacted by the invasion of waterhyacinth and hydrilla over the past several years. The Rio Grande is the main source of water for both agricultural and municipal uses in southern Texas and northern Mexico. Waterhyacinth and hydrilla have caused serious water distribution problems in the region. Everitt *et al*. (1999) measured the light reflectance characteristics of hydrilla and waterhyacinth and used airborne videography integrated with GPS and GIS technologies for detecting and mapping these two aquatic weeds in the Rio Grande River. Field light reflectance measurements made at several locations showed that waterhyacinth generally had higher NIR (0.76 to 0.90 μm) reflectance than associated plant species and water. Surfaced hydrilla had lower NIR reflectance than associated plant species and higher NIR reflectance than water. The low NIR reflectance of hydrilla was contributed to significantly by its open canopy and integration of water with the canopy which absorbed a large percentage of the NIR light (Myers *et al*., 1983; Everitt *et al*., 1989). Reflectance measurements made on hydrilla below the water surface had similar spectral characteristics to water.

Figure 4-A 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

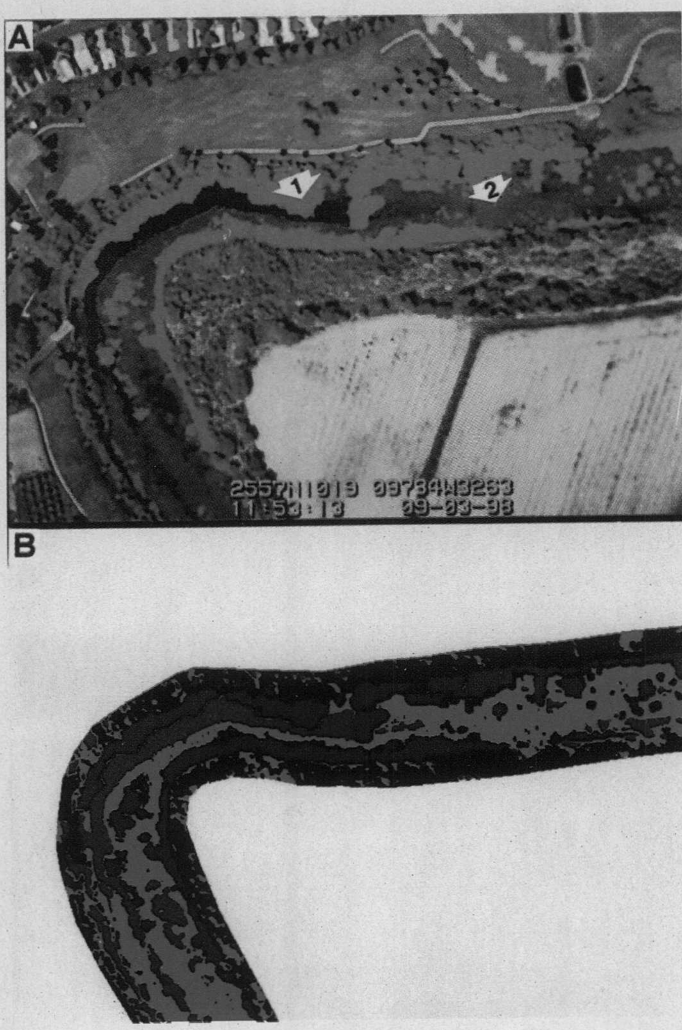

Fig. 4. Color-infrared digital video image (A) of a portion of the Rio Grande River near Brownsville, Texas, infested with waterhyacinth and hydrilla. Arrow 1 points to the conspicuous orange-red response of waterhyacinth, whereas arrow 2 points to the reddish-brown tonal response of hydrilla. The image was obtained on September 3, 1998. The GPS data is 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.

image response of waterhyacinth, whereas arrow 2 points to the reddish-brown image tone of surfaced hydrilla. Water has a black response, whereas woody plants (shrubs and trees) and herbaceous vegetation adjacent to the river have various red and magenta tones. Bare soil, roads, and homesites have whitish to light gray tones. The GPS data are displayed at the bottom of the video image. Integration of longitude-latitude co-ordinates with the video imagery is useful to locate waterhyacinth and hydrilla populations over remote and inaccessible areas.

Waterhyacinth and surfaced hydrilla had color tonal responses similar to that shown in Fig. 4-A in additional CIR video imagery acquired at numerous other locations along the Rio Grande and could be readily separated from other vegetation at all sites. However, hydrilla submerged 2.5 to 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 could not be distinguished in the video imagery. The conspicuous orange-red image of waterhyacinth was primarily attributed to its high NIR reflectance, whereas the reddish-brown or dark brown to nearly black image tones of hydrilla were attributed to its low NIR reflectance.

Figure 4-B shows an unsupervised classification of the CIR video image of the Brownsille site (Fig. 4-A). Color codes and respective per cent 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. 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 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

Table 2. An error matrix generated from video image classification data and ground data for a section of the Rio Grande River near Brownsville, Texas. Overall accuracy = 87.7%. Kappa = 0.828.

Actual category	Classified category					
	Accuracy	Hydrilla	Water-hyacinth	Riparian	Total	Producer's accuracy
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		

producer's accuracy and user's accuracy for all four categories were 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 that the classification has achieved an accuracy that is 83% better than would be expected from random assignment of pixels to categories.

Figure 5-A shows a regional GIS TIGER map of Starr, Hidalgo, Cameron, and Willacy Counties in the Lower Rio Grande Valley of south Texas. The Rio Grande 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 videographic imagery of the Rio Grande from 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 5-B. This area corresponds to the enclosed box in the upper map. With this map one can associate general land-use characteristics (i.e., streets, roads) with the GPS locations where hydrilla and waterhyacinth occur.

Giant salvinia

Giant salvinia (*Salvinia molesta* Mitchell) 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 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 (Barrett, 1989; 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). Giant salvinia has been found and eradicated in nurseries and ponds in the United States 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.

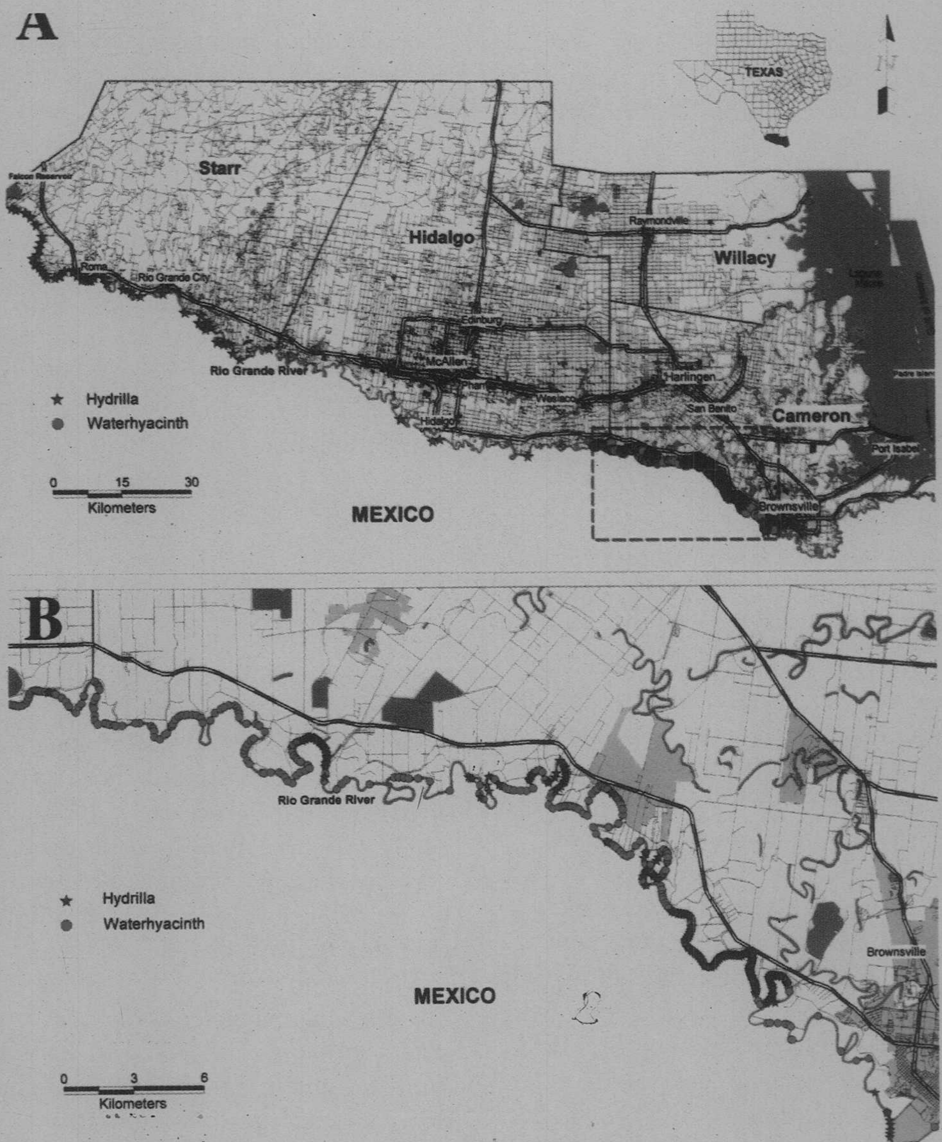

Fig. 5. *Regional GIS TIGER map (A) of Starr, Hidalgo, Cameron, and Willacy counties in the Lower Rio Grande Valley of south Texas. The Rio Grande River forms the lower boundary of the map with Mexico. Areas with green stars along the Rio Grande represent infestations of hydrilla, whereas red dots represent waterhyacinth infestations. A detailed GIS map (B) of Cameron County depicts infestations of hydrilla and waterhyacinth along the Rio Grande.*

Table 3. Mewan light reflectance measurements of giant salvinia and associated aquatic plant species in May 1999. Reflectance measurements were made at the visible green, visible red, and near-infrared wavelengths. Meaurements were made near Liberty and Raymondville, Texas

Plant species	Reflectance values[1] (%) for three wavelengths		
	Green	Red	Near-infrared
Alligator weed	5.6 c	3.0 c	34.8 b
American lotus	9.3 a	3.7 b	46.0 a
Arrowhead	5.1 cd	2.3 d	28.9 c
Hydrilla	2.9 e	1.8 e	13.1 e
Giant salvinia-green	7.0 b	4.6 a	31.1 bc
Giant salvinia-senesced	5.3 c	4.6 a	25.3 d
Smartweed	5.2 cd	2.5 d	33.7 bc
Waterhyacinth	4.4 d	1.7 e	43.3 a

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

Everitt *et al*. (2002) conducted a study to determine the potential of using aerial remote sensing techniques to detect giant salvinia infestations in Texas waterways.

Mean light reflectance values for giant salvinia and several associated species at three wavelengths at study sites near Liberty and Raymondville, Texas in May 1999 are presented in Table 3. American lotus [*Nelumbo lutea* (Wild.) Pers.] had higher visible green reflectance than the other species, whereas hydrilla had lower reflectance than the other species. Healthy green giant salvinia plants had lower green reflectance than American lotus, but higher reflectance than the other species. The green light reflectance of senesced giant salvinia (plants with mixtures of green and brown foliage) was similar to that of alligator weed [*Alternathera philoxeroides* (Mart.) Griseb.], arrowhead (*Sagittaria latifolia* Willd.), and smartweed (*Polygonum pensylvanicum* L.).

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. Differences in visible reflectance among the plant species were attributed to their different foliage colors (Myers *et al*., 1983). The species varied in color from blue-green for American lotus to very light green for green salvinia plants, 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. At the NIR wavelength, American lotus and waterhyacinth had higher reflectance than the other species, while hydrilla had lower reflectance than the other species. Differences in NIR reflectance among the species were attributed to their different vegetation densities (Myers *et al*., 1983). Reflectance measurements made at several other locations on different dates across

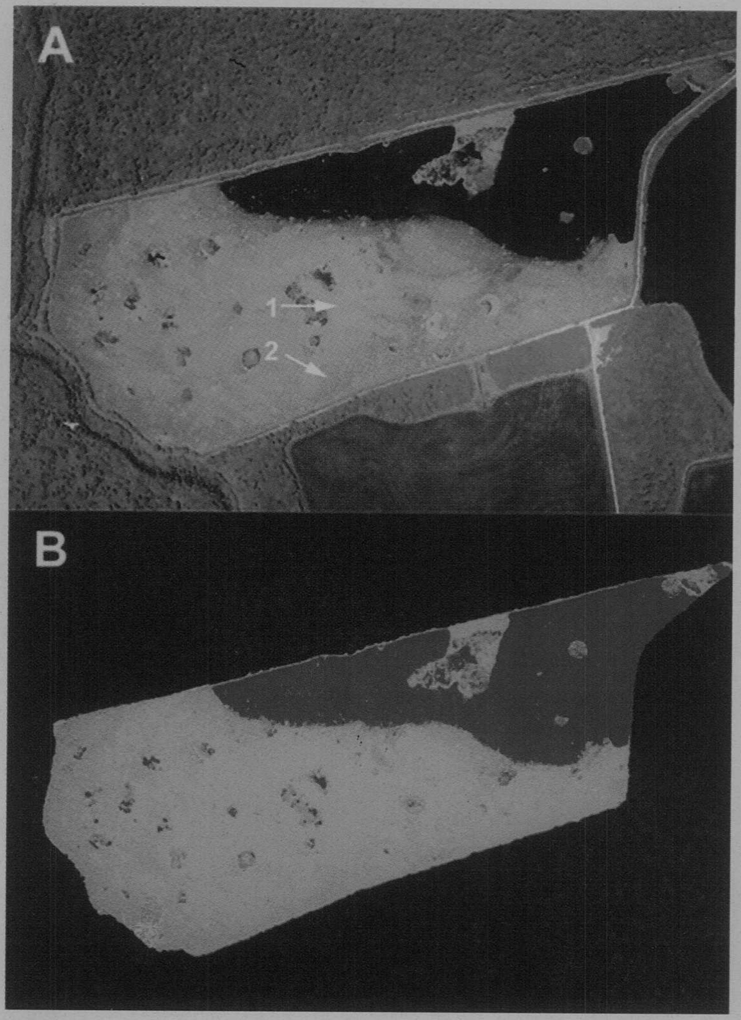

Fig. 6. Color-infrared photographic print (A) obtained on June 7, 2000 of a small lake near Mont Belvieu, Texas, infested with giant salvinia. Arrow 1 points to the pink image tone of green giant salvinia, whereas arrow 2 points to the grayish-pink response of senesced giant salvinia. The photograph 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.

the growing season showed that green giant salvinia and senesced giant salvinia could be spectrally distinguished from associated plant species.

Table 4. An error matrix generated from the classification data and ground data for the color-infrared photograph of the giant salvinia study site near Mont Belvieu, Texas. Overall accuracy = 87.0%. Kappa = 0.825

Classified category	Actual cateogry						
	Water	Woody plants	Senesced GS	Water-hyacinth	Green GS	Total	User'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%
Water-hyacinth	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%		

GS - giant salvinia.

Figure 6A shows a CIR positive photographic print obtained on June 7, 2000 of a small lake infested with giant salvinia near Mont Belvieu, Texas. The lake serves as a holding impoundment used for rice irrigation. 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 (*Cephalanthus occidentalis* L.) 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 Fig. 6A in additional CIR photographs obtained near Liberty, Bridge City, and Milam, Texas. The CIR image response of senesced giant salvinia varied from grayish-pink (Fig. 6A) to olive- green. Some senesced giant salvinia populations at other locations 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 (Fig. 6A) is shown in Figure 6B. 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 4 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 (Everitt *et al.*, 1987, 2002). 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.

Giant reed

Giant reed is a tall, robust perennial grass 2 to 8 m tall, growing in many-stemmed, cane-like clumps. The fleshy creeping rootstocks form compact masses from which arise tough fibrous roots that penetrate deeply into the soil (Perdue, 1958; Dudley, 2000). It spreads vegetatively either by rhizomes or plant fragments.

Giant reed is native to India, but has been widely introduced as an ornamental and for bank stabilization. Subsequently, it has become naturalized and invasive in many tropical, subtropical, and warm-temperate regions of the world (Dudley, 2000). It grows on a variety of soil types from loose sands and gravelly soils to heavy clays and river sediments. Optimum growth occurs in well drained soil with ample moisture, from freshwater to semi-saline soils at margins of brackish estuaries (Perdue, 1958; Dudley, 2000).

In addition to being used for erosion control and horticulture, giant reed canes are the primary source of reeds for woodwind instruments (Purdue, 1958). Commercial plantations of giant reed exist for musical instruments (Dudley, 2000). Giant reed has been used in light construction for plaster backing, concrete reinforcement and thatch. It is also a source of cellulose for rayon and paper pulp. The young stems and leaves are eaten by all livestock, including pigs and poultry (Cheatham and Johnston, 1995).

Giant reed was introduced into the United States in California in the early 1800's and quickly became naturalized. It is now found throughout the southern half of the United States from Maryland to California, but is most invasive along muddy banks of creeks and rivers in the southwestern United States, with the densest stands growing along coastal rivers of southern California and along the Rio Grande in west and southwest Texas (Dudley and Collins, 1995; Bell, 1997; Tracy and Deloach, 1999). Giant reed is a severe threat to riparian areas where it displaces native plants and animals because of the massive stands it forms and poses wildfire threat (Frandsen and Jackson, 1994). It also consumes excessive amounts of water, as much as 2,000 L m^{-1} of standing plant to supply its incredible rate of growth. Under optimum conditions it can grow more than 5 cm per day (Perdue, 1958; Bell, 1997). Giant reed stands are among the most biologically productive of all communities. Under ideal conditions they can produce more than 20 tons per hectare above-ground dry mass (Perdue, 1958). It also alters channel morphology by retaining sediments and constricting flows, and may reduce stream navigability (Dudley, 2000).

A study was recently initiated by the authors to determine the feasibility of using remote sensing techniques to distinguish giant reed in Texas. Table 5 shows the mean light reflectance measurements for giant reed, three associated species, mixed herbaceous species, and bare soil at three wavelengths in October 2001 near Weslaco, Texas. Bare soil had higher visible green and red reflectance than the associated plant species and mixtures of species. Giant reed had higher visible green and red reflectance than honey mesquite (*Prosopis glandulosa* Torr.), sandbar willow (*Salix exigua* Nutt.), Bermudagrass (*Cynodon dactylon* L.) and mixed herbaceous species. At the NIR wavelength, giant reed had higher reflectance than the other plant species, mixtures of species, and bare soil.

Table 5. Mean light reflectance measurements of giant reed, associated plant species and soil in south Texas in October 2001. Reflectance measurements were made at the visible green, visible red, and near-infrared wavelengths. Measurements were made near Weslaco, Texas

Plant species	Reflectance values[1] for threewavelengths		
	Green	Red	Near-infrared
Giant reed	9.0 b	5.1 b	37.5 a
Honey mesquite	4.3 d	2.9 d	29.5 c
Sandbar willow	5.5 c	3.7 c	34.2 b
Bermudagrass	5.4 c	3.7 c	25.9 c
Mixed herbaceous species	4.4 d	2.7 d	29.9 c
Bare soil	15.7 a	15.0 a	26.7 d

[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.

Fig. 7. Color-infrared aerial photograph of an infestation of giant reed along the Rio Grande River near Del Rio, Texas. The arrow points to the dark pink image response of giant reed. The print is a portion of a 23 cm photograph acquired on June 25, 2002 and has a scale of 1:10,500.

The higher green and red reflectance values of giant reed than those of the other species were attributed to its blue-green foliage that reflected more of the green light and absorbed less of the red light than the various green foliage colors of the other associated species and mixtures of species (Gausman, 1985). The higher NIR reflectance of giant reed than that of the other plant species and mixtures was attributed to its greater vegetative density (Tucker, 1979; Myers *et al*., 1983). The high visible reflectance and moderate NIR reflectance of bare soil agrees with the findings of other researchers (Bowers and Hanks, 1965; Gerbermann *et al*., 1987).

Figure 7 shows a CIR aerial photograph of an area along the Rio Grande River near Del Rio, Texas, infested wuth giant reed. The photograph was acquired in June 2002. The arrow points to the conspicuous dark pink image tonal response of giant reed that can be easily differentiated from the reddish-brown image tone of mixed brush, blue-gray image of dormant herbaceous vegetation, whitish response of bare soil/sparsely vegetated areas, and black tonal response of water. Giant reed had a similar image response to that shown in Fig. 7 at several other locations in southwest Texas. The CIR image response of giant reed was attributed to its distinct visible and NIR reflectance values (Table 5). These initial findings indicate that remote sensing techniques may have good potential for distinguishing infestations of giant reed along Texas river systems.

Conclusions

Data presented in this paper have demonstrated the value of aerial photography and videography for detecting invasive exotic weeds in terrestrial and aquatic ecosystems. Ground reflectance measurements of weed species can aid in determining their image responses. Aerial photography has been the most used form of remote sensing data for detecting noxious plants because of its fine spatial resolution. Airborne videdography has also shown great potential for this application. Video has lower resolution than photography, but it provides its users with quick turn-around data and surveys can be conducted for 25 to 50% the cost of photography (Everitt *et al*., 1992). Moreover, the electronic format of videography makes it highly compatible with computer image processing techniques, GPS, and GIS technologies. These technologies can enable resource managers to develop regional maps depicting where noxious weed infestations occur over large and inaccessible areas. Continuing technological developments in higher resolution video and true digital cameras, hyperspectral imaging, and satellite sensors (i.e., IKONOS) will lead to improvements in spatial and spectral resolution and an increase in their use for distinguishing noxious weeds.

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