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Remote Sensing of Exotic Invasive Weeds in the Rio Grande System of Texas: A Review

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ABSTRACT

Exotic invasive weeds are a serious problem in the Rio Grande system of Texas. This paper presents the results of several aerial remote sensing studies conducted from 2002 to 2006 on the Rio Grande from its mouth near Brownsville in south Texas to El Paso in west Texas. Weed species addressed include waterhyancith [*Eichhornia crassipes* (Mort.) Solms.], hydrilla [*Hydrilla verticillata* (L. F.) Royle], saltcedar (*Tamarix chinensis* Lour.), giant reed (*Arundo donax* L.), Eurasian watermilfoil (*Myriophyllum spicatum* L.), and wild taro [*Colocasia esculenta* (L.) Schott.]. Aerial photography and videography were used to detect plant species. Video imagery was integrated with global positioning system and geographic information system technologies to develop distribution maps denoting locations of waterhyacinth, hydrilla, saltcedar, giant reed, and Eurasian watermilfoil infestations. Computer analysis of aerial photographs was used to quantify infestations of wild taro and accuracy assessments were performed on the classified maps of the imagery.

Additional Index Words: light reflectance, color-infrared photography, color-infrared videography, normal color photography, normal color videography, global positioning system, geographic information system, image analysis, accuracy assessment, *Eichhornia crassipes, Hydrilla verticillata, Tamarix chinensis, Arundo donax, Myriophyllum spicatum, Colocasia esculenta.*

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The Rio Grande is one of the longest river systems in the United States. The river extends 3,040 km from its source in the San Juan Mountains of Colorado to the mouth at the Gulf of Mexico on the United States-Mexico border in extreme south Texas (Gilpin 1949). Approximately two-thirds (2,020 km) of the Rio Grande is the effective border between Texas and Mexico (Davis 2002). Construction of dams and reservoirs along the lower Rio Grande for flood control and for agricultural and municipal uses have resulted in losses of much of the natural vegetation (Lonard et al. 2000).

Today, extensive areas along the Rio Grande system in Texas have been invaded by exotic, invasive plant species that have ultimately displaced much of the original native vegetation. The Rio Grande is a major source of water for agricultural and municipal uses in Texas and northern Mexico. Water shortages in the Rio Grande have been significantly exacerbated by the invasion and spread of invasive weed species (Davis 2002).

Riparian zones and other wildland areas are often too large and inaccessible to determine their characteristics by ground surveys. Remote sensing techniques offer potentially timely, cost-effective means of obtaining reliable data for these areas (Tueller 1982). The value of remote sensing for distinguishing among plant species and communities is well established (Carter 1982; Driscoll et al. 1997). Aerial photography and airborne electronic imagery (videography and digital) imagery have been used to remotely detect weedy species over large and inaccessible areas (Gausman et al. 1977; Tueller 1989; Everitt et al. 1995; Lass and Callihan 1997; Ramsey et al. 2002).

During the past six years, scientists at the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Kika de la Garza Subtropical Agricultural Research Center in Weslaco, Texas, have been conducting research on the utilization of aerial photography and videography integrated with global positioning system (GPS) and geographic information system (GIS) technologies for detecting and mapping exotic invasive weeds in the Rio Grande system from the mouth of the river the near Boca Chica in extreme south Texas to El Paso in west Texas. In this paper the author's present an overview of their own research using spatial information technologies for detecting and mapping invasive weeds in the Rio Grande.

GENERAL PROCEDURES

All the 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 206T or Cessna 404 Titan 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 analysis can be obtained from the literature citations.

Ground control data were collected for the research studies presented here. Field reflectance measurements were made for most of the studies. Other ground data included ground photographs, description of vegetation, and plant cover. Standard statistical techniques were used to analyze and interpret data (Steel and Torrie 1980).

RESULTS AND DISCUSSION

Waterhyacinth and Hydrilla

Waterhyacinth [*Eichhornia crassipes* (Mort.) Solms] and hydrilla [*Hydrilla verticillata* (L. F.) Royle] are two 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 into the United States in the mid 1880's 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 6-18 days. Through the process of transpiration, the rate of water lost to the atmosphere in areas inundated with waterhyacinth may be 4-5 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 (Barnett and Schneider 1974; Schmitz 1990). Once established in a aquatic system, hydrilla can detrimentally alter the environment 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).

A study was conducted using airborne videography integrated with GPS and GIS technologies for detecting and mapping waterhyacinth and hydrilla infestations in the extreme lower portion of the Rio Grande of southern Texas (Everitt et al. 2003). Figures 1A and 1B show aerial normal color videographic images of waterhyacinth and hydrilla infestations, respectively, in the Rio Grande near Brownsville, Texas. The imagery was acquired on September 19, 2002. The arrow on Figure 1A points to the green to dark green smooth textured image response of waterhyacinth, while the arrow on Figure 1B points to the deep dark green to nearly black tonal response of surfaced hydrilla. Trees, shrubs, and herbaceous vegetation adjacent to the river have various green tonal responses, while bare soil and sparsely vegetated areas have white, light tan and light gray tones. The GPS data are displayed at the top of the images. The latitude-longitude coordinates superimposed on the images are useful for georeferencing waterhyacinth and hydrilla infestations in the river.

Both waterhyacinth and hydrilla had similar color tonal responses to those shown in Figures 1A and 1B, respectively, in all normal color video imagery obtained of the Rio Grande. However, only surfaced hydrilla populations could be readily distinguished. Hydrilla submerged greater than 7.5 cm below the

Fig. 1. Aerial normal color video images of infestations of waterhyacinth (A) and hydrilla (B) in the Rio Grande near Brownsville, Texas. The arrows point to waterhyacinth and hydrilla in each respective image. The imagery was obtained on September 19, 2002 at an altitude above ground level of approximately 600 m and had an original pixel size of approximately 0.70-m.

water surface generally could not be delineated from water. This agrees with the findings of the 1998 survey of the Lower Rio Grande (Everitt et al. 1999). The turbidity of the Rio Grande in this area contributes significantly to the inability to distinguish submerged hydrilla.

Waterhyacinth and hydrilla could be distinguished in aerial color-infrared (CIR) photography and CIR videography obtained of the Rio Grande on June 24, 2002 (imagery not shown). Waterhyacinth had a distinct red to orange-red image response, while hydrilla had a reddish-brown to dark brown image. Only surfaced hydrilla could be clearly delineated in the imagery.

The CIR photography had greater spatial resolution than the CIR or normal color videography. Consequently, it provided a more detailed image of hydrilla and waterhyacinth populations and aided in the interpretation of the coarser resolution videographic imagery. However, the videography was adequate for distinguishing most of the hydrilla and waterhyacinth. Normal color videography did a better job of penetrating the water than either the CIR photography or videography. This was attributed to its sensitivity in the visible blue (0.40 to 0.50 µm) portion of the spectrum (Avery and Berlin 1992). This is in general agreement with the findings of Benton and Newnam (1976) who reported that normal color photography was useful for detection of submerged aquatic vegetation. One advantage of videography over photography is its cost-effectiveness. Airborne video surveys using analog imagery can be flown for about 25% the cost of aerial photography (Everitt et al. 1992).

Ground surveys of sites selected from the aerial photography and videography resulted in visual correct identification of waterhyacinth and hydrilla at all locations. However, a considerable amount of submerged hydrilla was found at some sites that could not be detected in the imagery. We also found small clumps of water stargrass [*Heteranthera dubia* (Jacq.) MacM.] generally less than 0.75-m in diameter intermixed with hydrilla at two sites near Brownsville and several individual plants and small patches (less than 1-m in diameter) of waterlettuce (*Pistia stratiotes* L.) intermixed with waterhyacinth at one site west of Brownsville. Neither water stargrass nor waterlettuce could be distinguished in the imagery due to the small size of the plant populations.

The GPS latitude-longitude data obtained from the video imagery of the Rio Grande from the June, September, and October 2002 surveys were integrated with GIS technology to georeference populations of waterhyacinth and hydrilla on a regional basis. Figure 2A shows a regional GIS map of Starr, Hidalgo, Cameron, and Willacy counties of south Texas. The Rio Grande forms the lower boundary of the map adjacent to Mexico. The map shows the Rio Grande from its mouth in southeastern Cameron County to Falcon Dam in southwestern Starr County. Light to moderate populations of waterhyacinth have pink circles, while dense populations of waterhyacinth have red circles. The light green stars represent light to moderate populations of hydrilla, while dark green stars denote dense populations of hydrilla. For mixed populations of waterhyacinth and hydrilla, light magenta triangles represent light to moderate populations, while dark magenta triangles indicate dense populations. Due to the small scale of the map many of the symbols are stacked on each other. Most symbols represent composites of two to five video scenes. The highest populations of waterhyacinth and hydrilla occurred in southeastern Hidalgo and Cameron counties where a stretch of approximately 170 river-km was infested. Waterhyacinth was found only in Cameron and extreme southeastern Hidalgo counties. East of Brownsville most (60%) waterhyacinth infestations were dense, while most sites west of Brownsville (67%) had light to moderate infestations. With the exception of a relatively short stretch of the Rio Grande in southwestern Hidalgo County, hydrilla occurred along most of the river from southeast of Brownsville to Falcon Dam.

Figure 2B shows an enlarged GIS map of southeastern Hidalgo and Cameron counties depicting the heaviest populations of waterhyacinth and hydrilla in the lower Rio Grande. This area corresponds to the enclosed box in Figure 2A. This map shows greater detail of the area in regard to streets, roads, and hydrography associated with waterhyacinth and hydrilla populations.

The 2002 survey maps showed a marked increase in distribution of hydrilla in Hidalgo County as compared to the 1998 survey map of the area (Everitt et al. 1999). Hydrilla was found at only a few scattered locations in Hidalgo County in 1998 and had a distribution of about 5 river-km. Conversely, in 2002 hydrilla was found at numerous locations in Hidalgo County and had a distribution of approximately 50 river-km. Another notable change was the increase in the distribution of both waterhyacinth and hydrilla populations southeast of Brownsville in 2002. This represented an increase in distribution of approximately 70 river-km from the 1998 survey. This was probably due to the blockage of the mouth of the Rio Grande with silt and sand in 2001 and 2002 which decreased salinity levels in the lower stretch of the river and subsequently allowed waterhyacinth and hydrilla to move farther down stream. Blockage of the mouth of the river was

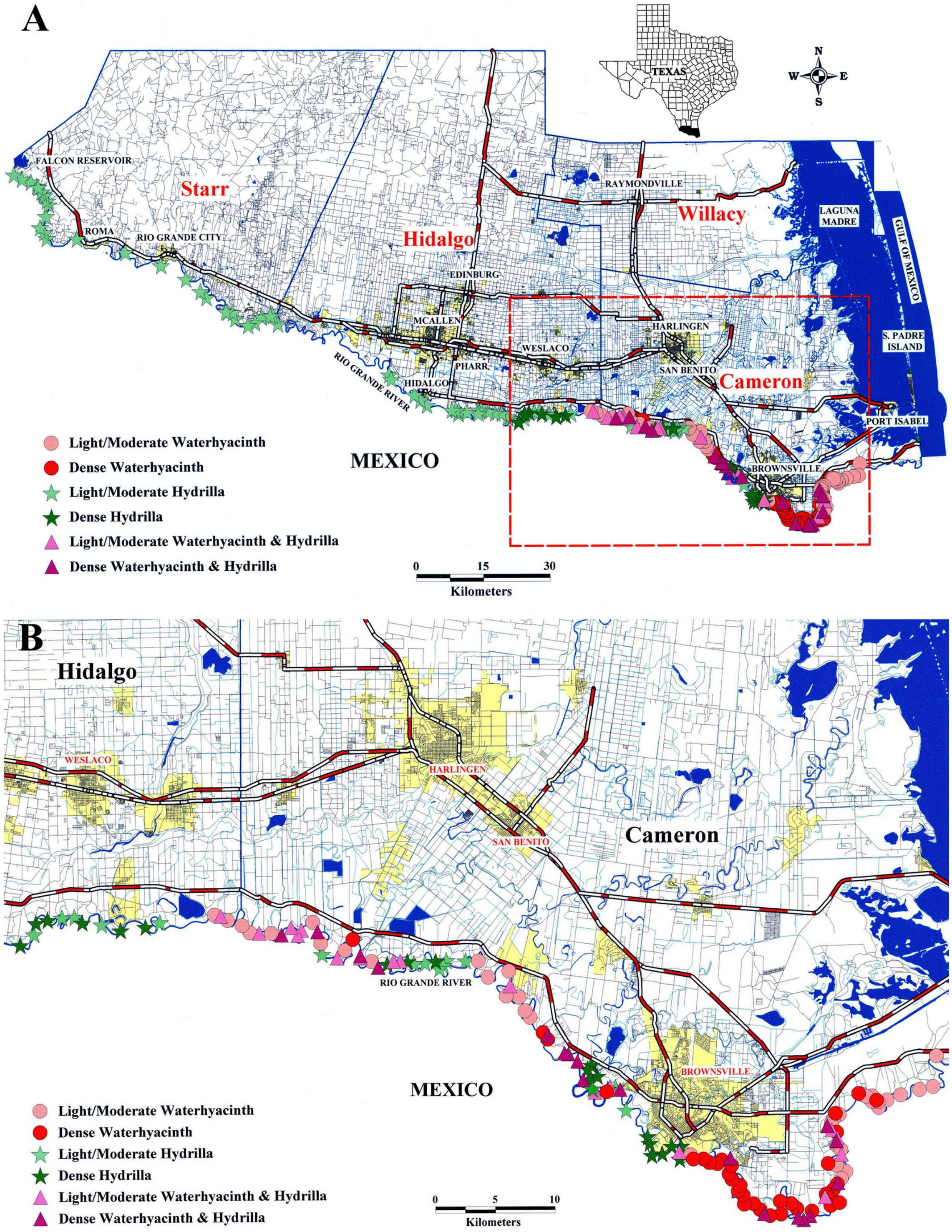


Fig. 2. Regional GIS map (A) of Starr, Hidalgo, Cameron, and Willacy counties in the Lower Rio Grande Valley of south Texas. The Rio Grande forms the lower boundary of the map with Mexico. A detailed GIS map (B) of southeastern Hidalgo and Cameron counties depicting infestations of waterhyacinth and hydrilla in the Rio Grande.

primarily due to reduced stream flow due to long-term drought. The severe infestations of weeds in the river in southeastern Hidalgo and Cameron counties probably also contributed to the reduced flow. The estimated increases in river-km of hydrilla are primarily based on surfaced beds, since few of the submerged plants could be distinguished. Therefore, our estimated total river-km of hydrilla is probably an underestimation of the actual number of river-km of this invasive species in the lower Rio Grande.

In the fall of 2003, two flood events occurred on the lower Rio Grande that washed most of the waterhyacinth infestations out of the river. Since then waterhyacinth populations have remained low in this portion of the Rio Grande. Aerial CIR photography was acquired of the study area in October 2007 and only small clusters of waterhyacinth could be detected in the imagery. Hydrilla populations have been reduced by the release of grass carp (*Ctenopharyngodon idealla* Valenciennes) into the Rio Grande in central Hidalgo and Cameron counties in 2003 However, hydrilla remains a problem in western Hidalgo and Starr counties. It is also increasing in abundance in the Rio Grande below Amistad Reservoir near Del Rio, Texas (Owens et al. 2005).

Saltcedar

Eight species of saltcedar (*Tamarix* sp.) have been introduced into the United States from Europe, Asia, and Africa for ornamentals, windbreaks, and erosion prevention of streambanks (Baum 1967). At least five species of saltcedar are found in Texas (Hatch et al. 1990). Two deciduous saltcedar species (*Tamarix ramosissima* Ledeb. and *Tamarix chinensis* Laur.) are invaders of riparian sites of the southwestern United States (including Texas) and northern Mexico. These two very similar species form 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). Research on herbarium specimens and growing plants of *Tamarix chinensis* and *Tamarix ramosissima* has shown that it is difficult to distinguish between the two species (Horton 1977). Molecular research on these two species indicates that some populations are genetically indistinguishable and that there is some evidence of hybridization among several species of saltcedar (Gaskin and Schall 2003). Although *Tamarix chinensis*, *Tamarix ramosissima*, and possible hybrids occur in west Texas, the saltcedar taxon that causes a nuisance in this area is generally referred to as *Tamarix chinensis*.

During the late fall and early winter, the foliage of saltcedar turns a yellow-orange to brown color prior to leaf drop. Research has shown 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 and videography (Everitt and Deloach 1990; Everitt et al. 1996).

Everitt et al. (2006) used airborne color photography and videography coupled with GPS and GIS technologies to distinguish and map saltcedar infestations on the Rio Grande in west Texas. Figures 3A and 3B show a normal color photograph and a normal color analog video image, respectively, of a saltcedar infestation on the Rio Grande north of Candelaria in west Texas. The photograph is a portion of a 23 cm photograph (1:10,000 scale), whereas the video image (3.0 m pixel size) was extracted from a slightly larger video scene. The arrows on the two images point to the orange-brown tonal response of a dense stand of saltcedar. Bare soil and sparsely vegetated areas have white to various light gray tones, shrubs have a dark gray or black image response, and water has light green to dark green tones. Although the video image has coarser resolution than the photograph, saltcedar can be easily distinguished. The GPS latitude-longitude coordinates of the area are displayed at the top of the video image. The distinct image response of saltcedar was due to its yellow-orange to orange-brown late fall foliage color prior to leaf drop. Saltcedar could be readily distinguished in all the normal color photography and videography obtained along the Rio Grande. Saltcedar has higher visible reflectance during this phenological stage that facilitates its detection on normal color photography and videography (Everitt and Deloach 1990; Everitt et al. 1996).

Figure 4A shows a GIS map of the 4-county area of west Texas where the aerial survey was conducted. The Rio Grande forms the left boundary of the map. The GPS latitude-longitude data provided on the aerial videographic imagery from the December 2002 survey of the Rio Grande have been integrated with the GIS to georeference infestations of saltcedar along the river. The red stars represent the densest populations of saltcedar, blue stars were moderate populations, and pink stars represented light populations. Many of the population symbols are stacked on each other because of the small scale of the map. We found that approximately 460 river-km of saltcedar occurred along the Rio Grande study area. The densest populations occurred in the eastern portion of Hudspeth County and the western part of Presidio County. A more detailed GIS map showing the

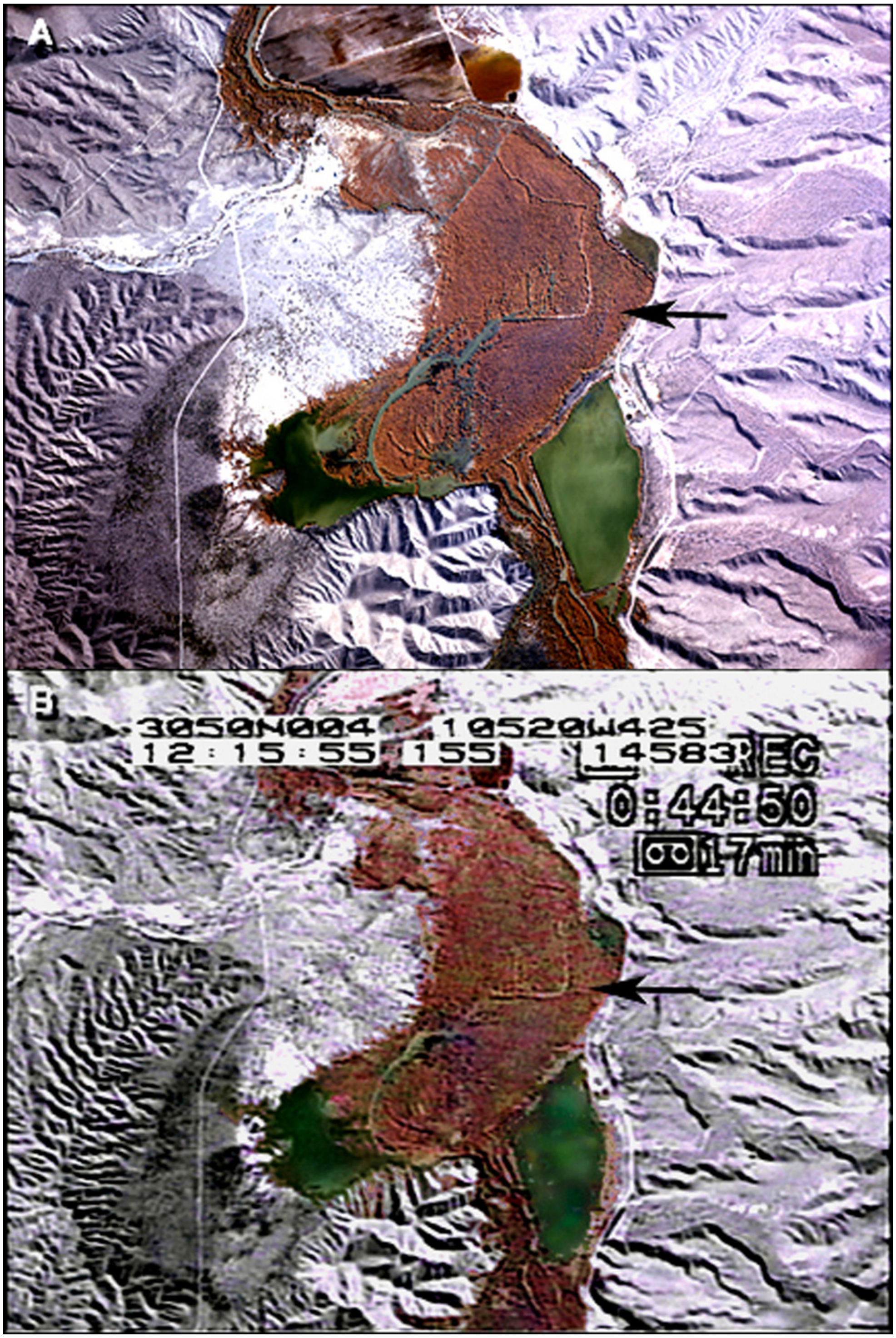


Fig. 3. Normal color photographic (A) and analog videographic (B) images obtained December 10, 2002 of a saltcedar infestation along the Rio Grande north of Candelaria in west Texas. The arrows point to a dense stand of saltcedar. The GPS data is superimposed at the top of the video image.

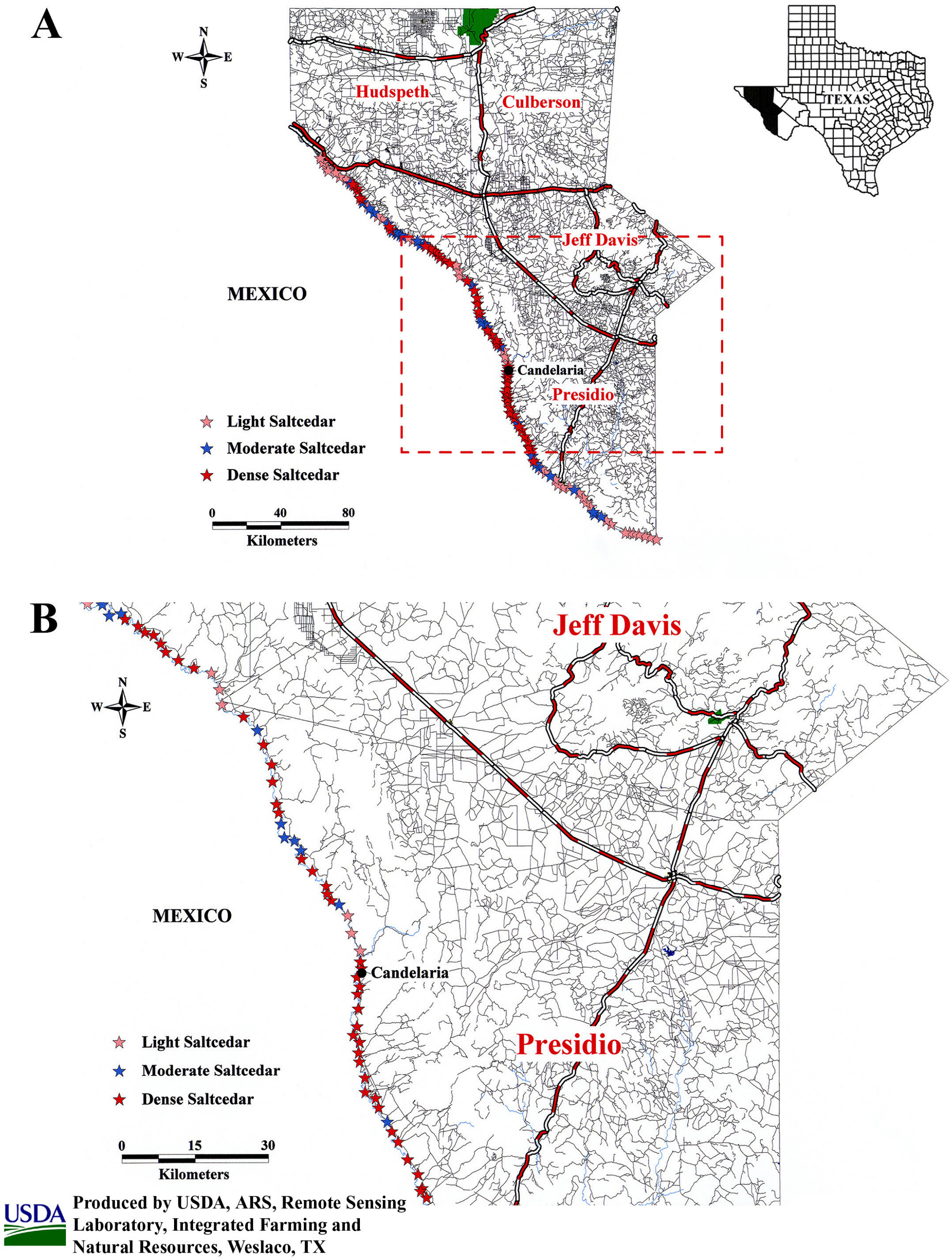


Fig. 4. Regional GIS map (A) of a four-county area in west Texas. The Rio Grande forms the western boundary of the map with Mexico. The symbols along the Rio Grande represent GPS latitude-longitude co-ordinates of saltcedar infestations obtained from the airborne video imagery. A detailed GIS map (B) of a portion of the Rio Grande showing locations of some of the densest saltcedar infestations.

densest populations of saltcedar is shown in Figure 4B. The area corresponds to the enclosed box in Figure 4A.

The 2002 survey map (Figure 4A) of saltcedar distribution was similar to a 1994 survey map of the same general area (Everitt et al. 1996). Total river-km of saltcedar was not computed in the 1994 survey, but a qualitative comparison between the two maps revealed that they are very similar. However, some of the saltcedar density levels differed between the two surveys. This was partially due to changes in plant populations over the 8-year interval between surveys, but was primarily attributed to using different criteria for assignment of population levels in the 1994 survey and acquisition of imagery at a different altitude. The 1994 imagery was obtained at altitudes ranging from 1,050 to 1,500 m, whereas the 2002 survey was obtained at an altitude of 3,050 m. The higher altitude imagery of the 2002 survey provided a much greater horizontal width of coverage of the Rio Grande floodplain and the detection of more saltcedar populations than in the 1994 survey.

Saltcedar remains a severe problem along the Rio Grande in west Texas. Recently, biological control techniques have been used with some success to control saltcedar at several locations in Texas, Nevada, and Wyoming (Deloach and Carruthers 2004; C. J. Deloach, USDA-ARS, Temple, Texas, personal communication).

Giant reed

Giant reed (*Arundo donax* L.) is a weedy perennial grass 3 to 10 m tall growing in many-stemmed cane-like clumps, spreading from horizontal root stocks below the soil and often forming dense colonies. It spreads vegetatively by either rhizomes or plant fragments (Perdue 1958; Dudley 2000). Giant reed is thought to be native to the Old World from Spain to India, but has been widely introduced as an ornamental and for strean bank stabilization (Polunin and Huxley 1987). This species has been cultivated in the Old World for thousands of years and has been widely planted in North and South America in the past two centuries (Perdue 1958; Dudley 2000). Giant reed was introduced to California from the Mediterranean in the 1820's and quickly became naturalized (Hoshovsky 1987). It now occurs throughout the southern United States from Maryland to California, but is most invasive along creeks and rivers in the southwestern United States. The densest infestations of giant reed occur along coastal rivers in California and along the Rio Grande in west and southwest Texas (Dudley and Collins 1995; Bell 1997; Tracy and Deloach 1998).

Giant reed uses about three times as much water as native vegetation, and under optimum conditions can attain growth rates of 0.7 m per week or 10 cm per day, putting it among the fastest growing plants (Perdue 1958; Bell 1997). It also alters channel morphology by retaining sediments and constricting flows and may reduce stream navigability (Bell 1997; Dudley 2000). In addition, giant reed is a threat to riparian environments where it displaces native plants and animals by forming massive stands that pose a wildfire threat (Frandsen and Jackson 1994).

Everitt et al. (2004) described the light reflectance characteristics of giant reed and demonstrated the application of aerial photography and videography for detecting and mapping giant reed infestations along the Rio Grande in west and southwest Texas. Figures 5A and 5B show CIR photographic and videographic images, respectively, obtained June 25, 2002 of an area along the Rio Grande near Del Rio infested with giant reed. The photographic image is a portion of a 23 cm photograph (1:10,000 scale), while the video image (3.0 m pixel size) was extracted from a larger video scene. The arrows on the two images point to the pink tonal response of giant reed. Mixed brush has a reddish-brown image, mixed herbaceous vegetation has reddish-gray, gray or dark gray tones, soil has a light gray to white color, and water has a black response. The distinct image response of giant reed is attributed to it high visible green and near-infrared spectral reflectance (Everitt et al. 2004). The photographic and video images have similar color tonal responses. The GPS data are displayed at the top of the video image. Giant reed had a similar color tonal response to those shown in Figures 5A and 5B in all the photographs and video images obtained along the Rio Grande and could be distinguished at all locations.

Figure 6A shows a regional GIS map of an 8-county area of southwest and west Texas. The Rio Grande forms the boundary of the map adjacent to Mexico. The GPS latitude-longitude data provided on the aerial videographic imagery of the Rio Grande from the June 2002 over flight have been integrated with the GIS to georeference infestations of giant reed along the river. Areas with red stars represent the densest populations of giant reed, those with blue stars have moderate populations, and those represented by pink stars have light populations. Approximately 600 river-km of the Rio Grande area surveyed was infested with giant reed. The densest populations of giant reed are located in Kinney and Maverick counties in southwest Texas. Due to the small scale of the map, many of the symbols are stacked on each other. Consequently, some symbols represent a composite of

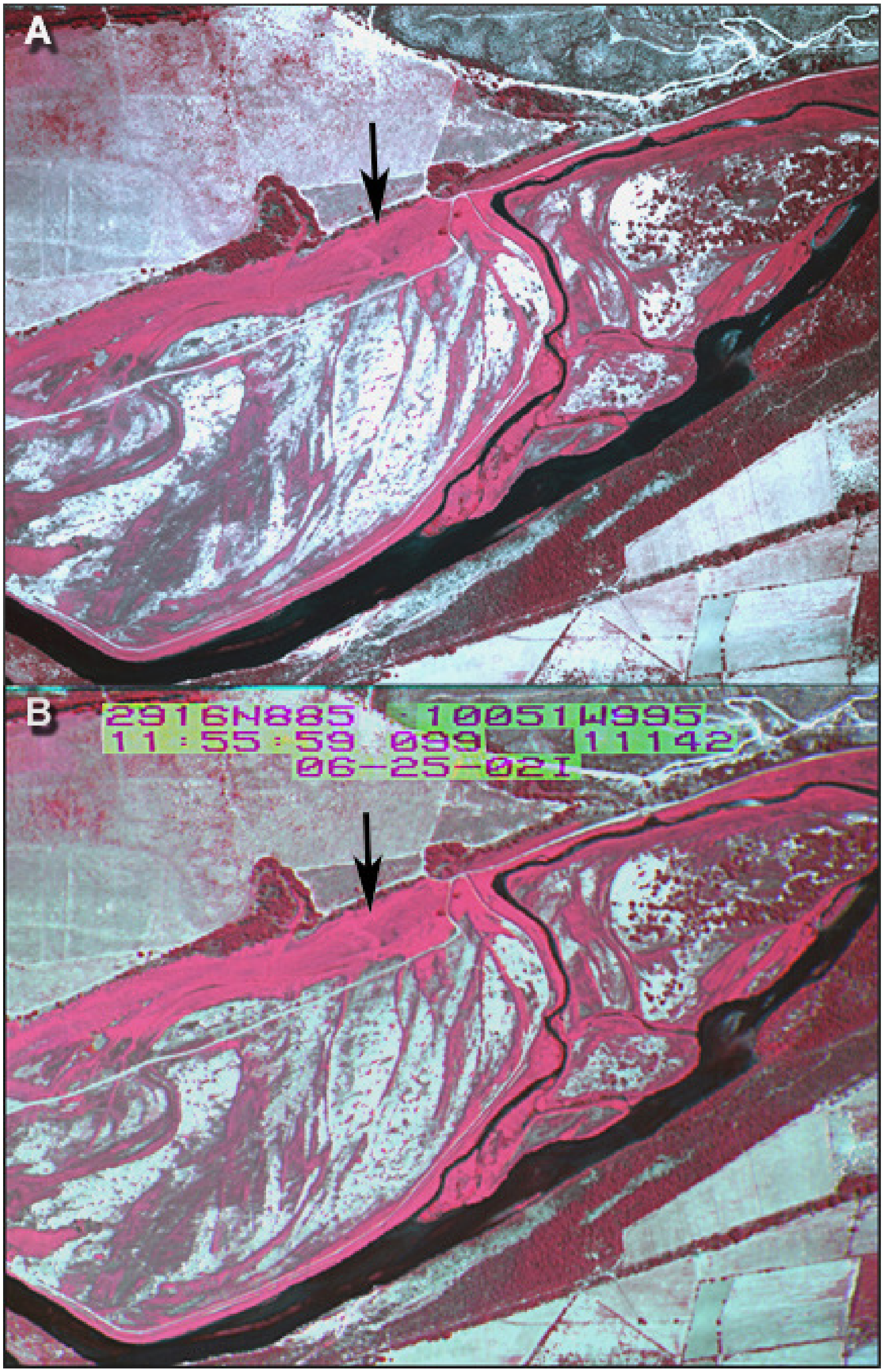
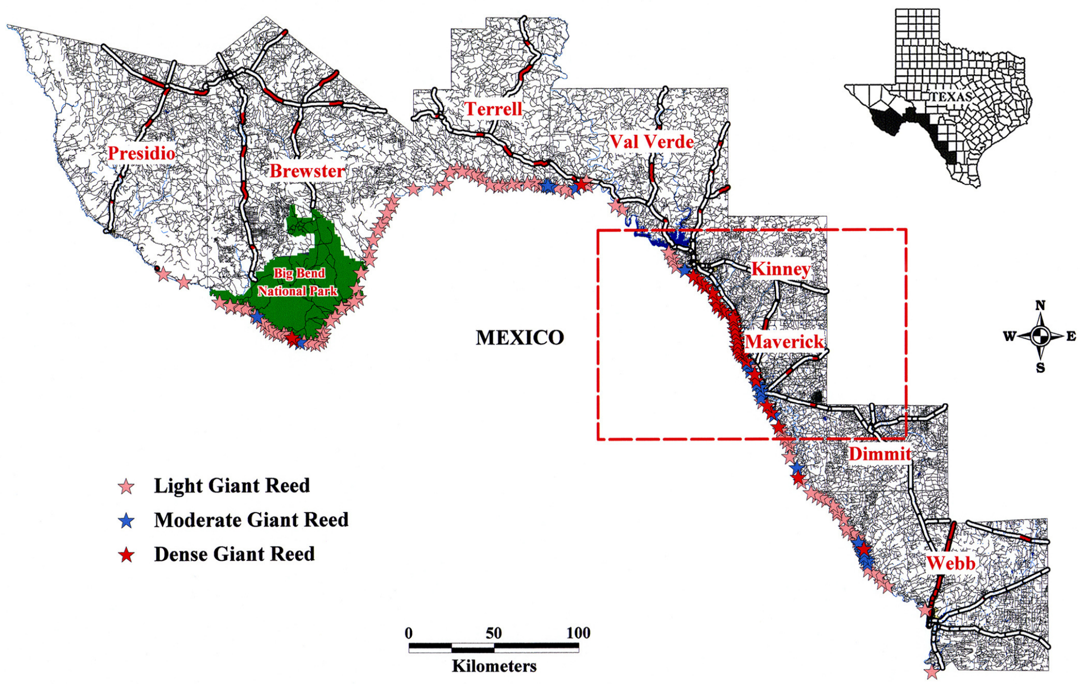


Fig. 5. Color-infrared photographic (A) and videographic (B) images obtained June 25, 2002 of an area along the Rio Grande near Del Rio, Texas, infested with giant reed. The arrows point to the pink image tonal response of giant reed. The GPS data is superimposed at the top of the video image.

A



B

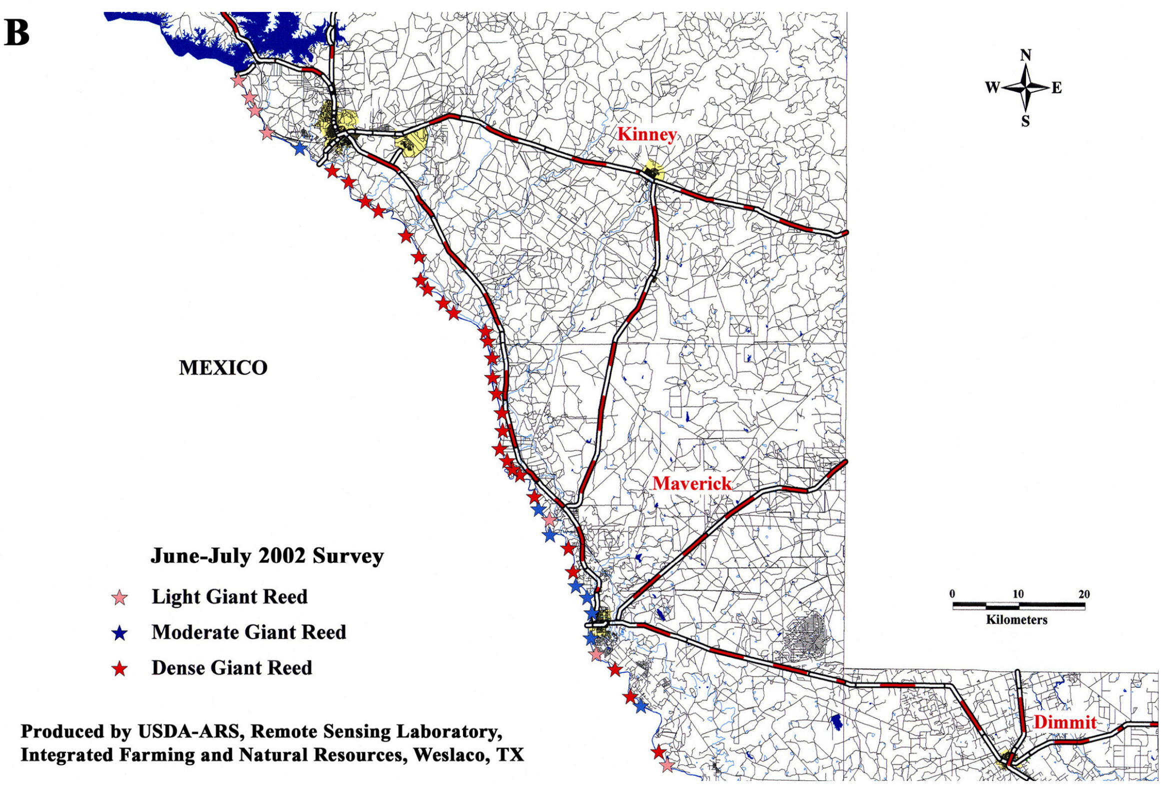


Fig. 6. Regional GIS map (A) of an 8-county area along the Rio Grande in southwest and west Texas. The Rio Grande forms the western boundary of the map with Mexico. The symbols along the Rio Grande represent GPS latitude-longitude coordinates of giant reed infestations obtained from airborne video imagery. A detailed GIS map (B) of a portion of the Rio Grande with several dense infestations of giant reed.

3 or 4 video scenes. Ground surveys confirmed the presence of giant reed at all the plotted locations on the map. Small stands or individual plants of common reed (*Phragmites australis* Trin.) were found growing in association with giant reed at several scattered locations. However, very little common reed could be distinguished in the imagery. Where it could be differentiated, common reed generally had a reddish-pink image response as compared to the pink image tone of giant reed.

Figure 6B shows a more detailed GIS map of the portion of the Rio Grande with the densest infestations of giant reed in Kinney and Maverick counties and corresponds to the enclosed box in Figure 6A. This map more clearly depicts the infested areas and allows one to associate the general land-use characteristics (i.e., highways, roads) with the GPS locations where giant reed occurs.

Giant reed continues to increase in distribution and density along the Rio Grande in southwest and west Texas. Research efforts are underway at the USDA-ARS laboratory in Weslaco, Texas, and USDA-APHIS facilities in Edinburg, Texas, evaluating insects for possible biological control of giant reed (John Goolsby, USDA-ARS, Weslaco, Texas, personal communication).

Eurasian watermilfoil

Eurasian watermilfoil (*Myriophyllum spicatum* L.) is a submersed, perennial aquatic plant native to Europe and Asia that was introduced to North America in the 1880s (Reed 1977; Nichols and Shaw 1986). Since that time it has spread from coast to coast in both the United States and Canada where it is a nuisance plant species. Eurasian watermilfoil is an aggressive species capable of displacing native submerged plant species, reducing both habitat diversity and plant species diversity. When overabundant, this species can impede water flow, reduce boat access, reduce access to other recreational activities such as swimming and skiing, and lower dissolved oxygen levels (Reed 1977; Nichols and Shaw 1986; DiTomaso and Healy 2003).

Everitt et al. (2007a) recently completed a study describing the spectral characteristics of Eurasian watermilfoil and using airborne remote sensing techniques integrated with GPS and GIS technologies for detecting and mapping this aquatic weed in Texas waterways, including the Rio Grande in southwest Texas. They showed that Eurasian watermilfoil had distinct visible and near-infrared reflectance from other associated wetland and aquatic plant species. Figure 7A shows an aerial CIR photograph of a cove on Coleto Creek Reservoir near Goliad, Texas. The print is 2X enlargement of a portion of a 23 cm photograph obtained on August 17, 2001, at an altitude above ground level of approximately 750 m (1:2,500 scale). The arrow points to the grayish-pink image response of a bed of Eurasian watermilfoil. Most of the plants on the left side of the cove are surfaced. The faint pink tones on the right side of the cove are Eurasian watermilfoil plants either barely surfaced or slightly submerged (0.5-2.5 cm) below the water surface. Most of the Eurasian watermilfoil submerged deeper than 2.5 cm could not be distinguished in the photos. Some dead trees are adjacent to the Eurasian watermilfoil on the left side of the cove. Deeper water has a dark blue image, whereas shallow water has a whitish-blue tonal response. Trees and green herbaceous vegetation have various red and magenta image tones, while senesced herbaceous vegetation has a dark gray color. Bare soil areas adjacent to the water have a white tonal response.

Figures 7B and 7C show an aerial CIR photograph and CIR video image, respectively, obtained along the Rio Grande near Del Rio. The imagery was acquired on September 8, 2004 at an altitude of 3,050 m (1:10,000 scale) above ground level. The photographic print is a portion of a 23 cm photograph. The video image has a ground pixel size of about 2.4 m. The GPS data is superimposed at the top of the video image. The arrows on both images point to the grayish-pink image response of a bed of Eurasian watermilfoil in the Rio Grande. Mixed woody species have a reddish-brown tone, giant reed has a dark pink response, sparsely vegetated/bare soil areas have various grayish-white, white or light blue tones, and water has a dark blue color. The slight differences in tonal responses of the video image, as compared to the photograph, were attributed to electronic coding of the video image versus chemical emulsion layers of the film.

Eurasian watermilfoil had similar image responses to those shown in Figure 7 (A, B, and C) at numerous sites at Coleto Creek Reservoir and on the Rio Grande. Despite the much coarser spatial resolution of the videography than that of the photography acquired simultaneously of the Rio Grande study sites, most Eurasian watermilfoil beds could be distinguished in the videography. However, Eurasian watermilfoil had a more distinct image response in the photograph (Figure 7B) than in the video image (Figure 7C). Small patches (beds) of Eurasian watermilfoil less than 2.5 m in length or width generally could not be distinguished in the videography. The water clarity at all sites was very good with little or no turbidity. This contributed greatly to the similar image tones of Eurasian watermilfoil at the various sites.

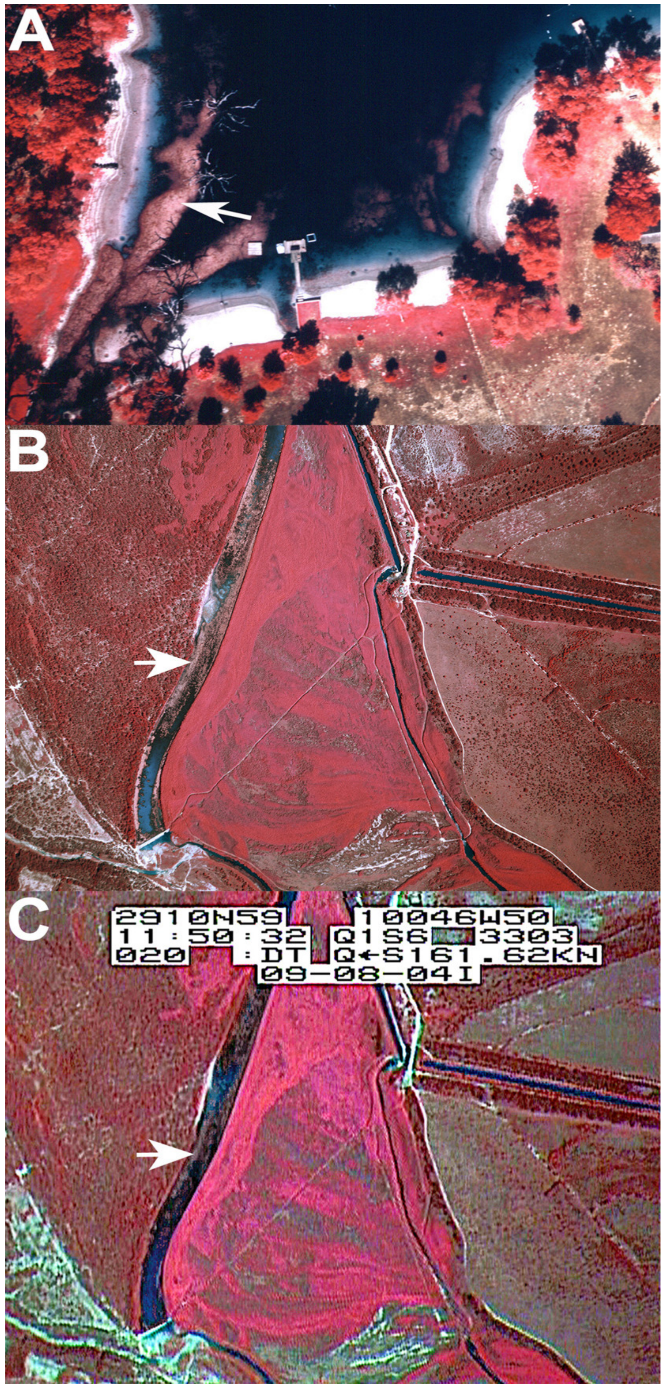


Fig. 7. Large scale (1:2,500) color-infrared photographic print (A) of a cove on Coleto Creek Reservoir near Goliad, Texas, with an infestation of Eurasian watermilfoil. Prints B and C show a small scale (1:10,000) color-infrared photograph and a color-infrared video image (2.4 m pixel resolution), respectively, of the Rio Grande near Del Rio, Texas, with an infestation of Eurasian watermilfoil. The arrows on the three images point to the grayish-pink image response of surfaced beds of Eurasian watermilfoil. The GPS data is superimposed at the top of the video image.

Figure 8A shows a regional GIS map of a 4-county area along the Rio Grande in southwest Texas. The Rio Grande forms the western boundary of the map adjacent to Mexico. The GPS latitude-longitude data provided on the aerial videographic imagery of the Rio Grande from a September 2004 over-flight have been integrated with the GIS to georeference locations of Eurasian watermilfoil infestations in the river. The stars represent locations of Eurasian watermilfoil infestations. Eurasian watermilfoil occurred at 24 sites over a stretch of approximately 66 river-km in the Rio Grande. Due to the small scale of the map, many of the symbols are stacked on each other. Ground surveys confirmed the presence of Eurasian watermilfoil at all the plotted locations on the map. However, submerged hydrilla was found intermixed with Eurasian watermilfoil at 2 locations. Some small patches of water stargrass were found near the bank intermixed with Eurasian watermilfoil at three locations. We also observed traces of algae (*Spirogyra*) on some of the surfaced beds that were out of the stronger water current. Neither hydrilla, water stargrass, nor algae could be delineated in the photography or videography.

Figure 8B shows a more detailed GIS map of the locations where Eurasian watermilfoil occurred and corresponds to the enclosed box in Figure 8A. This map provides much greater detail of the locations infested with Eurasian watermilfoil.

Eurasian watermilfoil infestations in the Rio Grande primarily occur from below Amistad Dam to north of Eagle Pass, Texas. This weed appears to be expanding at alarming rates in the Rio Grande. Owens et al. (2005) reported that Eurasian watermilfoil had greatly increased in abundance from a survey in 2001 to another survey in 2003. They indicated that this weed could pose a serious threat to the river if conditions allowed the plant population to increase and disperse.

Wild taro

Wild taro [*Colocasia esculenta* (L.) Schott.], also known as elephant ear, is an exotic ornamental plant that has become naturalized in many fresh water wetlands throughout the southern United States (Nelson and Getsinger 2000). It also occurs in Pennsylvania and Hawaii (Glomski and Danbar 2006). Wild taro is native to India and southeast Asia and was brought to the United States as a food for slaves to be used as a possible substitute for potatoes (Glomski and Danbar 2006). Today, wild taro is considered an invasive weed in the United States where it forms dense, monotypic stands that reduce the diversity of native vegetation (Nelson and Getsinger 2000). Wild taro is also of little value to wildlife (Stutzenbaker 1999).

Several river systems in Texas have well established populations of wild taro (Akridge and Fonteyn 1981; Owens et al. 2001), including the Rio Grande in southwest Texas below Amistad Reservoir (Owens et al. 2005). Everitt et al. (2007b) recently completed a study describing the light relectance characteristics of wild taro and evaluating CIR aerial photography for distinguishing infestations of wild taro along the Rio Grande below Amistad Reservoir. They reported that wild taro had significantly different visible and near-infrared reflectance from other associated plant species that facilitated its detection on CIR aerial photography.

Figure 9A shows a CIR positive photographic print of a wild taro study area on the Rio Grande below Amistad Reservoir. The print is a portion of a 23 cm photograph (original scale 1:5,000). The arrow on the print points to the bright red image tonal response of wild taro. Giant reed, the dominant plant species on the study site, has dark pink or gray-pink tonal responses. Mixed woody vegetation has dull red to reddish-brown tones, soil has a white color, and water is dark blue. The distinct image response of wild taro was primarily attributed to its low visible red reflectance, although its high near-infrared reflectance also contributed to its tonal response. The pink image tone of giant reed was attributed to its high visible green and near-infrared reflectance. Mixed brush species have low to moderate visible and near-infrared reflectance that gives these plants duller red to reddish-brown image responses. (Everitt 1985; Everitt et al. 2004).

The supervised classification map of the CIR photograph of the wild taro study area is shown in Figure 9B. Table 1 shows an error matrix comparing the classified data with the ground data for the 100 observations from the supervised classification of site 1. The overall accuracy was 94%, indicating that 94% of the category pixels in the image were correctly identified in the classification map. The producer's accuracy of individual categories ranged from 89.7% for giant reed to 100% for wild taro and soil. The user's accuracy ranged from 80% for soil to 100% for wild taro and mixed woody vegetation. Thomlinson et al. (1999) set a target of an overall accuracy of 85% with no class lower than 70%. Based on these guidelines, the overall accuracy was excellent, as well as both the producer's and user's accuracies for wild taro and most of the other classes. The kappa estimate was 0.920, indicating the classification achieved an accuracy that is 92% better than would be expected from the random assignment of pixels to classes. Accuracy assessments performed on classified maps

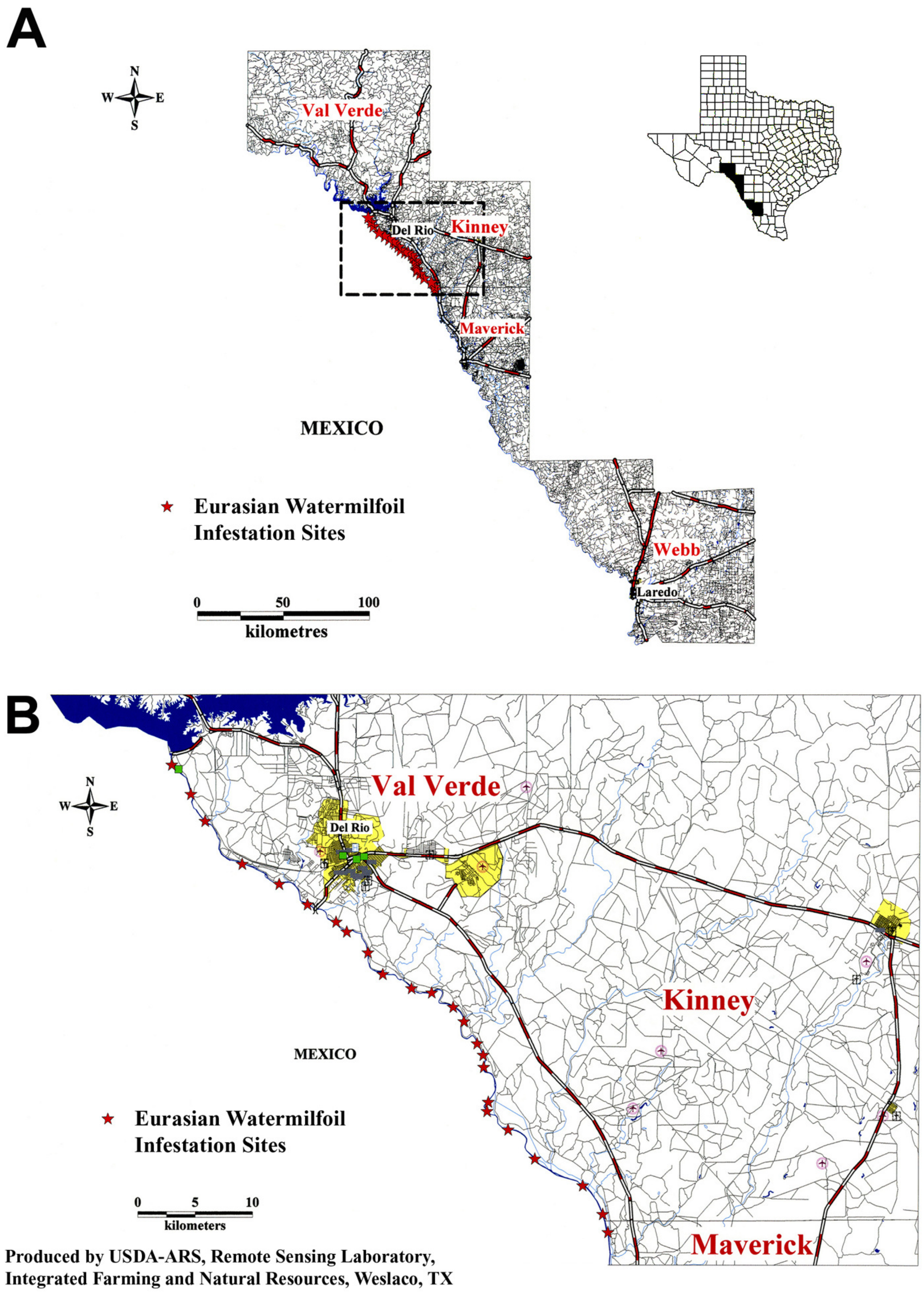


Fig. 8. Regional GIS map (A) of a four-county area in southwest Texas. The Rio Grande forms the western boundary of the map with Mexico. The symbols on the Rio Grande represent GPS latitude-longitude coordinates of Eurasian watermilfoil infestations obtained from the airborne video imagery. A detailed GIS map (B) of the locations where Eurasian watermilfoil occurred. This map corresponds to the area in the enclosed box in Figure 7A.

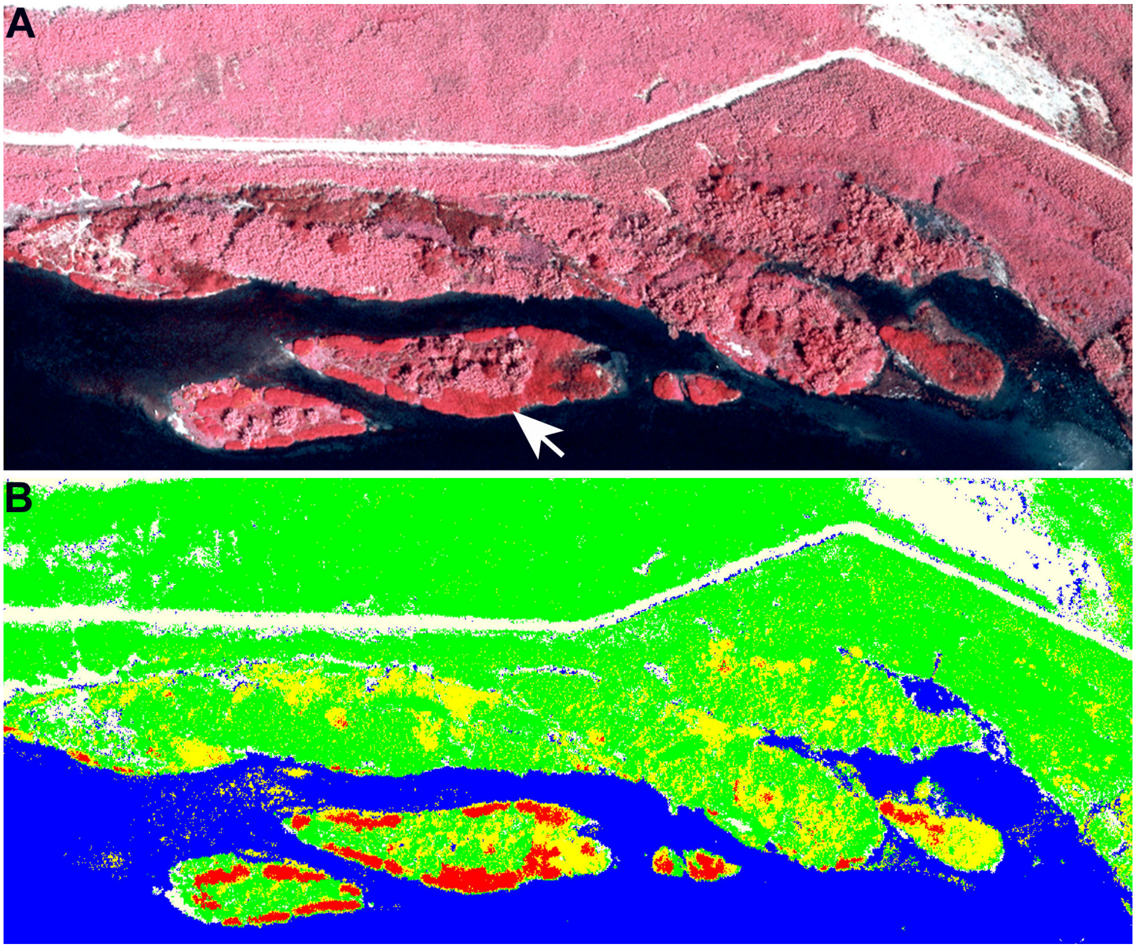


Fig. 9. Color-infrared aerial photographic image (A) obtained June 15, 2006 on the Rio Grande near Del Rio, Texas. The arrow on print A points to the bright red color of wild taro. Supervised classification (B) of the photograph. Color codes for the map classes are: red, wild taro; green, giant reed; yellow, mixed woody vegetation; white, soil; and blue, water.

Table1. An error matrix for the supervised classification generated from the classification data and ground data for the color-infrared photograph of the site 1 wild taro study area on the Rio Grande near Del Rio, Texas.

Classified Category	Actual Category					Total	User's Accuracy
	Soil	Giant reed	Wild taro	Woody	Water		
Soil	12	3	0	0	0	15	80.0%
Giant reed	0	35	0	0	1	36	97.2%
Wild taro	0	0	10	0	0	10	100%
Woody[1]	0	0	0	14	0	14	100%
Water	0	1	0	1	23	25	92.0%
Total	12	39	10	15	24	100	
Producer's Accuracy	100%	89.7%	100%	93.3%	95.8%		

Overall classification accuracy = 94.0%. Overall kappa = 0.920.
[1]Woody = mixed woody vegetation.

from two additional CIR photographs of wild taro had producer's and user's accuracies ranging from 83.3% to 100%. We did not compute the number river-km of wild taro populations along the Rio Grande, but it occurred in the same approximate area as the Eurasian watermilfoil infestations from below Amistad Reservoir to north of Eagle Pass. It appears to be well established along this portion of the Rio Grande (Owens et al. 2005).

CONCLUSIONS

Results from these studies have shown that airborne remote sensing, GPS, and GIS technologies are valuable tools for detecting and mapping exotic, invasive weeds in/along the Rio Grande system of Texas. Our findings indicated that approximately 1,285 river-km of the Rio Grande was plagued by infestations of waterhyacinth, hydrilla, saltcedar, giant reed, Eurasian watermilfoil, and wild taro. The aquatic species waterhyacinth and hydrilla infested approximately 225 river-km in the extreme southern portion of the Lower Rio Grande Valley of Texas. The wetland species saltcedar infested approximately 460 river-km from Lajitatas to near El Paso in west Texas. Giant reed infested approximately 600 river-km along the Rio Grande from near Laredo in south Texas to near Presidio in west Texas. Eurasian watermilfoil occurred along a 66 river-km area from below Amistad Reservoir near Del Rio to north of Eagle Pass in southwest Texas. This area was not included in the total river-km infestation because it occurred in the same general area infested by giant reed. We did not compute the number of river-km of wild taro along the Rio Grande, but it occurred in the same approximate area as Eurasian watermilfoil.

The integration of airborne videography with GIS technology can serve as a permanent geographically located image data base to monitor future contraction or spread of invasive weeds over time. The GIS database can be used to record attribute information for areas of interest. The joint use of these technologies provides important information on the distribution of invasive weeds in the Rio Grande system along the Texas-Mexico border. It is anticipated that these technologies can be used for a variety of other natural resource management applications.

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