Invasive Plant Science and Management 2011 4:402–410

Mapping Giant Reed (*Arundo donax*) Infestations along the Texas–Mexico Portion of the Rio Grande with Aerial Photography

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Giant reed is an invasive weed throughout the southern half of the United States, with the densest stands growing along the coastal rivers of southern California and the Rio Grande in Texas. The objective of this study was to use aerial photography to map giant reed infestations and to estimate infested areas along the Texas–Mexico portion of the Rio Grande. Aerial color-infrared photographs were taken along the Rio Grande between Brownsville and El Paso, TX, in June and July 2002. Based on the aerial photographs and ground surveys, the portion of the river from San Ygnacio to Lajitas, which has a river length of 898 km (558 mi), was found to be infested with giant reed. To estimate infested areas along both sides of the river, 65 (13.5%) of the 480 aerial photographs taken between Lajitas and San Ygnacio were randomly selected. The aerial photographs were digitized, rectified to Google Earth imagery, and then classified using maximum-likelihood classification techniques. The infested areas on both sides of the river, as well as water area and river length, from each photographic image were determined. Based on the estimates from the 65 aerial photos, the ratio of giant reed area to water area and the ratio of giant reed area to river length were calculated. The total giant reed area along the Rio Grande between Lajitas and San Ygnacio was estimated to be 5,981 ha (14,779 ac) with 3,714 ha or 62% on the U.S. side and 2,267 ha or 38% on the Mexican side. This study provides the first accurate estimates of giant reed infestations along the Texas–Mexico portion of the Rio Grande and will be useful for both land owners and government agencies for the estimation of water usage and economic loss and for the management and control of giant reed.

Nomenclature: Giant reed; *Arundo donax* L.

Key words: Invasive weed, area estimation, image classification, maximum likelihood classifier.

Giant reed (*Arundo donax* L.) is a nonindigenous, perennial grass that has become an invasive weed in many tropical, subtropical, and warm-temperate regions of the world (Dudley 2000). It was intentionally introduced to California from the Mediterranean for erosion control and for use in thatching and basket weaving, but giant reed has gradually naturalized throughout the southern half of the United States from Maryland to California (Bell 1997). Today, the densest stands are found along coastal rivers of southern California (Bell 1997; Dudley and Collins 1995) and along the Texas–Mexico portion of the Rio Grande (Everitt et al. 2004; Tracy and Deloach 1999).

DOI: 10.1614/IPSM-D-10-00081.1

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Giant reed is a robust, bamboo-like plant that can grow up to 10 m (32.8 ft) tall. It consumes much more water than native vegetation to supply its incredible rate of growth (Iverson 1994). During warm months with ample water, giant reed culms are reported to attain a growth rate of 0.7 m wk^{-1} and can produce more than 20 t ha^{-1} aboveground dry mass (Perdue 1958). Giant reed is a relentless threat to riparian areas and watersheds in affected states of the United States. It spreads by either rhizomes or plant fragments and can displace native vegetation, leading to the destruction of wildlife habitats (Khudamrongsawat et al. 2004; Kisner 2004). The presence of giant reed in streambeds and along stream banks affects the stream hydrology and stream morphology by retaining sediments and channeling flows (Oakins 2001). Giant reed reduces riparian arthropod diversity and abundance in riparian ecosystems where this invasive species has become a dominant component (Herrera and Dudley 2003). The

Interpretive Summary

Giant reed is an invasive weed throughout the southern half of the United States, with the densest stands growing along the coastal rivers of southern California and the Rio Grande in Texas. One of the most important steps for successful management of giant reed is to map its spatial distribution and determine infested areas. Because of the great expanse and inaccessibility of these areas, remote sensing provides a useful tool for mapping the spatial extent of giant reed infestations and for distinguishing it from associated plant species. This study provides the first accurate estimates of giant reed infestations along the Texas–Mexico portion of the Rio Grande based on 2002 aerial photography. The total giant reed area along the Rio Grande between Lajitas and San Ygnacio, TX, was estimated to be 5,981 ha with 3,714 ha (62%) on the U.S. side and 2,267 (38%) on the Mexican side. Furthermore, the United States and Mexico each had about 50% of the giant reed along the portion of the river between Lajitas and Del Rio, TX, whereas the United States had two-thirds of the giant reed on the portion of the river between Del Rio and San Ygnacio, TX. The results from this study will be useful for both land owners and government agencies for the management and control of this invasive weed along the Rio Grande in both the United States and Mexico. These results and the aerial photographs are currently being used for the planning and release of biological agents for the control of giant reed along the river and for the estimation of water usage and economic loss. Moreover, this study is an important first step toward the complete documentation of giant reed infestations along the river and for the long-term control and management of giant reed in the entire Rio Grande basin.

stems and leaves contain several toxic or unpalatable chemicals that probably protect it from most native insects and other grazers (Newhouser et al. 1999). Giant reed, which is commonly referred to as Carrizo cane in Texas, is also a major impediment to border patrol operations of the U.S. Department of Homeland Security's Customs and Border Protection along the international border between Laredo and Del Rio, TX, overrunning border access roads, reducing visibility, and providing dense cover for illegal activities (Cleere 2007). Homeland Security Department officials have called for an immediate operational plan to control Carrizo cane.

The key to effective control of established giant reed is to kill its root system. Mechanical removal with heavy machinery has been ineffective because the rhizome fragments buried under the soil will resprout, and prescribed burning has not been successful because it does not affect the rhizomes (Dudley 2000). Chemical treatment with systemic herbicides may require continued application for several years and has the side effects of spraying surrounding vegetation and water (Newhouser et al. 1999). Typically, a mechanical cut followed by herbicide application is used for better control. Nevertheless, these approaches have not been very successful and infestations of giant reed continue to expand. Biological control is another control strategy for long-term management of invasive weeds (Culliney 2005). Giant reed is an excellent candidate for biological control because there are several specialist insects from the native range in Europe, and giant reed has no close relative in North or South America (Tracy and Deloach 1988). A biological control program was initiated for giant reed at the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS) Research Center at Weslaco, TX, a few years ago, and four agents have been introduced from Europe for evaluation in quarantine (Goolsby et al. 2007). One of the agents, the eurytomid wasp (*Tetramesa romana* Walker), was evaluated and found to be specific to giant reed and unlikely to harm native or cultivated plants in the Americas (Goolsby and Moran 2009). This wasp was released in a section along the Rio Grande in Laredo, TX in 2009, and other agents are still under evaluation and hopefully will be released in the near future for the biological control of giant reed throughout the Rio Grande basin.

The first important step for successful management of giant reed is to map its spatial distribution and determine infested areas. Because of the great expanse and inaccessibility of these areas, remote sensing provides a useful tool and has the potential for mapping the spatial extent of giant reed infestations and for distinguishing it from associated plant species. Oakins (2001) evaluated color-infrared (CIR) aerial photography for mapping giant reed along the Salinas River near Gonzales, California, and the results showed that giant reed can be differentiated from other riparian vegetation classes, such as willow (*Salix* spp.) and cottonwood (*Populus* spp.). DiPietro et al. (2002) used an Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) hyperspectral imagery for detecting and mapping giant reed in riparian areas in southern California. 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 in riparian areas in Texas. More recently, Everitt et al. (2005, 2008) evaluated both 2.8-m QuickBird and 10-m SPOT 5 satellite imagery for distinguishing giant reed infestations along the Rio Grande in southwest Texas. Their results showed that high-resolution satellite imagery could be used to detect and map giant reed infestations along the river. Yang et al. (2009) used 40 QuickBird images acquired between 2002 and 2007 from the Mexican portion of the Rio Grande basin to estimate giant reed–infested areas, and an estimated 4,775 ha of giant reed existed along the major tributaries in the Mexican portion of the basin.

The Rio Grande basin lies within three U.S. states and five Mexican states. The Rio Grande is the source of life for more than 13 million people and its ecosystems. The basin as a whole is arid or semiarid with limited water resources and many threatened and endangered plants and animals. The rapid spread of invasive weeds, such as giant reed and

https://doi.org/10.1614/IPSM-D-10-00081.1 Published online by Cambridge University Press

saltcedar (*Tamarix* spp.), is threatening to worsen the water shortage and degrade the ecosystem in the basin. Therefore, it is very important to map the distribution of giant reed and quantify its infested areas in the basin. Yang et al. (2009) mapped the distribution of the giant reed and quantified its infested areas in the Mexican portion of the basin. Everitt et al. (2004) mapped the distribution of giant reed along the Rio Grande in Texas, but total infested areas along the river have not been determined. Because of the severity of the problems caused by giant reed, the area estimation was urgently needed by governmental authorities and shareholders in the United States and Mexico. This information was also necessary to gain approval for release of biological control agents and allows estimates of water use, economic loss, and control and management of this invasive weed. The research findings from the few remote-sensing studies of giant reed in California and Texas have demonstrated that aerial photography, videography, hyperspectral imagery, and high-resolution satellite imagery can all be used for detecting and mapping giant reed infestations. Aerial photography is relatively inexpensive and provides finer spatial resolution than airborne and satellite digital imagery. The objective of this study was to use aerial CIR photography to estimate giant reed–infested areas along the Texas–Mexico portion of the Rio Grande.

Materials and Methods

Study Area. The Rio Grande is one of the longest rivers of North America. It flows from its sources in southwestern Colorado to the Gulf of Mexico and serves as a natural boundary along the border between Texas and Mexico. The length of the whole Rio Grande is 3,033 km (1,885 mi), and the segment of the river that forms the border has a length of 2,018 km. This study was conducted along the Texas–Mexico portion of the Rio Grande between El Paso and Brownsville, Texas.

Acquisition of Aerial Photography. Aerial CIR photography was chosen as the remote-sensing data for this study. A large-format, 23-cm (9 in) photographic camera[1] was used for the acquisition of aerial photography. The CIR film[2] used was sensitive in the green (500 to 600 nm), red (600 to 700 nm), and near-infrared (NIR; 700 to 900 nm) wave bands. Aerial CIR photographs were acquired of the Rio Grande from Brownsville to El Paso, TX, in June and July 2002. A Cessna 404 twin-engine aircraft,[3] with multiple camera ports in the floor, was used as the platform, and all photographs were taken at altitudes of 3,050 to 3,350 m (10,000 to 11,000 ft) aboveground between 10:30 A.M. and 2:00 P.M. Central Standard Time under sunny conditions. Each film frame covered a square area with a side of 2.3 to 2.5 km, and there was an overlap of 20 to 30% between successive frames.

Based on CIR video imagery, acquired simultaneously with the aerial photography, and the global positioning system (GPS) coordinates superimposed at the bottom of the video imagery, Everitt et al. (2004) developed a geographic information system (GIS) map showing the distribution and density of giant reed infestations along the Rio Grande in Texas. They found that giant reed existed along a stretch of the river between Lajitas and San Ygnacio and that little giant reed existed outside that portion of the river. They also assigned levels of giant reed to each scene based on the approximate width of the stands growing in corridors using the following criteria: $>$ 120 m wide, dense; 60 to 120 m wide, moderate; and $<$ 60 m wide, light. Dense populations of giant reed were located below Del Rio, TX, with the densest populations between Del Rio and Eagle Pass in Kinney and Maverick counties of Texas, whereas light populations existed above Del Rio, TX. Ground surveys confirmed the presence of giant reed at all the plotted locations on the map. More than 480 aerial photographs were taken between Lajitas and San Ygnacio, TX.

Image Processing and Analysis. Considering the time and cost for image processing and classification, 65 aerial photos were randomly selected for area estimation with 35 (54%) between Lajitas and Del Rio, TX, and 30 (46%) between Del Rio and San Ygnacio, TX. If two consecutive photos were selected, one of them was removed to avoid overlap. Figure 1 shows the center locations of the 65 aerial photos selected. These CIR photographic transparencies were scanned at 400 dots in^{-1} (dpi) using a scanner.[4] The equivalent ground–pixel size was approximately 0.65 m.

Figure 1. A map showing the center locations of 65 aerial photographs (blue circles) selected for giant reed area estimation between Lajitas and San Ygnacio, TX, along the Texas–Mexico portion of the Rio Grande. The solid yellow circle between Del Rio and San Ygnacio, TX, depicts the location of the photograph shown in Figure 2.

The digitized CIR photographic images consisted of three spectral bands (NIR, red, and green), and the pixels in each band had a spectral digital count value ranging from 0 to 255.

Because of the difficult accessibility for most of the imaging areas, it was not practical to collect GPS points on the ground to rectify or georeference each aerial photo. Therefore, Google Earth imagery[5] was chosen for georeferencing the digitized photos. To determine the positional accuracy of Google Earth imagery, three aerial photos were rectified to their corresponding Google Earth images and to the ground control points (GCPs) collected from the three sites with a submeter-accuracy GPS receiver.[6] Comparison results showed that Google Earth imagery was acceptable for rectifying the aerial photos (see "Results and Discussion"). The 65 digitized aerial photos were then rectified to the Universal Transverse Mercator (UTM) coordinate system (zones 13 and 14) based on 10 to 15 points extracted from Google Earth imagery. The ERDAS IMAGINE software[7] was used for image rectification.

Image Classification and Area Determination. Previous studies indicated that giant reed could be accurately distinguished from the associated vegetation species and other cover types using either unsupervised or supervised classification techniques (Everitt et al. 2004, 2008; Oakins 2001). In this study, giant reed was the main cover type to be identified, and its spectral appearance and ground information were generally known on the image. Therefore, supervised classification was chosen for image classification. ERDAS IMAGINE software provided several parametric classifiers, including minimum distance, Mahalanobis distance, and maximum likelihood (Lillesand et al. 2004; Richards 1999; Schrader and Pouncey 2002). Yang et al. (2009) compared the three classifiers to classify QuickBird imagery along the Rio Grande for identifying giant reed. Their results indicate that, although all three classifiers provided excellent classification results, the maximum-likelihood classifier produced the highest overall accuracy and individual-class accuracy values. The producer's accuracy and user's accuracy for giant reed were 94 to 100% based on the maximum classifier.

An aerial photograph (29°16′57″N, 100°51′58″W) taken along the Rio Grande near Del Rio, TX, on June 25, 2002, was used to compare the differences in classification results among the three classifiers for this study. This photo was classified using unsupervised classification in a previous study (Everitt et al. 2004). The classes in the study sites consisted of giant reed, mixed brush, mixed herbaceous vegetation, bare soil, and water. Because of the spatial variation within each class, each class was further divided into two to three subclasses for supervised classification. Different numbers of areas were visually selected from each subclass to extract training samples. Because of the distinct spectral response of giant reed, it could be easily identified in the image based on our knowledge of the weed. As for the other two vegetation classes, no attempt was made to identify the specific species on the image, but the training pixels for each subclass were selected based on the color tones of those species in the CIR image. Before the classification, all signatures calculated from the training samples were evaluated. The image was then classified into the five classes using the three classifiers.

For accuracy assessment of these three classification maps, the same 100 ground-verified points used for accuracy assessment of the unsupervised classification map in our previous study were used. Error matrices for each classification map were generated by comparing the classified classes with the actual classes at those points. Overall accuracy, producer's accuracy, user's accuracy, and κ coefficients were calculated based on the error matrices, and κ analysis was also performed to test whether each classification was significantly better than a random classification and whether any two classifications were significantly different (Congalton and Green 1999).

Accuracy assessment of the three classification maps showed that maximum likelihood performed better than the other two classifiers (see "Results and Discussion"). Therefore, all 65 aerial photographic images were classified using the maximum-likelihood classifier. Because each photographic image covered extra areas, where no giant reed existed, an area of interest (AOI) was defined for each image to eliminate those areas outside the AOI during image classification. Based on our previous studies on the use of aerial photography and high-resolution satellite imagery for mapping giant reed (Everitt et al. 2004, 2005; Yang et al. 2009), giant reed can be accurately identified from associated species and cover types in the Rio Grande basin with about 90% accuracy. Therefore, it was not necessary to perform the same accuracy assessment procedures for each of the 65 images classified in this study. Nevertheless, care was taken to ensure giant reed was correctly identified by visually comparing each classification map with its original CIR photographic image. In addition, ground verifications were made for areas that could be confused with other vegetation. Giant reed area and water area were estimated from each classification map and the ratio of giant reed area to water area was then calculated. The river length, which is the curved length of the river on each image, was also determined from each classification map, and the ratio of giant reed area to river length was calculated. To determine the giant reed areas on the U.S. and Mexican sides of the river, a new AOL was defined to include only the U.S. side of each classification map. The giant reed area on the U.S. side was first determined, and the giant reed area on the Mexican side

Table 1. Comparison on positional accuracy between Google Earth imagery and GPS points for rectifying three aerial photos taken along the Texas–Mexico portion of the Rio Grande.[a]

Site	Image center coordinates	No. of points	Positional shift relative to GPS points			RMS errors for Google Earth–rectified images			RMS error for GPS-rectified images		
			x	y	Total	x	y	Total	x	y	Total
			m								
1	27°42′11″N, 99°44′32″W	12	−11.2[b]	−6.5	12.9	1.0	0.8	1.3	0.8	1.0	1.3
2	28°22′51″N, 100°44′32″W	14	−12.7	0.0	12.7	5.5	2.3	6.0	1.3	2.0	2.4
3	29°10′13″N, 100°45′57″W	12	14.3	−3.1	14.7	0.8	0.8	1.1	0.9	0.7	1.2

[a] Abbreviation: RMS, root mean square.

[b] Negative number means that the Google Earth coordinate is smaller than GPS coordinate.

was calculated by subtracting the area on the U.S. side from the total giant reed area on the classification map. The total giant reed area was estimated by the river length times the mean ratio of giant reed area to river length.

Results and Discussion

Table 1 summarizes positional differences for the selected GCPs between the Google Earth images and the GPS points for the three sites. The root mean square (RMS) errors for rectifying the three photos based on the two different reference data sources are also shown in Table 1. Relative to the GPS points, the points extracted from the Google Earth images were 11.2 m to the west, and 6.5 m to the south for site 1; 12.7 m to the west, and the same in the y-direction for site 2; and 14.3 m to the east, and 3.1 m to the south. The total shift was about 13 to 15 m for the three sites. The RMS errors for sites 1 and 3 were very low (1.1 to 1.3 m total) for both reference data sources, indicating that the Google Earth images on the two sites had very little distortion even though there were some offsets (13 to 15 m total) relative to their true positions. The total RMS error for site 2 was 6.0 m, based on the Google Earth image, and 2.4 m based on the GPS points. The relatively higher error for the image rectified with GPS points was partially because of the distortion of the aerial photo because the photo may have not been taken at a perfect nadir position. However, the much higher RMS error for the image rectified with Google Earth points was due to the GCPs being extracted from two Google Earth images that were mosaicked. Generally, geographic coordinates extracted from the transitional areas, where multiple images were pieced together, have higher positional errors. Nevertheless, these errors were acceptable for area estimation considering the extent of the area involved in this study.

Table 2 summarizes the accuracy assessment results for the classification maps based on the three classification methods for the aerial photographic image near Del Rio, TX. Overall, accuracy was 82% for minimum distance, 85% for Mahalanobis distance, and 86% for maximum likelihood. The κ pairwise analysis showed that there were

Table 2. Accuracy assessment results for classification maps generated from an aerial photographic image using three classifiers for a giant reed–infested area along the Texas–Mexico portion of the Rio Grande.[a]

Classifier	Overall accuracy	Overall κ	Giant reed		Mixed brush		Mixed herbaceous		Bare soil		Water	
			Producer's accuracy (PA) and user's accuracy (UA)									
			PA	UA	PA	UA	PA	UA	PA	UA	PA	UA
	%		%									
MD	82.0	0.766	83.3	100.0	90.9	100.0	76.9	62.5	75.0	77.8	100.0	100.0
MAHD	85.0	0.805	87.50	100.0	90.9	90.9	84.6	68.8	78.6	84.6	90.9	100.0
ML	86.0	0.818	91.7	95.7	90.9	90.9	84.6	73.3	78.6	84.6	90.9	100.0

[a] Abbreviations: MD, minimum distance; MAHD, Mahalanobis distance; ML, maximum likelihood.

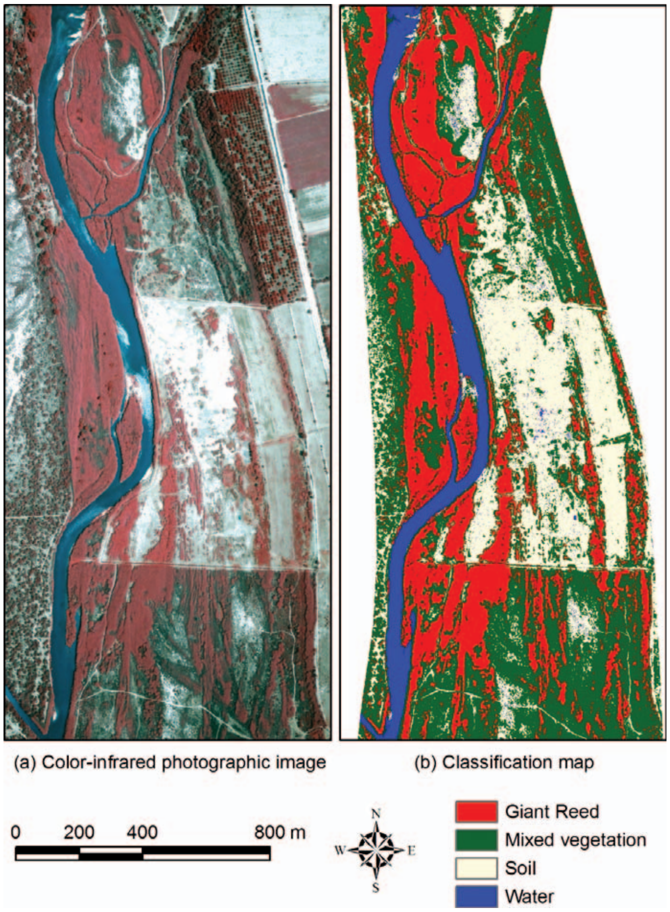

Figure 2. (a) A color-infrared photographic image, and (b) a four-class classification map for a giant reed–infested site (28°59′21″N, 100°°38′53″W) along the Rio Grande as shown by the solid yellow circle in Figure 1. The United States is on the east side of the river.

no significant differences among the three classifiers for the overall classifications. However, maximum likelihood provided more reasonable producer's and user's accuracy values for giant reed. For example, the maximum-likelihood classifier resulted in a producer's accuracy of 92% and a user's accuracy of 96% for giant reed, compared with a producer's accuracy of 83% and a user's accuracy of 100% for giant reed from the minimum-distance classifier, and a producer's accuracy of 87.5% and a user's accuracy of 100% for giant reed from the Mahalanobis-distance classifier. These results indicate that 92% of the giant reed area on the ground was correctly identified as giant reed on the maximum-likelihood–based classification map, whereas 96% of the area called giant reed on the classification map was actually giant reed. In contrast, although 100% of the areas called giant reed on the minimum-distance–based classification map were actually giant reed, only 83% of the giant reed areas on the ground were correctly identified as giant reed on the map, indicating that 17% of the giant reed on the ground was not identified on the map. All three classifiers provided excellent classification results for the mixed brush and water classes. However, the producer's and user's accuracy values were generally lower for the mixed-herbaceous and bare-soil classes because of confusion between the two classes.

Because the focus of this study was to estimate the giant reed area along with the water area in each image, the other three classes (mixed brush, mixed-herbaceous vegetation, and soil) were merged as one single class, so that each classification map had three classes (giant reed, water, and mixed cover). As expected, the overall accuracy increased to 96% for maximum likelihood, although the producer's and user's accuracy remained the same for both giant reed and water. It should be noted that these results are based on one photographic images, and results may vary for different photographic images. Nevertheless, our previous studies have showed that maximum likelihood is a reliable and accurate classifier for mapping giant reed in the Rio Grande basin (Everitt et al. 2005; Yang et al. 2009). Therefore, all 65 aerial photographic images were classified using maximum likelihood into the five major classes, which were then optionally merged into three classes (giant reed, water, and mixed cover) or four classes (giant reed, water, mixed vegetation, and soil).

Figure 2 shows an aerial CIR photographic image and a four-class classification map based on maximum likelihood for a site near Quemado, TX. The CIR image reveals diverse cover types within the scene. On the CIR image, giant reed shows a bright reddish tone, whereas mixed woody species have a dark reddish color. Mixed herbaceous species have a greenish tone because of the dry ground conditions. Water is dark blue, and bare soil has a bright white to grayish color. A visual comparison of the four-class classification map with the CIR image indicates that giant reed and the other cover types within the image were well separated on the classification map.

Giant reed has unique spectral characteristics that distinguish it from associated plant species. Field spectral measurements taken in July indicate that giant reed has higher green and NIR reflectance than do associated woody and herbaceous species (Everitt et al. 2004). Therefore, giant reed can be accurately separated from other vegetation species. However, some agricultural crops, grass species, and woody species can cause confusion with giant reed at certain times of the year. Generally, most of these vegetation areas can be eliminated from the image with the definition of areas of interest before image classification. However, if species with similar spectral response to giant reed were included in the portion of the image to be classified, more training pixels were selected from the species to distinguish them from giant reed and minimize the confusion.

Table 3. Summary of estimates of giant reed area, water area, and river length determined from 35 aerial photos between Lajitas and Del Rio, TX, and 30 aerial photos between Del Rio and San Ygnacio, TX, along the Texas–Mexico portion of the Rio Grande.

Statistics	Giant reed area: Both sides	Giant reed area: U.S. side	Giant reed area: Mexican side	Water area	River length
	ha	ha	ha	ha	km
From Lajitas to Del Rio, TX					
Minimum	0.0	0.0	0.0	4.6	2.3
Maximum	35.3	20.1	22.6	55.0	6.0
Mean[a]	15.5 ± 3.2	7.7 ± 1.9	7.8 ± 1.9	16.6 ± 3.3	3.7 ± 0.3
STD	9.4	5.5	5.5	9.6	0.8
SUM	542.5	270.1	272.4	581.4	128.7
From Del Rio to San Ygnacio, TX					
Minimum	6.8	2.1	2.3	14.2	2.4
Maximum	74.5	53.9	28.0	43.0	5.8
Mean[a]	29.3 ± 7.3	19.7 ± 5.5	9.6 ± 2.5	22.9 ± 2.5	3.1 ± 0.3
STD	19.5	14.7	6.8	6.6	0.7
Sum	879.7	591.9	287.8	687.4	92.0

[a] 95% confidence interval.

Table 3 shows the simple statistics for the estimates of total giant reed area on both sides of the river, the area on the U.S. side, the area on the Mexican side, water area, and river length determined from the 35 aerial photographic images between Lajitas and Del Rio, TX, and from the 30 aerial photographic images between Del Rio and San Ygnacio, TX, along the Rio Grande. The mean giant reed–infested area was 15.5 ha (38.3 ac) for the 35 images between Lajitas and Del Rio and 29.3 ha for the 30 images between Del Rio and San Ygnacio.

Table 4 gives the statistics for the estimates of the ratio of giant reed area to river length and the ratio of giant reed area to water area determined from the photographic images for the two segments of the river. The mean giant reed area to water area ratio was 1.07 ha ha^{-1} between Lajitas and Del Rio, TX, and 1.37 ha ha^{-1} between Del Rio and San Ygnacio, TX, indicating there were 1.07 ha and 1.37 ha of giant reed for every hectare of water area for the respective river segment. The ratio of mean giant reed area to river length was 4.05 ha km^{-1} (16.10 ac mi^{-1})

Table 4. Summary of estimates of the ratio of giant reed area to river length and to water area determined from 35 aerial photos between Lajitas and Del Rio, TX, and 30 aerial photos between Del Rio and San Ygnacio, TX, along the Texas–Mexico portion of the Rio Grande.

Statistics	Ratio of giant reed to river length: Both sides	Ratio of giant reed to river length: U.S.side	Ratio of giant reed to river length: Mexican side	Ratio of giant reed to water
	ha km^{-1}	ha km^{-1}	ha km^{-1}	ha ha^{-1}
From Lajitas to Del Rio, TX				
Minimum	0.00	0.00	0.00	0.00
Maximum	9.37	6.01	4.99	3.20
Mean[a]	4.05 ± 0.77	2.03 ± 0.51	2.02 ± 0.42	1.07 ± 0.25
STD	2.25	1.48	1.21	0.74
From Del Rio to San Ygnacio, TX				
Minimum	2.04	0.83	0.64	0.29
Maximum	27.54	20.41	7.61	4.72
Mean[a]	9.74 ± 2.53	6.62 ± 1.99	3.12 ± 0.73	1.37 ± 0.40
STD	6.78	5.33	1.96	1.07

[a] 95% confidence interval.

Table 5. Giant reed area estimates based on the ratio of giant reed to river length and the river length between Lajitas and Del Rio, TX, and those between Del Rio and San Ygnacio, TX, along the Texas–Mexico portion of the Rio Grande.

River segment	River length	Estimated giant reed area			Giant reed percentage	
		Total[a]	U.S. side	Mexican side	U.S. side	Mexican side
	km	ha			%	
Lajitas to Del Rio	486	1,967 ± 375	987 ± 247	980 ± 202	50.2	49.8
Del Rio to San Ygnacio	412	4,014 ± 1,043	2,727 ± 820	1,287 ± 301	67.9	32.1
Total	898	5,981 ± 1,019	3,714 ± 783	2,267 ± 345	62.1	37.9

[a] 95% confidence interval.

between Lajitas and Del Rio, TX, and 9.74 ha km^{-1} between Del Rio and San Ygnacio, TX, indicating there were 4.05 ha and 9.74 ha of giant reed for each river kilometer for the respective river segment. Clearly, there was more giant reed on the portion of the river east of Del Rio, TX, than on the portion of the river west of Del Rio, TX. The significantly lower giant reed area on the western portion of the river from Del Rio, TX, is mainly due to that portion of the river being surrounded by mountains with a limited floodplain in which giant reed can grow.

Table 5 gives the total giant reed areas for both sides of the river and for either side of the river, estimated from the river length and the ratio of giant reed area to river length as well as the percentages of giant reed area, calculated from the mean areas. The total giant reed area on both sides of the river was estimated to be 1,967 ha along the Rio Grande between Lajitas and Del Rio, TX, and 4,014 ha between Del Rio and San Ygnacio, TX. The total giant reed area along the Rio Grande between Lajitas and San Ygnacio, TX, was estimated to be 5,981 ha, with 3,714 ha or 62% on the U.S. side and 2,267 ha or 38% on the Mexican side. The United States and Mexico each had about 50% of the giant reed distribution on the portion of the river west of Del Rio, TX. However, the U.S. had 68% or two-thirds of the giant reed, whereas Mexico had only 32% or one-third of the giant reed on the portion of the river between Del Rio and San Ygnacio, TX. Although the exact cause of the greater invasiveness on the U.S. side is unknown for the eastern portion of the river, grazing animals are known to affect riparian vegetation and may also have an effect on giant reed populations (Belsky et al. 1999; Jansen and Robertson 2001). Cattle, goats, and sheep are common grazing animals in the riparian habitats. During drought conditions, grazing animals are known to feed on the new shoots of giant reed. Some ranchers along the Rio Grande burn back giant reed each year, and this practice stimulates new growth for grazing. The USDA Animal and Plant Health Inspection Service "Tick Fence," along portions of the Rio Grande from Brownsville to El Paso, TX, was constructed to prevent animal movement in the United States to restrict the spread of cattle fever ticks (*Rhipicephalus microplus* and *Rhipicephalus annulatus*). There are no data regarding the effect of grazing on giant reed, but ranchers and landholders in the Rio Grande basin frequently state that grazing limits giant reed growth. Giant reed infestations appear to be denser in the absence of grazing. Differences in grazing practices between the United States and Mexico may partially contribute to the difference in giant reed invasiveness on both sides of the river.

In summary, this study provides the first accurate estimates, to our knowledge, of giant reed infestations along the Texas–Mexico portion of the Rio Grande based on 2002 aerial photography. The total giant reed area along the Rio Grande between Lajitas and San Ygnacio, TX, was estimated to be 5,981 ha, with 3,714 ha or 62% on the U.S. side and 2,267 or 38% on the Mexican side. Furthermore, the United States and Mexico each had about 50% of the giant reed along the portion of the river between Lajitas and Del Rio, TX, whereas the United States had two-thirds of the giant reed on the portion of the river between Del Rio and San Ygnacio, TX. In our previous study, an estimated 4,775 ha of giant reed existed along the major tributaries in the Mexican portion of the Rio Grande basin. Clearly, more giant reed existed along the Rio Grande than existed in the Mexican portion of the basin.

The results from this study will be useful for both land owners and government agencies for managing and controlling this invasive weed along the Rio Grande in both the United States and Mexico. These results and the aerial photographs are currently being used for the planning and release of the eurytomid wasp for the biological control of giant reed along the river. Moreover, this study is an important first step toward the complete documentation of giant reed infestations along the river and for the long-term control and management of giant reed in the entire Rio Grande basin. Although it is important to know the total areas of giant reed on both sides of the river, the eventual goal is to develop a GIS database to document the giant reed distribution and to monitor its progression for every kilometer of river between Lajitas and San Ygnacio, TX. The 2002 aerial photography provides an initial baseline for monitoring the change of this invasive weed in the future. Work is underway to acquire new multispectral and hyperspectral digital imagery to document the changes and to develop the database.

Sources of Materials

[1] Type K-37 photographic camera, Fairchild Imaging, 1801 McCarthy Boulevard, Milpitas, CA 95035.

[2] Aerochrome CIR Type 1443 film, Eastman Kodak Company, 343 State Street, Rochester, NY 14650.

[3] Cessna 404 twin-engine aircraft, Cessna Aircraft Company, One Cessna Blvd., Wichita, KS 67215.

[4] Expression 10000XL scanner, Epson America, Inc., 3840 Kilroy Airport Way, Long Beach, CA 90806.

[5] GPS Pathfinder Pro XRS receiver, Trimble Navigation Limited, 935 Stewart Drive, Sunnyvale, CA 94085.

[6] Google Earth software, Google Inc., 1600 Amphitheatre Parkway, Mountain View, CA 94043.

[7] ERDAS IMAGINE, version 9.3, ERDAS, Inc., 5051 Peachtree Corners Circle, Suite 100, Norcross, GA 30092.

Acknowledgments

The authors thank Rene Davis and Fred Gomez (USDA-ARS, Weslaco, TX) for acquiring the aerial photographs, and Jim Forward and Isabel Cavazos (USDA-ARS, Weslaco, TX) for assistance in rectifying and classifying the photos.

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Received November 16, 2010, and approved July 22, 2011.