J. Aquat. Plant Manage. 49: 94-100

Evaluation of hyperspectral reflectance data for discriminating six aquatic weeds

JAMES H. EVERITT, CHENGHAI YANG, KENNETH R. SUMMY, LEEANN M. GLOMSKI, AND CHETTA S. OWENS*

ABSTRACT

In situ hyperspectral reflectance data were studied at 50 wavebands (10 nm bandwidth) in the 400 to 900 nm spectral range to determine their potential for discriminating among 6 aquatic weed species: curly-leaf pondweed (*Potamogeton crispus* L.), hydrilla (*Hydrilla verticillata* [L.F.] Royle), Eurasian watermilfoil (*Myriophyllum spicatum* L.), northern milfoil (*Myriophyllum sibiricum* Kom.), hybrid milfoil (*Myriophyllum spicatum* * *Myriophyllum sibiricum*), and parrotfeather (*Myriophyllum aquaticum* [J.M. da Conceicao] Vellozo). The species were studied on 3 dates: May 11, May 30, and July 1, 2009. All 6 species were studied on the 2 May dates, while only 4 species (hydrilla, Eurasian watermilfoil, hybrid milfoil, and parrotfeather) were studied on the July date. To determine the optimum bands for discriminating among the species, 2 procedures were used: multiple comparison range test and stepwise discriminant analysis. Multiple comparison range test results for both May dates showed that most separations among species occurred at bands in the green-red edge, red, and red–near-infrared (NIR) edge spectral regions. For the July date, the largest number of separations among species occurred at all green and most red bands, as well as some red-NIR edge and NIR bands. Using stepwise discriminant analysis, 9 bands for May 11 and 10 bands for May 30 in the blue to NIR spectral regions had the highest power of discrimination among the 6 species. For the July date, 7 bands in the red-NIR edge and NIR regions were useful for discriminating among the 4 species.

Key words: aquatic weeds, *Hydrilla verticillata*, hyperspectral reflectance, multiple comparison range test, *Myriophyllum aquaticum*, *Myriophyllum sibiricum*, *Myriophyllum spicatum*, *Myriophyllum spicatum x Myriophyllum sibiricum*, *Potamogeton crispus*, spectral signature, stepwise discriminant analysis.

INTRODUCTION

The invasion of aquatic ecosystems by noxious plant species presents a serious problem to management of these areas. The inaccessibility and often great expanses of many aquatic systems make ground inventory and assessment difficult, time consuming, expensive, and often inaccurate (Scarpace et al. 1981). Wetland resource managers need rapid techniques for management and assessment of aquatic ecosystems. Remote sensing techniques offer rapid acquisition of data with generally short turn-around time at lower costs than ground surveys (Tueller 1982, Everitt et al. 1992).

The value of remote sensing for wetland management is well established (Carter 1982, Tiner 1997). Multispectral airborne and satellite imagery have been used extensively to distinguish and map aquatic vegetation (Carter 1982, Martyn et al. 1986, Tiner 1997, Venugopal 1998, Jakubauskas et al. 2002, Everitt et al. 2008). Multispectral ground reflectance measurements have also been used to characterize and differentiate among wetland and aquatic plant species. Best et al. (1981) studied the multispectral reflectance of 10 wetland and emergent plant species and concluded that there were significantly different visible and near-infrared (NIR) spectra among the species. Everitt et al. (1999) reported that the 2 submersed species hydrilla (*Hydrilla verticillata* [L.F.] Royle) and water stargrass (*Heteranthera dubia* [Jacq.] MacM.) could be distinguished in the green (520 to 600 nm), red (630 to 690 nm), and NIR (750 to 900 nm) spectral bands. In another study, Everitt et al. (2000) showed that hydrilla could be separated from waterhyacinth (*Eichhornia crassipes* [Mart.] Solms) and American lotus (*Nelumbo lutea* [Willd.] Pers.) in the green, red, and NIR bands. More recently, Everitt et al. (2007) reported that Eurasian watermilfoil (*Myriophyllum spicatum* L.) could be differentiated from hydrilla in the green and red bands. Although these broadband systems and instrumentation have been widely used for wetland assessment, they are often constrained due to their coarse spatial and spectral resolution (Turner et al. 2003).

More recently, hyperspectral remote sensing including both imaging systems and ground-based radiometers, which can simultaneously acquire spectral data in many narrow contiguous spectral bands, has been used for a variety of natural resource management applications (Gong et al. 1997, Martin et al. 1998, Thenkabail et al. 2000, Fung et al. 2003, Ge et al. 2006, Yang et al. 2009). Hyperspectral ground reflectance measurements have been used to develop spectral signatures of aquatic and wetland plant species and to ultimately identify the optimum bands to separate plant species. Ullah et al. (2000) studied the hyperspectral reflectance of 3 emergent macrophytes and reported that the best separation among the species occurred at several bands in the NIR region (optimum bands: 882 and 885 nm). These researchers

*First and second authors: Rangeland Scientist and Agricultural Engineer, USDA-ARS, Integrated Farming and Natural Resources Research, 2413 E. Highway 83, Weslaco, TX 78596; third author: Associate Professor, Department of Biology, University of Texas-Pan American, Edinburg, TX 78539; fourth and fifth authors: Research Biologist and Ecologist, U.S. Army Engineer Research and Development Center, Lewisville Aquatic Ecosystem Research Facility, Lewisville, TX 75057. Corresponding author's E-mail: james.everitt@ars.usda.gov. Trade names are included for information purposes only and do not imply endorsement of or a preference for the product listed by the United States Department of Agriculture. Received for publication May 2, 2010 and in revised form February 20, 2011.

also reported that the 554, 557, and 565 nm green bands were useful for differentiating among the 3 species. Becker et al. (2005) evaluated hyperspectral reflectance measurements for identifying dominant botanical and substrate classes of Great Lakes coastal wetlands. They identified 8 optimum bands in the green (515 and 560 nm), red-NIR edge (686 and 732 nm), and NIR (812, 824, 836, and 940 nm) spectral regions for separation among the various classes.

Little information is available on using hyperspectral reflectance data for distinguishing among aquatic weeds. The objectives of this research were to use hyperspectral ground reflectance measurements to develop spectral signatures of 6 freshwater aquatic weeds in the 400 to 900 nm spectral range and to identify the optimum bands for discriminating among the species.

MATERIALS AND METHODS

The 6 aquatic weeds studied in this experiment included: curly-leaf pondweed (*Potamogeton crispus* L.), hydrilla, Eurasian watermilfoil, northern milfoil (*Myriophyllum sibiricum* Kom.), hybrid milfoil (*Myriophyllum spicatum* × *Myriophyllum sibiricum*), and parrotfeather (*Myriophyllum aquaticum* [J.M. da Conceicao] Vellozo). Curly-leaf pondweed, hydrilla, Eurasian watermilfoil, and parrotfeather are introduced weeds to the United States, while northern milfoil is native. It is debatable whether hybrid milfoil is introduced or native because half the genotype is nonnative. Moody and Les (2007) reported that hybrid milfoil was not introduced to the United States but first occurred in our lakes when Eurasian watermilfoil and northern milfoil crossed. All 6 species are widely distributed in the United States and can potentially occur together in the same waterway (USDA, NRCS 2007). Curly-leaf pondweed, hydrilla, Eurasian watermilfoil, northern milfoil, and hybrid milfoil are submersed species that form dense mats at the water surface. Parrotfeather is an emergent species that also forms dense mats at the surface of the water column, with the stems extending above the water.

This study was conducted at the US Army Engineer Research and Development Center, Lewisville Aquatic Ecosystem Research Facility (LAERF) in Lewisville, Texas. The plants studied in this experiment were propagated in 1100 L tanks filled with alum-treated Lake Lewisville water. Six 3.78 L pots filled with LAERF pond sediment were used as a medium for each of the species. The pond sediment was amended with 3 g L^{-1} Osmocote (16-8-12), and three 15 cm apical tips of each species were planted in each pot. Six pots of each species were placed in each of the 1100 L water-filled tanks. Eurasian watermilfoil, northern milfoil, hybrid milfoil, parrotfeather, and curly-leaf pondweed pots were placed in the tanks in early November 2008, whereas the hydrilla pots were placed in the tanks in mid-January 2009. Hydrilla plant material came from LAERF; curly-leaf pondweed came from Lake Austin, Texas; and parrotfeather from Mississippi State University, Starkville, Mississippi. Eurasian watermilfoil, northern milfoil, and hybrid milfoil came from Lake Minnetonka, Bush Lake, and White Bear Lake, Minnesota, respectively. The hybrid milfoil was confirmed genetically at Grand Valley State University, Allendale, Michigan.

By early May 2009, all 6 aquatic weeds had reached peak foliage development in the tanks and had formed mats at the water surface. Plant material from the 6 pots for each species in each tank spread out at the top of the water column and tended to interlock, essentially forming a single mat for each species. Spectral reflectance measurements of each species were measured *in situ* using a FieldSpec[4] dual VNIR spectroradiometer, sensitive in wavelengths from 350 to 1100 nm, and Viewspace Pro software (Analytical Spectral Devices, Inc., Boulder, CO). Each wavelength had a 0.5 nm bandwidth. The spectroradiometer was equipped with a target sensor designed to measure reflectance from ground features. For calibration, a remote cosine receptor was used to measure incident radiation. Reference measurements were taken on a spectralon plate at the time of measurements and converted to percent reflectance. Plants were measured on 3 dates: May 11, May 30, and July 1, 2009. All 6 species were measured on the 2 May dates, but because curly-leaf pondweed and northern milfoil had senesced by the July sampling date, only hydrilla, Eurasian watermilfoil, hybrid milfoil, and parrotfeather were measured in July. Reflectance measurements were originally planned on 4 dates, including a mid-June date; however, the June date was canceled due to unsuitable weather conditions. Measurements were made at 10 randomly selected locations from the plant mat of each species on each sampling date. The spectroradiometer sensor had an 18° field-of-view. Measurements were made at 0.50 m above each species with a ground area field-of-view of approximately 0.16 m^2. All data were collected under clear and sunny conditions between 11 am and 2 pm central standard time.

Spectral measurements were studied only from the 400 to 900 nm spectral range. The signals measured in the lower and upper ends of the wavelength range were discarded due to sensor noise. Twenty 0.5 nm bandwidths were averaged to represent 10 nm bandwidths from the 400 to 900 nm spectral range for a total of 50 bands. Each band was based on the midpoint between the bandwidth; for example, the first band encompassing the 400 to 410 nm bandwidth was named band 405. Reflectance data for each of the 50 bands were analyzed using analysis of variance techniques. Spectral reflectance was the dependent variable and plant species was the independent variable for the analysis. Duncan's multiple range test was used to test significance at the 0.05 probability level among means (Steel and Torrie 1980).

Stepwise discriminant analysis was also used to identify a subset of significant spectral bands from the 50 bands for discriminating among the plant species for each date. At each step, the band that contributed the most to the discrimination was entered into the discriminant model. The model was then examined, and the band that contributed the least in the model was removed. The stepwise selection process stops when all the bands in the model are significant at the 0.001 level, and none of the other bands meet the 0.01 significance level to enter. Discriminant analysis was performed based on the subsets of significant bands for classifying the weed species. SAS software was used for this analysis (SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

The spectral signatures for the 6 species of aquatic weeds were recorded for the first 2 sampling dates, May 11 (Figure 1) and May 30 (Figure 2). A comparative visual study of the reflectance curves reveals that most of the species had similar spectral patterns for the 2 dates. Parrotfeather (the emergent species) had generally higher visible reflectance (400 to 750 nm) and much greater NIR reflectance (750 to 900 nm) than the other 5 submersed species. Among the submersed species, hydrilla generally had lower visible reflectance than the other species on both dates, while curly-leaf pondweed had higher visible reflectance than the other submersed species on May 30. Several of the submersed species had similar NIR reflectance on both sampling dates.

Spectral signatures for hydrilla, curly-leaf pondweed, Eurasian watermilfoil, and hybrid milfoil on July 1 (Figure 3) exhibited similar reflectance patterns to those shown on the 2 May sampling dates, when parrotfeather had higher visible and NIR reflectance than the 3 submersed species. Hydrilla generally had lower visible reflectance than the other species.

Visible reflectance in vegetation is primarily affected by plant pigments and carotenoids (Gausman 1985, Campbell 1996). Foliage colors varied from bright glaucous green of parrotfeather, to duller light to gray-green of curly-leaf pondweed, hybrid milfoil, and Eurasian watermilfoil, to darker green of northern milfoil and hydrilla. The darker green foliage of hydrilla and northern milfoil generally reflected less of the green light and absorbed more of the blue and red light than the various lighter green foliage of the other 4 species (Myers et al. 1983, Gausman 1985, Campbell 1996). Although all species had water integrated with the surfaced or emergent plant material, this was deemed to have little effect on their visible reflectance because the visible spectrum is not sensitive to water (Myers et al. 1983, Gausman 1985).

Near-infrared reflectance in vegetation is highly correlated with vegetative biomass and density (Gausman 1985, Campbell 1996). The high NIR reflectance of parrotfeather was directly attributed to its emergent foliage that forms a relatively dense canopy exposed above the water surface. The other 5 submersed species had most of their biomass below the water surface, and the surfaced mats had water integrated with the plant canopy, which absorbed a large percentage of the NIR light causing much lower NIR reflectance (Myers et al. 1983, Wiesnet et al. 1997, Everitt et al. 1999). Although parrotfeather had higher NIR reflectance than the other species, water integrated with the canopy likely had a negative effect on its NIR reflectance (Myers et al. 1983, Gausman 1985).

A summary of ANOVA and multiple comparisons for the 6 species at the 50 bands on May 11 (Table 1) indicated that

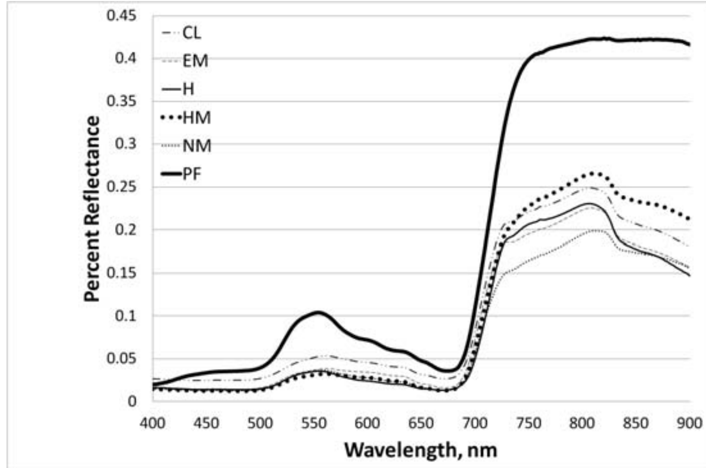

Figure 2. Mean light reflectance spectra in the 400 to 900 nm spectral range of 6 aquatic weed species on May 30, 2009. Letters used to designate species are: CL = curly-leaf pondweed; EM = Eurasian watermilfoil; H = hydrilla; HM = hybrid milfoil; NM = northern milfoil; and PF = parrotfeather.

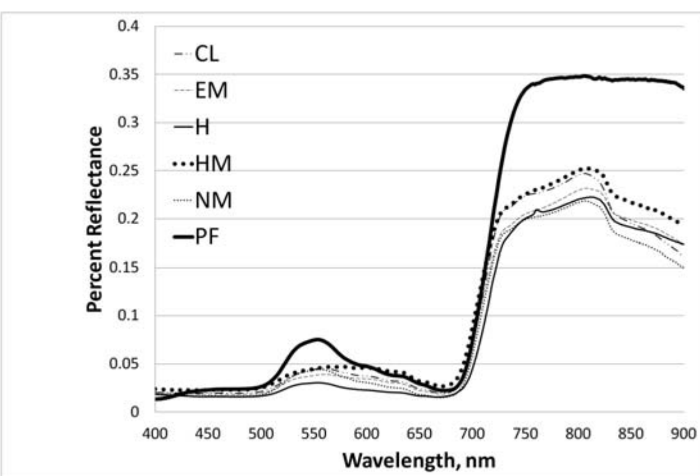

Figure 1. Mean light reflectance spectra in the 400 to 900 nm spectral range of 6 aquatic weed species on May 11, 2009. Letters used to designate species are: CL = curly-leaf pondweed; EM = Eurasian watermilfoil; H = hydrilla; HM = hybrid milfoil; NM = northern milfoil; and PF = parrotfeather.

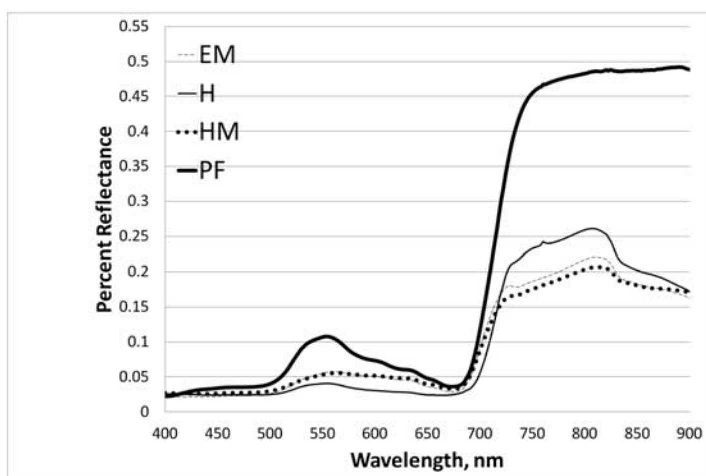

Figure 3. Mean light reflectance spectra in the 400 to 900 nm spectral range of 4 aquatic weed species on July 1, 2009. Letters used to designate species are: EM = Eurasian watermilfoil; H = hydrilla; HM = hybrid milfoil; and PF = parrotfeather.

TABLE 1. SUMMARY OF ANOVA AND MULTIPLE COMPARISON RESULTS FOR 6 AQUATIC WEED SPECIES BASED ON REFLECTANCE SPECTRA FOR 50 WAVEBANDS (405 TO 895 NM) FOR THE MAY 11, 2009 SAMPLING DATE.

			Species[1,2]					
Band[3] (nm)	F	R^2	CL	EM	H	HM	NM	PF
405-435	8.7-18.6	0.45-0.63	b	bc	de	a	cd	e
445-505	14.0-23.9	0.55-0.68	b	bc	d	a	cd	a
515-565	35.5-76.0	0.76-0.88	b	c	d	b	b	a
575-585	57.3-64.9	0.84-0.86	c	d	e	b	d	a
595-615	52.6-57.4	0.83-0.84	b	b	d	a	c	a
625-635	46.7-49.4	0.81-0.82	c	c	e	a	d	b
645-665	28.6-40.4	0.73-0.78	c	c	d	a	d	b
675-685	23.9-28.8	0.69-0.72	b	b	c	a	c	b
695-705	56.7-58.8	0.83-0.84	c	c	e	a	d	b
715-735	20.8-29.5	0.66-0.73	b	c	d	b	cd	a
745-785	25.9-29.2	0.71-0.73	b	b	b	b	b	a
795-895	22.5-49.3	0.68-0.82	bc	bc	bc	b	c	a

[1]Species: CL = curly-leaf pondweed; EM = Eurasian watermilfoil; H = hydrilla; HM = hybrid milfoil; NM, northern milfoil; and PF = parrotfeather.
[2]Species with the same letter in a row indicate their reflectance values do not differ for the given wavebands at the 0.05 probability level, according to Duncan's multiple range test.
[3]Bands are expressed as a range for brevity because their multiple comparison range test results were the same. For example, bands 405 to 435 includes bands 405, 415, 425, and 435. Reflectance data for the 6 species are given in Figure 1. The F and R^2 values show the range for the bands represented.

the visible blue bands (405 to 495 nm) and initial visible green band (505 nm) were not useful for separating among the species. Hybrid milfoil was the only species that could be distinguished in the blue region (bands 405 to 435 nm). At the visible green bands 515 to 565 nm, parrotfeather, curly-leaf pondweed, and hydrilla could be distinguished. For bands 575 and 585 nm on the green-red edge, parrotfeather, hybrid milfoil, curly-leaf pondweed, and hydrilla could be separated. Visible red bands 625 and 635 nm were also useful where hybrid milfoil, parrotfeather, northern milfoil, and hydrilla could be distinguished. These same 4 species could also be separated at the 695 and 705 nm bands on the red-NIR edge. Red-NIR edge bands 715 to 745 nm and NIR bands 755 to 895 nm were only useful for separating parrotfeather.

The ANOVA and multiple comparison results for the 6 species at the 50 bands on May 30 (Table 2) show that although several species could be distinguished at multiple bands, certain bands were superior to others. Green-red edge bands 585 and 595 nm, red bands 605 and 615 nm, and red-NIR edge bands 685 to 725 nm were optimum and could differentiate parrotfeather, curly-leaf pondweed, Eurasian watermilfoil, and hydrilla. The blue bands (405 to 495 nm) and most of the green bands (505 to 575 nm) were generally the least valuable for differentiating among species.

TABLE 2. SUMMARY OF ANOVA AND MULTIPLE COMPARISON RESULTS FOR 6 AQUATIC WEED SPECIES BASED ON REFLECTANCE SPECTRA FOR 50 WAVEBANDS (405 TO 895 NM) FOR THE MAY 30, 2009 SAMPLING DATE.

			Species[1,2]					
Band[3] (nm)	F	R^2	CL	EM	H	HM	NM	PF
405-425	35.2-57.0	0.71-0.84	a	b	b	b	b	a
435-515	69.0-181.4	0.86-0.94	b	c	c	c	c	a
525-575	225.4-302.8	0.94-0.96	b	c	cd	d	cd	a
585-615	151.7-195.3	0.93-0.94	b	c	e	d	d	a
625-655	125.8-138.5	0.92-0.93	b	c	d	d	d	a
665-675	92.2-104.0	0.89-0.91	b	c	c	c	c	a
685-725	87.2-180.8	0.89-0.94	b	c	e	d	d	a
735-765	213.9-228.3	0.95-0.96	bc	d	cd	b	e	a
775-795	213.0-221.9	0.94-0.95	b	c	c	b	d	a
805-895	198.1-408.2	0.95-0.97	c	d	d	b	d	a

[1]Species: CL = curly-leaf pondweed; EM = Eurasian watermilfoil; H = hydrilla; HM = hybrid milfoil; NM = northern milfoil; and PF = parrotfeather.
[2]Species with the same letter in a row indicate their reflectance values do not differ for the given wavebands at the 0.05 probability level, according to Duncan's multiple range test.
[3]Bands are expressed as a range for brevity because their multiple comparison range test results were the same. For example, bands 405 to 425 includes bands 405, 415, and 425. Reflectance data for the 6 species are given in Figure 2. The F and R^2 values show the range for the bands represented.

The ANOVA and multiple comparison results for 4 species at the 50 bands for July 1 (Table 3) indicate that because fewer species were present on July 1, a larger number of bands could be used to distinguish among the 4 weeds. Parrotfeather and hydrilla could be separated in all the green bands (505 to 595 nm) and a large number of the red bands (605 to 665 nm). These 2 species could also be differentiated in the red-NIR edge bands 735 and 745 nm and at bands 755 to 815 nm in the NIR spectral region. The blue bands (405 to 495 nm) were generally the least useful for separating among the species.

The higher visible reflectance of Eurasian watermilfoil than that of hydrilla at several bands in the green and red spectral regions (Figures 1, 2, and 3; Tables 1, 2, and 3) in this study generally agree with the findings of Everitt et al. (2007) who reported similar findings in the broadband green and red spectral regions using a multispectral radiometer. The importance of several red-NIR edge bands for distinguishing among a greater number of species in this study generally concur with the results of Becker et al. (2005). These researchers reported that the 686 and 732 nm red-NIR edge bands contained the most information for differentiating among botanical and substrate classes in a coastal wetland. The value of the 555 and 565 nm green bands for distinguishing 3 species on the May 11 study date in this study agrees with the findings of Ullah et al. (2000), who found comparable bands to be useful to identify emergent plant species.

A summary of the results from stepwise discriminant analysis for the 3 dates (Table 4) identifies 9 and 10 spectral bands as significant to discriminate among the 6 species on May 11 and 30, respectively, while 7 bands were found to be significant to distinguish among the 4 species on July 1. Bands in the blue to NIR regions were selected for the May dates, but only bands in the red-NIR edge and NIR regions were found to be useful for the July date. Bands 405, 575, and 845 nm were identified for both May dates, and bands 705 and 895 nm were selected for May 11 and July 1. Fung et al. (2003) used stepwise discriminant analysis to select the optimum bands to discriminate among subtropical tree species and identified many of the same bands selected in this study, particularly in the green, red, and red-NIR edge spectral regions. Becker et al. (2005) used the second derivative analysis procedure to select a subset of optimum bands to discriminate among coastal wetland cover classes and identified several bands in the green, red-NIR edge, and NIR regions comparable to those selected in this study.

Classification accuracy values were determined for the measured reflectance spectra using linear discriminant functions derived from the selected bands for the 3 dates (Table 5). The resubstitution classification accuracy was 100% for all 3 dates, and the cross-validation classification accuracy was 100% for the 2 May dates and 97.5% for the July date, indicating the discriminant models can be used to accurately distinguish among the weed species based on the selected bands.

This study demonstrated that hyperspectral reflectance data taken in the field did distinguish among aquatic weeds on 3 dates (May 11, May 30, and July 1, 2009). Results from both multiple comparison range tests and stepwise discriminant analysis identified optimum bands for weed species recognition. Multiple comparison results showed that the optimum bands for separating among species on the 2 May dates occurred in the green-red edge, red, and red-NIR edge spectral regions where 6 bands were identified on May 11 and 9 bands on May 30. For the July date, the largest number of separations among species occurred at all green and most red bands, as well as some red-NIR edge and NIR bands where 26 bands were identified.

The 2 approaches produced different sets of optimum bands for separating the plant species because the multiple comparison range test evaluates the discriminating power of each band individually, whereas stepwise discriminant analysis selects a subset of the bands for discriminating the species. If a user is interested in only a few bands (e.g., 1 to 3 bands), the results from the multiple comparison range test may be most useful. However, if the user is interested in more bands (e.g., 7 to 10 bands), stepwise discriminant analysis will be more appropriate.

Spectral data presented here were obtained from surfaced mats of the submersed plant species. Therefore, a significant proportion of the submersed species could not be detected. Everitt et al. (1999) reported that ground reflectance mea-

Table 3. Summary of ANOVA and multiple comparison results for 4 aquatic weed species based on reflectance spectra for 50 wavebands (405 to 895 nm) for the July 1, 2009 sampling date.

			Species[1,2]			
Band[3] (nm)	F	R^2	EM	H	HM	PF
405-425	2.3-4.2	0.16-0.26	b	ab	a	a
435-495	6.5-12.8	0.35-0.51	b	b	b	a
505-665	11.6-142.7	0.49-0.92	b	c	b	a
675-725	7.1-120.9	0.37-0.90	bc	c	b	a
735-815	120.1-145.2	0.90-0.92	c	b	c	a
825-895	131.6-200.9	0.92-0.94	b	b	b	a

[1]Species: EM = Eurasian watermilfoil; H = hydrilla; HM = hybrid milfoil; and PF = parrotfeather.
[2]Species with the same letter in a row indicate their reflectance values do not differ for the given wavebands at the 0.05 probability level, according to Duncan's multiple range test.
[3]Bands are expressed as a range for brevity because their multiple comparison range test results were the same. For example, bands 405 to 425 includes bands 405, 415, and 425. Reflectance data for the 4 species are given in Figure 3. The F and R^2 values show the range for the bands represented.

Table 4. Significant bands and partial R-squared values identified using stepwise discriminant analysis for separating 6 weed species on May 11 and 30 and 4 species on July 1.

May 11		May 30		July 1	
Significant bands[1]	Partial R-square	Significant bands	Partial R-square	Significant bands	Partial R-square
405	0.68	405	0.56	685	0.70
445	0.75	545	0.69	705	0.84
525	0.60	575	0.53	725	0.70
575	0.67	655	0.48	755	0.60
695	0.39	715	0.66	815	0.89
705	0.39	735	0.41	875	0.52
805	0.70	775	0.43	895	0.47
845	0.63	845	0.49		
895	0.58	865	0.56		
		885	0.56		

[1]All bands entered in the model are significant at the 0.001 level.

Table 5. Classification accuracy of measured reflectance spectra using linear discriminant functions based on selected spectral bands for 3 dates.

Date	Number of spectra	Resubstitution classification (%)	Cross-validation classification (%)
May 11	60	100.00	100.00
May 30	60	100.00	100.00
July 1	40	100.00	97.50

surements on hydrilla submerged at depths from 2.5 to 15.0 cm could not be distinguished from those of non-turbid water in the visible green spectral region. The reflectance values of hydrilla submerged at depths from 15.0 to 30.0 cm could not be differentiated from those of non-turbid water in either the visible red or NIR spectral regions. Chlorophyll in the water and turbidity contribute to the inability to distinguish submerged aquatic vegetation (Carter 1982). Thus, conventional remote sensing surveys using airborne sensors for mapping these species would likely result in underestimation of the area of infestation. Remote sensing surveys may also be limited when mixtures of species occur in the same community due to mixed pixel values.

Our results provide insight into determining the optimum bands when using hyperspectral imagery captured from aircraft (e.g., CASI, AISA+) or satellite (e.g., Hyperion) platforms to identify the aquatic weeds studied here. The optimum time to obtain imagery of all 6 species would be May to mid-June because some species senesce by late June (curly-leaf pondweed, northern milfoil). For hydrilla and Eurasian watermilfoil, imagery could be acquired over a broader time period (May to Sep; Everitt et al. 1999, 2007).

These data should be of interest to wetland resource managers and weed scientists for determining the feasibility of using remote sensing techniques to map individual weed species. The spectral profiles for each species are valuable for developing a spectral library database for aquatic vegetation and provide previously unavailable information on 50 visible and NIR wavebands for the 6 species studied.

ACKNOWLEDGEMENT

Thanks are extended to Kerstin Hoesel for her assistance in setting up the experiment and maintaining the plants during the course of the study.

LITERATURE CITED

Becker BL, Lusch DP, Qi J. 2005. Identifying optimal spectral bands from *in situ* measurements of Great Lakes coastal wetlands using second-derivative analysis. Remote Sens. Environ. 97:238-248.

Best RG, Wehde ME, Linder RL. 1981. Spectral reflectance of hydrophytes. Remote Sens. Environ. 11:27-35.

Campbell JB. 1996. Introduction to remote sensing. Guilford Press, New York. 626 p.

Carter V. 1982. Application of remote sensing to wetlands, pp. 284-300. In: C. J. Johannsen and J. L. Sanders (*eds.*). Remote Sensing in Resource Management. Soil Conservation Society of America, Ankeny, IA.

Everitt JH, Alaniz MA, Escobar DE, Davis MR. 1992. Using remote sensing to distinguish common (*Isocoma coronopifolia*) and Drummond goldenweed (*Isocoma drummondii*). Weed Sci. 49:621-628.

Everitt JH, Davis MR, Nibling FL. 2007. Using spatial information technologies for detecting and mapping Eurasian watermilfoil. Geocarto Int. 22(1):49-61.

Everitt JH, Escobar DE, Webster CF, Lonard RI. 2000. Light reflectance characteristics and film image relations among three aquatic plant species. Texas J. Sci. 52(2):153-158.

Everitt JH, Fletcher RS, Elder HS, Yang C. 2008. Mapping giant salvinia with satellite imagery and image analysis. Environ. Monit. Assess. 139:35-40.

Everitt JH, Yang C, Escobar DE, Webster CF, Lonard RI, Davis MR. 1999. Using remote sensing and spatial information technologies to detect and map two aquatic macrophytes. J. Aquat. Plant Manage. 37:71-80.

Fung T, Fung H, Ma Y, Siu WL. 2003. Band selection using hyperspectral data of subtropical tree species. Geocarto Int.18 (4):3-12.

Gausman HW. 1985. Plant leaf optical parameters in visible and near-infrared light. Graduate Studies Texas Tech University, No. 29. Texas Tech University Press. Lubbock, TX. 78 p.

Ge S, Everitt JH, Carruthers R, Gong P, Anderson G. 2006. Hyperspectral characteristics of canopy components and structure for phenological assessment of an invasive weed. Environ. Monit. Assess. 120:109-126.

Gong P, Pu R, Yu E. 1997. Conifer species recognition: an exploratory analysis of *in situ* hyperspectral data. Remote Sens. Environ. 62:189-200.

Jakubauskas ME, Peterson DL, Campbell SW, Campbell SD, Penny D, deNoyelles F Jr. 2002. Remote sensing of aquatic plant obstructions in navigable waterways. Proceedings of 2002 ASPRS-ACSM Annual Conference and FIG XXII Congress, April 22-25, 2002, Washington, D.C. ASPRS, Bethesda, MD. CD-ROM.

Martin ME, Newman SD, Aber JD, Congalton RG. 1998. Determining forest species composition using high spectral resolution remote sensing data. Remote Sens. Environ. 65:249-254.

Martyn RD, Noble RL, Bettoli PW, Maggio RC. 1986. Mapping aquatic weeds with aerial color-infrared photography and evaluating their control by grass carp. J. Aquat. Plant Manage. 24:46-56.

Moody ML, Les DH. 2007. Geographic distribution and genotypic composition of invasive hybrid milfoil (*Myriophyllum spicatum* x *M. sibiricu*m) populations in North America. Biol. Invasions. 9:559-570.

Myers VI, Bauer ME, Gausman HW, Hart WG, Heilman JL, McDonald RB, Park AB, Ryerson RA, Schmugge TJ, Westin FC. 1983. Remote sensing in agriculture, pp. 2111-2228. In: R. N. Colwell (*ed.*). Manual of Remote Sensing. American Society of Photogrammetry, Falls Church, VA.

Scarpace FL, Quirk BK, Kiefer RW, Winn SL. 1981. Wetland mapping from digitized aerial photography. Photogramm. Eng. Remote Sens. 47:829-838.

Steel RGD, Torrie JH. 1980. Principles and procedures of statistics. McGraw-Hill, New York. 481 p.

Thenkabail PS, Smith RB, De Pauw E. 2000. Hyperspectral vegetation indices and their relationship with agricultural crops. Remote Sens. Environ. 71:158-182.

Tiner RW. 1997. Wetlands, pp. 475-494. In: W. R. Philipson (*ed.*), Manual of Photographic Interpretation, 2nd edition, American Society of Photogrammetry and Remote Sensing, Bethesda, MD.

Tueller PT. 1982. Remote sensing for range management, pp. 125-140. In: C. J. Johansen and J. L. Sanders (*eds.*). Remote Sensing for Resource Management, Soil Conservation Society of America, Ankeny, IA.

Turner W, Spectro S, Gardiner N, Fladeland M, Sterling E, Sterninger M. 2003. Remote sensing for biodiversity science and conservation. Trends Ecol. Evol. 18:306-314.

Ullah A, Rundquist DC, Derry DP. 2000. Characterizing spectral signatures for three selected emergent aquatic macrophytes: a controlled experiment. Geocarto Int. 15(4):29-39.

USDA, NRCS. 2007. The PLANTS Database. http://plants.usda.gov. National Plant Data Center, Baton Rouge, LA 70874-449 USA. Accessed October 16, 2009.

Venugopal G. 1998. Monitoring biological control of water hyacinths using remotely sensed data: a case study of Bangalore, India. Singapore J. Trop. Geogr. 19(1):91-105.

Wiesnet DR, Wagner CR, Philpot WD. 1997. Water, snow, and ice, pp. 257-267. In: W. R. Philipson (*ed.*). Manual of Photographic Interpretation, 2nd edition. American Society of Photogrammetry and Remote Sensing, Bethesda, MD.

Yang C, Everitt JH, Fletcher RS, Jensen RR, Mausel PW. 2009. Evaluating AISA+ hyperspectral imagery for mapping black mangrove along the South Texas Gulf Coast. Photogramm. Eng. Rem. Sens. 75:424-435.