Remote Sensing for Environmental Monitoring and Change Detection
(Proceedings of Symposium HS3007 at IUGG2007, Perugia, July 2007). IAHS Publ. 316, 2007.

Mapping and monitoring wetlands using airborne multispectral imagery

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Abstract Wetland areas in the semiarid west of the United States play an important eco-hydrological role. The size, location and function of wetlands are affected by numerous factors such as variations in water availability, water quality, geomorphic characteristics and anthropogenic factors such as runoff from irrigation systems, or discharge of urban effluents. Typically, wetland vegetation occurs in patches of variable size and plant species composition, requiring high-resolution imagery to accurately identify distribution and extent of the different wetland habitat types when mapping these complex systems. Airborne multispectral digital imaging offers several advantages, including cost-effectiveness and ability to resolve wetland features ranging in size from a few meters to hundreds of hectares. This paper describes the mapping of wetland habitats within the Great Salt Lake Ecosystem using high resolution multispectral imagery (1-m pixels). Image classification was based on supervised signature extraction supported by comprehensive ground truth. An error analysis was conducted using independent ground truth data, and the resulting classification accuracy for the final wetland resource map was 92%.

Key words airborne multispectral digital imaging; wetland mapping

INTRODUCTION

The Great Salt Lake Wetlands Ecosystem (GSLWE) provides critical breeding and staging areas for millions of migratory birds travelling the Pacific and Central Flyways. These wetlands are being rapidly degraded because of rapid urbanization along the Wasatch Front and lack of integrated conservation planning at the municipal (i.e. city) level. Wetlands play an important role in the support and sustenance of aquatic life in and around the Great Salt Lake. Loss in the abundance, distribution and condition of wetlands can not only adversely affect wetland-dependent migratory birds and other wildlife, but can also affect water quality and the sustainability of aquatic life in receiving waters (e.g. the Great Salt Lake and its freshwater tributaries). Wetlands play an important role in regulating water quality and providing habitat for numerous species. In the semiarid western United States these systems are particularly fragile and subject to fluctuations in the hydrological cycle. Many wetland areas have resulted or have been augmented by decades of irrigation runoff.

The Wasatch Front borders the GSLWE and is the most populated region in the State of Utah. The rapid urban growth and development experienced over the past decade has resulted in the inadvertent destruction, fragmentation, and alteration of numerous wetland systems located in this area due to a lack of integrated planning of urban municipalities. This pressure on wetlands has occurred despite a steady growth in wetland awareness over the same time period. The majority of municipalities bordering the GSLWE do not have accurate, detailed, and up-to-date inventories of wetland systems and, therefore, have not been able to fully consider the environmental, regulatory and/or economic consequences of their fragmentation and loss in their planning efforts.

Traditional methods of delineating wetland systems involve considerable field effort and can involve manual classification, including sketching of polygons over printed aerial photography or satellite imagery, delineation with Global Positioning Systems (GPS), vegetation transects and other labour intensive methods, which are very time consuming and sometimes it is impossible to conduct in some riparian and wetland systems due to inaccessibility and complexity (Martin *et al*., 1998). In spite of the inaccessible terrain, Gaussman *et al.* (1977) were among the first to delineate woody plant species by using reflectance measurements. Colour Infrared (CIR) aerial photographs were used to conduct inventory and classification of wetland and wildlands (Bonner, 1981; Everitt & Deloach 1990; Lonard, 1998). Everitt *et al.* (1986) used field spectral radiometric measurements to separate weed, wetland, and rangeland species. Everitt (1998) used textural image responses in addition to radiometric responses in CIR photographs to delineate vegetation types.

Efforts by resource scientists realized that airborne multispectral video remote sensing systems (Meisner & Lindstrom, 1985; Vlcek & King, 1985; Hutchinson & Schowengerdt, 1990; Everitt *et al.*, 1991; Neale, 1992) provided faster information turn around time than aerial photography or spectral field radiometry, and at less cost. Bartz *et al.* (1994); Redd *et al.* (1994); Shoemaker *et al.* (1994), and Neale (1997) used airborne multispectral videography to map riparian and wetland systems. May *et al.* (2000) mapped the remote areas of the Escalante River in Utah using airborne digital imagery. Satellite multispectral imagery, by virtue of its ability to cover large areas, has also been used to map riparian vegetation (Williams, 1992). Limitations with satellite imagery are: (1) difficulties faced in distinguishing fine ecological divisions between certain wetland and riparian classes; and (2) the pixel resolution of satellite imagery is coarser than the fine scale variability present in wetlands.

A Special Area Management Plan (SAMP) is a comprehensive plan for the purpose of achieving a reasonable balance between the need for economic development and wetland conservation goals, such as emphasis on protection, enhancement, and restoration of existing wetlands over creation of new wetlands, ensuring a net gain of wetland functions and values. A SAMP is a component within a City's General Plan that identifies a specific geographic area in which certain wetlands will be protected and preserved, and other wetlands will be allowed for development provided specific mitigation criteria are met. The SAMP process is intended to provide accurate and up-to-date scientific information for local planning and decision-making; provide opportunities for public involvement; reflect the needs of the local community; facilitate a holistic, watershed approach for the management of wetlands and aquatic resources; and meet United States Federal Clean Water Act Section 404 regulatory requirements. Implementation of a SAMP requires a General Permit from the US Army Corps of Engineers to authorize development in certain wetland areas in exchange for the City's adoption of the approved wetland protection, preservation and mitigation measures.

In early 2003, Brigham City and Perry City retained the environmental consulting company Frontier Corporation USA to begin work on the preparation of a SAMP. The project was partially funded by an Environmental Protection Agency (EPA) wetlands grant, administered by the Box Elder County Economic Development Department. The study area for the SAMP included approximately 6000 ha of land within the incorporated boundaries of Brigham City and Perry City.

This paper describes the methodology used in the wetland mapping and the results from the classification and accuracy assessment. The results presented are from an additional 1514 ha wetland mitigation area for the SAMP study, located west of Brigham City, Utah.

METHODS

Airborne remote sensing

High-resolution multispectral imagery was acquired with the Utah State University (USU) airborne multispectral digital system (Neale & Crowther, 1994; Cai & Neale, 1999) at a nominal pixel resolution of 1-m over the entire SAMP project area. The USU system consists of three Kodak Megaplus 4.2i digital cameras with interference filters forming spectral bands in the green (0.545–0.555 μm), red (0.665–0.675 μm) and near infrared (NIR) (0.790–0.810 μm) wavelengths. The cameras are mounted through a porthole in a Piper Seneca II aircraft, dedicated for remote sensing missions. The cameras are controlled through specific software using Epix boards in a Pentium IV computer, mounted in an equipment rack. The system also uses an Inframetrics 760 thermal infrared camera mounted through a separate porthole that acquires images in the 8–12 μm range. No thermal imagery was acquired for this study.

The shortwave images were acquired at a nominal overlap of 60% along the flight lines and 30% in between flight lines. The flight lines were planned to cover the entire SAMP area, including the Wetland Mitigation Area (Bank) west of Highway I-15. The resulting swath width at 1-m pixel resolution was 2 km.

The system digital cameras were calibrated in a separate experiment against a radiance standard. On the day of the flight, a barium sulfate standard reflectance panel with known bi-directional properties was set up adjacent to the study area near Brigham City, with an Exotech 4-band radiometer placed looking down on the panel from nadir and recording radiance at every minute interval. These measurements were later used to calibrate the image strips along the flight lines, based on the time of image acquisition. All clocks were set to local standard time.

The image acquisition flight occurred under clear sky conditions during the middle of May 2003, prior to the onset of the irrigation season. April and May are usually the wettest months in northern Utah and thus by mid-May there is the highest likelihood of having the peak amount of water in the system from natural precipitation. Later in May, the irrigation season begins and drainage from surface irrigation could be mixed in with precipitation water in certain parts of the study area. The other advantage of flying early in the season is to capture the wetland vegetation species at different maturation rates. In mid-May, wetland plants in wet meadow habitats will have “greened up” while marsh vegetation will still be senesced, allowing for easier differentiation between them.

Image processing: rectification and generation of the mosaics

The individual spectral band images acquired were geometrically corrected for radial distortions (Sundararaman & Neale, 1997), radiometrically adjusted for lens vignetting effects (Neale & Crowther, 1994) and registered into 3-band images.

The 3-band images were rectified to black and white 1:24 000 scale digital orthophoto quads, using common control points visible in both sets of imagery and second order polynomials. The rectified images were mosaicked into larger image strips along the flight lines using approximately the centre 1/3 of each rectified image. Individual mosaicked strips along each flight line were then calibrated in terms of reflectance using the system calibration and the panel data separately, and all the calibrated strips were stitched together to generate the final calibrated mosaic covering the study area. The coordinate system projection of this mosaic was Universal Transverse Mercator (UTM), using NAD83 as the datum.

The final calibrated image mosaic was cut to the boundaries of the Brigham and Perry Cities SAMP areas as well as the Brigham City wetland mitigation area. Figure 1 shows the false colour composite (FCC) of the 3-band mosaic of the wetland mitigation area using the near-infrared, red and green image bands of the system.

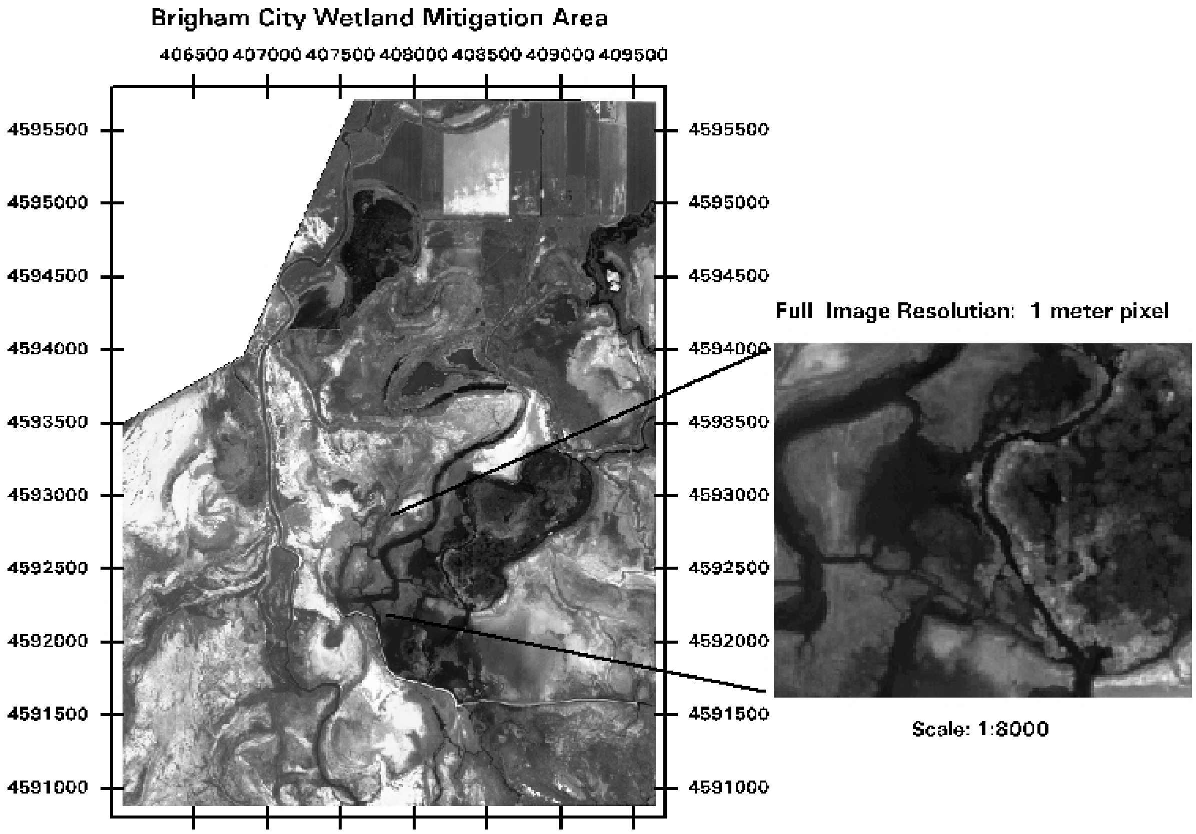

Fig. 1 Brigham City wetland mitigation area of 1514 ha, showing high-resolution detail of a portion of a marsh and surrounding wet meadows and mudflat playa.

Habitat land classification and ground truth

The SAMP study area was separated into three zones, primarily based on elevation: (1) low lake plains; (2) high lake plains; and (3) mountain slopes and benches. A total of nine habitat classes were identified, including: upland range, pasture/turf/crop, bare, open water, riparian forest/shrub, mudflat/playa, emergent wet meadow, emergent marsh, pasture/turf/crop, orchards, upland rangeland, sagebrush/grassland, and talus/bedrock/gravel. Also identified were six non-habitat land classifications, including asphalt, roads, structures, shadows, and urban landscape vegetation.

The Brigham City wetland mitigation area was contained entirely in the low lake plains, below 4220 feet in elevation above means sea level, west of US Interstate Highway 15 (I-15) that are potentially within the historic flood plain of the Great Salt Lake. The wetlands in this habitat zone are associated with the Black Slough and its tributaries, the network of irrigation and drainage ditches, and the depression areas that are permanently or seasonally flooded. Depth to groundwater is generally shallow. The habitat classes that were mapped in this zone are described below.

Upland Rangeland Upland habitat within the low lake plains mostly consists of semiarid rangeland that is used primarily for livestock grazing. These uplands are dispersed throughout the low lake plains and are generally situated on “islands” of topographically higher ground that are not irrigated. Uplands also occur in disturbed areas, such as the shoulders of dirt roads and spoil piles for drainage and irrigation ditches. Common plant species include: little barley (*Hordeum pusillum*), cheatgrass (*Bromus tectorum*), curly cup gumweed (*Grindelia squarrosa*), clasping pepperweed (*Lepidium perfoliatum*), foxtail barley (*Hordeum jubatum*), and prickly lettuce (*Lactuca serriola*). Cheatgrass, clasping pepperweed, and prickly lettuce are considered nuisance weeds, and their presence is probably contributed by livestock grazing.

Pasture/Turf/Crop Pasture/turf/crop is a conglomerate of upland types that are irrigated and intensively managed. Irrigated pastures are variable in plant species composition, but are typically dominated by: Kentucky bluegrass (*Poa pratensis*), meadow fescue (*Festuca pratensis*) and red clover *(Trifolium pratense)*. Turf consists of turf grasses managed for athletics fields, public parks, schools, etc. Crop consists of cultivated fields that are typically irrigated and planted with winter wheat or alfalfa.

Bare soil Bare soil is an upland class that consists of non-vegetated areas that were either recently ploughed in preparation of agricultural plantings or cleared of vegetation in preparation for construction development. This class also encompasses dirt access roads and spoils piles resulting from the maintenance of irrigation and drainage ditches.

Open water Open water consists of permanent and semi-permanent water bodies that are usually greater than 2 feet in depth. Open water includes man-made impoundments, stream channels, slough channels, and ponds. Open water was classified into three categories: treatment ponds, lentic, and lotic water bodies.

Mudflat/playa Mudflat/playas are special aquatic sites that are seasonally ponded during the winter and spring months. Soil salinity/alkalinity is usually high as evidenced by crusty layers of salt deposits that are present on many mudflat surfaces, which limits the amount and type of vegetation present. Plant communities tend to have <10% vegetative cover, and are mainly comprised of halophytic (i.e. salt tolerant) plant species, including: saltgrass (*Distichlis spicata*), pickleweed (*Salicornia* spp.), seepweed (*Suaeda* sp.), and iodine bush (*Allenrolfea occidentalis*).

Emergent wet meadow Emergent wet meadows are seasonally flooded wetlands. These wetlands are typically transitional habitats situated around the perimeter of the mudflats and bordering uplands. They are also present in irrigated pastures. Plant species composition is variable and appears to be influenced by grazing pressure and proximity to water sources. Common plants include: saltgrass (*Distichlis spicata*), foxtail barley (*Hordeum jubatum*), rabbitfoot grass (*Polypogon monspeliensis*), spikerushes (*Eleocharis* spp.), bulrushes (*Scirpus* spp.), seepweed (*Suaeda* sp.), rushes (*Juncus* spp.), sedges (*Carex* spp.) and curly dock (*Rumex crispus*).

Emergent marsh Emergent marshes are permanently or semi-permanently flooded wetlands. Marsh habitat generally consists of patches of open water, common cattail (*Typha latifolia*), common reed (*Phragmites australis*), and bulrushes (*Scirpus* spp.) that are situated within drainages and depressional areas. Sedges (*Carex* spp.), rushes (*Juncus* spp.), and spikerushes (*Eleocharis* sp.) usually occur around the periphery of the marshes.

The ground truth campaign consisted of visiting the study area with printed and laminated 1:5000 scale image maps, covering the property in order to identify the vegetation species and habitat type associated with different spectral signatures visible on the image mosaic. Prior to the visit, the digital image was carefully reviewed on-screen in the laboratory, to identify different spectral signatures and surfaces and plan the field campaign. During the field campaign, a GPS was used to navigate to certain features requiring identification and to mark waypoint positions of others. Wherever possible, clumps of individual plant types were identified on the image maps and polygons were drawn on the lamination using waterproof felt tip pens. In many cases, there were mixes of different plant type such as sedges, rushes and grasses in the wet meadows, or bulrushes, cattails and phragmites in the marshes. These mixes were identified with a polygon and the approximate percentages of each noted on the maps. Digital photographs were taken as a record and to aid the spectral signature extraction later in the laboratory. A second field-verification visit was conducted after the image was classified, to obtain additional ground data for the accuracy assessment.

Image classification

Supervised classification techniques were used to classify the calibrated image mosaic into the different surface types. The signature extraction relied on the ground truth field maps and digital pictures for information on the surface type. Approximately 60% of the ground truth data was separated to be used later in classification accuracy procedures and thus was not used in signature extraction. The ERDAS Imagine 8.5 software was used in all image processing tasks (ERDAS, 2000). The signature extraction tool was used, setting the spectral Euclidean distance value to optimize polygon growth after conducting an analysis of bright and dark surfaces in the image.

In an attempt to identify the maximum number of individual vegetation species in the image, the signature extraction was conducted as an iterative process. First a few dozen signatures were extracted to represent different vegetation types, playa, water, bare soil and other surfaces. A statistical analysis was then conducted using the Transformed Divergence (TD) method (ERDAS, 2000). This method compares signature statistics in the three spectral bands and produces an index number in between 0 and 2000 (or 0 and 2), a value of 2000 indicating that the two signatures are totally separable and 0 indicating the opposite. Signature pairs with values below 1300 had considerable confusion and signatures with the most conflict with others were deleted from the set. Signature pairs with TD values greater than 1800 were considered separable. Signatures with values in between 1300 and 1800 were analysed on a case-by-case basis. If the signature pair belonged to the same surface class and no considerable confusion occurred with other signatures in the set representing different vegetation or surface types, they were allowed to remain in the set. This allowed the inclusion of signatures that capture nuances in early vegetation growth or senesced vegetation, or differences in soil background or water background.

Once this statistical analysis was completed, the image was classified using the remaining signature set, using the Maximum Likelihood scheme and setting the unclassified rule to “unclassified”. This forced classes that were not represented by signatures in the set, to remain unclassified and thus appear black on the resulting classified image. The resulting image was then used to guide the extraction of additional signatures to represent the different vegetation and surface types in a new iteration following the same process described above. The iterative procedure continues until no large unclassified polygons are left in the image and mostly salt-and-pepper unclassified pixels remain. The final classification is conducted with the unclassified rule set to “parametric”, thus forcing unclassified pixels into the closest spectral class.

RESULTS

The supervised classification procedure resulted in a 122 class image very similar to the original 3-band multispectral mosaic, indicating that it properly captured the variability of classes and vegetation in the image. The 122 classes were then recoded to the seven major habitat types described above, using the Recode function in ERDAS Imagine. The recoded image was then run through a Majority 3 × 3 filter to remove salt-and-pepper pixels from the classification, resulting in a minimum mapping unit of 9 m^2, or 0.001 ha. Figure 2 shows the 122 class image resulting from the supervised classification and the recoded habitat image map of the study area.

An accuracy assessment of the recoded habitat image was conducted using the portion of the ground truth data separated for this purpose, augmented with data from a second visit to the field after the classification was completed. For such, additional stratified random points were generated over the classified re-coded image, the coordinates of these points identified and visited in the field to verify the classification. The results of the accuracy assessment are presented in a contingency table shown in Table 1. The contingency table provides for the analysis of errors of omission (error of under estimation) and commission (error of over estimation). The overall accuracy of the classification map was 92%. If just the wetland classes are examined, the resulting accuracy was 93%.

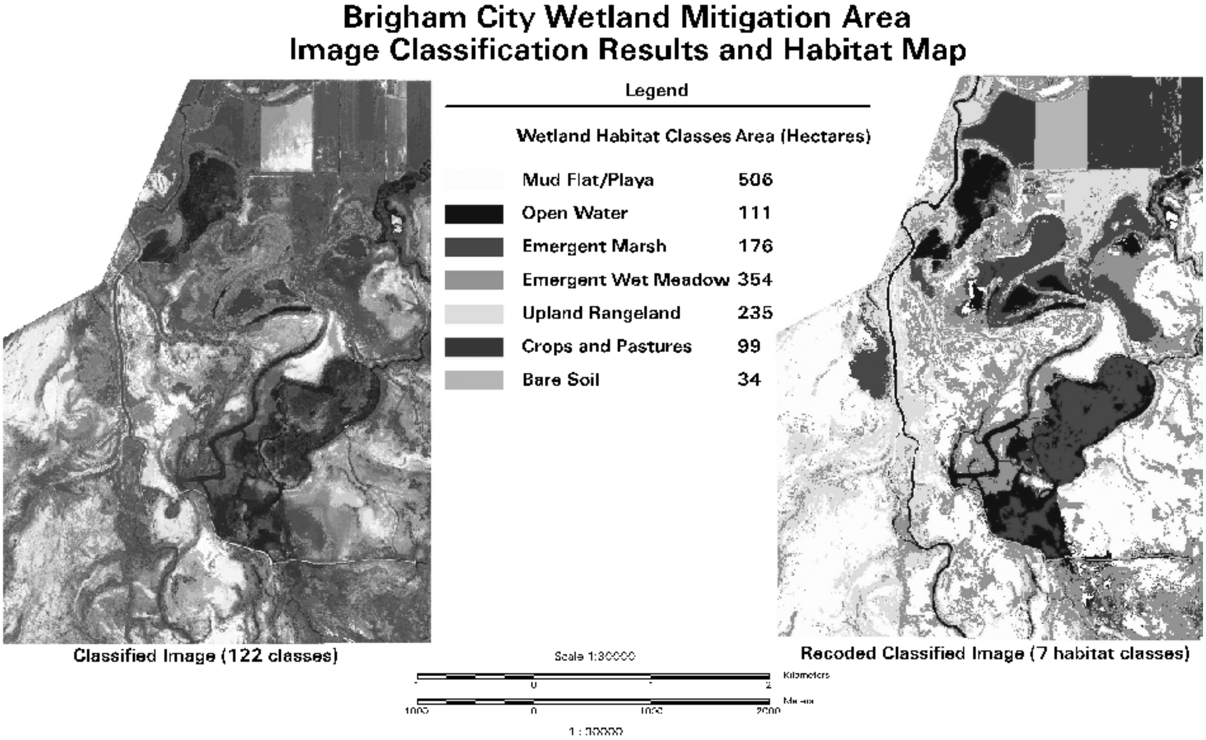

Fig. 2 Results of the supervised classification of the multispectral 3-band mosaic along with the final re-coded wetland habitat image map.

Table 1 Classification error contingency table for the final recoded wetland habitat map.

	Map classification	Ground truth observation							Commission error		
		UPR	MF*	EWM*	EM*	CRP	BS	W*	Total	% Correct	
	UPR	95	1	9	4				109	87	
	MF*	1	116	3	2				122	95	
	EWM*	5		121	5				131	92	
	EM*	6		5	78				89	88	
	CRP					10			10	100	
	BS						12		12	100	
	W*				1			49	50	98	
Omission Error	Total	107	117	138	90	10	12	49	523		TO
	% correct	89	99	88	87	100	100	100		481	TC
										92%	OA

Class	Abbrev.		
Upland rangeland	UPR		*Wetland Classes
Mudflat/Playa*	MF*	Total Observations (TO)	391
Emergent wet meadow*	EWM*	Total Correct (TC)	364
Emergent marsh*	EM*	Wetland Class Accuracy	93%
Crops	CRP		
Bare soil	BS	Overall Accuracy (OA)	92%
Open water	W*		

CONCLUSIONS

Airborne multispectral imagery can be acquired at different pixel resolutions by varying the altitude of the aircraft, allowing better matching of the imagery to the scale of variability in wetland systems. Wetland systems in the semiarid US can present very fine scales of variability among wetland vegetation species of only a few meters, but can cover areas of hundreds of hectares requiring high resolution aerial imagery to resolve the variability and map these systems. Higher resolution satellite multispectral imagery from sensors such as Ikonos (4 m pixels) and Quickbird (2.8 m pixels) would not have the resolution to resolve smaller water bodies and channels or the complex variability within wet meadows and marshes encountered in this wetland ecosystem.

Airborne multispectral digital imagery is a low cost alternative to traditional aerial photography with the advantage of allowing for the calibration of the imagery and the reproduction of results in future monitoring campaigns.

The classification accuracy of 92% obtained in the mapping of the Brigham City wetland mitigation area was considered very good in light of the savings obtained with the considerably reduced field work effort and costs, more than offsetting the cost of acquiring, processing and analysing the multispectral imagery.

Acknowledgements This paper was supported in part by the Utah Agricultural Experiment Station and the Remote Sensing Services Laboratory, Department of Biological and Irrigation Engineering, Utah State University. Wetland mapping work was financed by Brigham City and Perry City with partial support by the Environmental Protection Agency (EPA) wetlands grant, administered by the Box Elder County Economic Development Department.

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