ACCURACY ASSESSMENT OF HIGH RESOLUTION MULTISPECTRAL SATELLITE IMAGERY FOR REMOTE SENSING IDENTIFICATION OF WETLANDS AND CLASSIFICATION OF VERNAL POOLS IN EASTERN SACRAMENTO COUNTY, CALIFORNIA

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Abstract

of

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Conservation of wetlands and their functions is important for maintaining biodiversity. California's vernal pool wetlands are unique habitats that support a suite of species with local, regional, and global conservation significance. However, due to development and agricultural conversion, vernal pool habitat has been significantly reduced throughout California and particularly in Sacramento County.

Conservation of vernal pool wetlands depends on accurate identification and classification of vernal pools. Although remote sensing has been extensively used to detect wetlands, few studies have been conducted that examine the accuracy of satellite remote sensing methods to identify and classify wetlands as small as vernal pools. Consequently, this study addresses the hypothesis that remote sensing classification of high resolution satellite imagery can accurately identify wetland plant communities and classify vernal pool deep and shallow communities to a 95% level of accuracy. Three study sites were used to assess accuracy by statistically comparing high-resolution multispectral satellite imagery classification with reference areas classified through ground-surveys. Reference areas were classified into 6 land cover classes using a

classification key that incorporated the USACE Wetland Delineation Manual (1987) for wetland identification and Barbour et al. (2003) for classification of vernal pool deep and shallow communities.

Wetland land cover classes were correctly identified between 74 and 92% of the time across study sites. Overall site classification accuracies for all 6 land cover classes ranged from 50 to 62% and did not differ significantly among sites. Mean accuracies of land cover classes ranged from 26 to 94% and differed significantly across site. Only the upland cover class accuracy significantly differed among sites. Results show that high resolution multispectral satellite imagery can accurately identify open water wetlands, but do not accurately identify or classify other wetland types, including vernal pools and vernal pool sub-communities.

This study demonstrates that remote sensing identification and classification of vernal pools using high resolution multispectral imagery is a potentially valuable method of identifying open water wetlands, such as inundated vernal pools, but suggests that limitations still exist to achieving a high level of accuracy for other wetland classes. If methods are developed to address the limitations identified in this study, future studies should be able to accurately identify wetlands and classify vernal pools.

_____, Committee Chair
Dr. James W. Baxter

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INTRODUCTION

Because wetlands are among the most productive and dynamic ecosystems in the world, loss of wetlands due to development and agricultural conversion is of critical concern for the conservation of biodiversity (Tiner 1989, 2003; Halls 1997). Wetlands provide important functions, such as surface and subsurface water storage, nutrient cycling, particulate removal, plant and animal habitat, water filtration, and groundwater recharge (Brinson 1996; Marble 1992; Tiner 2003). Together these functions benefit society by reducing erosion, flooding, and flood damage, improving water quality, and providing essential habitat for fish and wildlife (Leibowitz 2003; Tiner 2003; Marble 1992). Despite the functional importance of wetlands, it is estimated that 50% of the world's wetlands have been lost since 1900 (Moser et al. 1996). Since the colonization of European settlers in North America, wetlands have been viewed as unproductive areas in need of conversion to other uses, such as development and agriculture. Between the 1780s and 1980s, the lower 48 conterminous United States lost 53% of its wetlands to draining, dredging, filling, and flooding; during this period, California lost over 91% of its original wetlands (Dahl 1990). Of wetland losses occurring between 1986 and 1997, 30% were attributed to urban development, 26% to agriculture, 23% to silviculture, and 21% to rural development (Dahl 1990). Such wholesale loss of wetlands and wetland species poses a serious threat to biodiversity and the maintenance of wetland functions.

In particular, the California floristic province is considered a global "hotspot" for conservation of biodiversity, due to the significant loss of habitat coupled with the high percentage of endemic species it contains (Myers et al. 2000). Within this floristic province, California's vernal pool wetlands are unique habitats that support a suite of species with local, regional and global conservation significance (Zedler 2003; Barbour et al. 2003; Keeley and Zedler 1998; King 1998; Holland 1976). Vernal pools are a unique type of seasonal wetland in which their flora and fauna are largely dependent on edaphic characteristics and ephemeral hydrology normally associated with Mediterranean climates (Zedler 1987; Ferren and Fiedler 1993; Keeler-Wolf et al. 1998). Vernal pool wetlands in particular provide a variety of hydrological, biogeochemical, and habitat functions on which species depend (Leibowitz 2003; Butterwick 1998). However, anthropogenic disturbances have resulted in significant losses of vernal pool wetlands, with an estimated loss of 15-33% of the biodiversity originally associated with them (King 1998). According to Holland (1998), approximately 4 million acres of vernal pools existed in California's Central Valley prior to European settlement. That number declined to 1 million as of 1997, a 75% loss of the State's vernal pools. Based on Holland's (1998) assessment of vernal pool losses, California is losing an average of 1.5% of its vernal pools each year in the Central Valley. If this rate continues, only 12% of California's original vernal pools will remain by the year 2044. In 1972, Sacramento County contained 83,497 acres of vernal pools and by 1997 only 37% (30,727 acres)

remained, an average loss of 1.5% per year (Holland 1998). This rate of loss suggests that to date, Sacramento County has lost 51% of the vernal pools that existed in 1972.

Because of their high species richness and endemism, California's few remaining vernal pools provide an important refuge for a variety of endemic plants and animals (Simovich 1998; Thorne 1984; Holland 1976; Zedler 2003). Of the vernal pool endemic species found in California and Oregon, 15 plant and five animal species have been federally listed as threatened or endangered by the U.S. Fish and Wildlife Service (USFWS) under the Endangered Species Act (ESA). For example, the threatened vernal pool fairy shrimp (*Branchinecta lynchi*), endangered vernal pool tadpole shrimp (*Lepidurus packardi*), threatened California tiger salamander (*Ambystoma californiense*), threatened slender Orcutt grass (*Orcuttia tenuis*), and endangered Sacramento Orcutt grass (*Orcuttia viscida*), are federally listed vernal pool endemic species found in Sacramento County, California. Vernal pools also support 13 species of special concern, such as the California fairy shrimp *(Linderiella occidentalis)* and western spadefoot toad (*Spea hammondii*). In addition, specialized ground-nesting bees in the family Andrenidae pollinate vernal pool plant species and use the pollen to feed their young (Thorp and Leong 1998). Certain vernal pool grassland areas are also federally designated as critical habitat for four vernal pool crustaceans and 11 different vernal pool plant species (USFWS 2003). Consequently, the biological uniqueness of vernal pools makes them critical areas for the conservation of biological diversity (Tiner 2003).

Key to the conservation of biodiversity is the accurate identification and classification of species and their habitats (Miller 2005; Ozesmi and Bauer 2002; Turner et al. 2003). Accurate identification and classification of habitat is necessary for planners to preserve biologically important areas, for managers to monitor populations and changes in habitat baselines, and for scientists to study spatial distributions and associations with various biotic and abiotic factors. Understanding key habitat associations can provide insight into underlying ecological processes. For example, plant composition of vernal pools at Beale Air Force Base differed between soil formations and species richness was positively correlated with vernal pool depth and surface area (Platenkamp 1998). In eastern Merced County, Metz (2001) found that vernal pool density (i.e., number of vernal pools per ha) was correlated with geological soil formations. In Sacramento County, the Sacramento County Planning Department (2006) is developing a South Sacramento Habitat Conservation Plan (SSHCP) using aerial photo interpretation to identify vernal pools and to create a vernal pool wetland acre density index. This density index was developed to assess the spatial distribution of vernal pools and their associations with different soil formations. Accurate classification is also important for understanding habitat variability and planning for the avoidance of those specific habitats associated with special status species. For example, the SSHCP (2006) describes federally listed and special status species that rely on different classes of vernal pools; Sacramento Orcutt grass (*Orcuttia viscida*) and slender Orcutt grass (*Orcuttia tenuis*) depend on deeper vernal pools, whereas dwarf Downingia (*Downingia pusilla*) depends on shallow pools. Barbour et al. (2003) also found that specific vernal pool

community types are directly associated with other rare plant species. Studies such as these facilitate our understanding of critical habitats and their spatial variability, which in turn can aid in planning for the protection of this diversity.

Historically, classification of vernal pool vegetation has been conducted at the whole pool level, meaning that no distinction is made between the shallow and deep bands of vegetation often observed in vernal pool wetlands (Barbour et al. 2003). Barbour et al. (2003) recently recognized 16 vernal pool vegetation community types throughout northern California's Central Valley and Sierra Nevada foothills. Contrary to the way vernal pool wetlands have been classified in the past, Barbour et al. (2003) found that vernal pools are often a mosaic of sub-communities that are geographically autonomous. Vernal pools in these regions are now collectively known as a new class called *Downingio bicornutae-Lasthenietea fremontii*. Additional studies are being conducted to establish diagnostic species and a hierarchal classification of these community types (Barbour et al. 2005). To date, Barbour et al. (2003) have established two distinct vernal pool orders under this new classification system: deep vernal pool communities (order *Lasthenietalia glaberrimae)* and shallow vernal pool communities (order *Downingio bicornutae-Lasthnietalia fremontii*). The deep vernal pool order is recognized by a dominance of rayless goldfields (*Lasthenia glaberrima*) and spike rush (*Eleocharis macrostachya*), whereas the shallow vernal pool order is recognized by a lack of dominance of either of these species (Barbour et al. 2003). The diagnostic species that characterize these communities are often different genera and have contrasting

canopy structures and flower colors. Because these communities may be spectrally distinct from one another, remote sensing methods may be able to identify and classify these types of vernal pool sub-communities for conservation purposes.

Remote sensing is becoming an increasingly powerful tool for identifying and classifying bio-physical properties for watershed, landscape, and eco-region based conservation efforts (Tiner 2004; Turner et al. 2003; Edwards et al. 1998; Biswas et al. 2002). Remote sensing of vernal pools may also provide more complete datasets, which may lead to a better understanding of the relationship between vernal pools and underlying soil conditions (Metz 2001). Furthermore, compared to traditional ground surveys, remote sensing can be a cost-effective means of acquiring habitat management data, especially for large geographic areas (Miller 2005; Turner et al. 2003; Ozesmi and Bauer 2002; Best 1982). However, the utility of remote sensing for conservation efforts depends on its overall accuracy and its ability to quantify bio-physical properties and ecological functions on a landscape scale (Glenn and Ripple 2004). Since conservation agencies rely on wetland mapping to quantify losses to wetlands and federally listed species habitat, it is important to assess and refine such techniques for future conservation efforts.

Two federal laws regulate the conservation of wetlands and federally listed species: the ESA and the Clean Water Act (CWA). The USFWS regulates vernal pools and other wetlands because they provide potential habitat for federally listed species

under the ESA. Pursuant to ESA requirements, the USFWS has prepared a vernal pool recovery plan for California and Southern Oregon to address the threats to federally listed vernal pool species (USFWS 2005). This recovery plan specifically identifies the refinement of Geographical Information Systems (GIS) and remote sensing techniques as a top priority action to meet recovery criteria (USFWS 2005). Under the CWA, the U.S. Army Corps of Engineers (USACE) regulates the discharge of dredged or fill material into waters of the United States, including wetlands. The USACE (1987) Wetland Delineation Manual states that remote sensing is one of the most useful sources of information in identifying wetland plant communities (USACE 1987). Indeed, remote sensing may provide a more efficient means of wetland identification.

Historically, wetland maps have been generated using aerial photo interpretation, ground survey, remote sensing, or a combination of these methods (Baker et al. 2006; Lyon 2001). However, photo interpretation of vernal pools may be less accurate than remote sensing methods using high resolution multispectral satellite imagery (Miller 2005). A potentially significant advantage of using a remote sensing approach for wetland mapping is that it may reduce inconsistencies and alleviate repeatability concerns associated with photo interpretation methods (Baker et al. 2006). Remote sensing also provides a means of assessing wetlands in cases where access to property cannot be obtained or ground-based methods are impractical.

The use of remote sensing techniques to identify and classify wetlands has been extensively applied over the past few decades (Glenn and Ripple 2004). However, one of the major limitations of satellite imagery has been the lack of adequate spatial resolution to resolve wetlands less than 2 acres (FGDC 1992). Most traditional satellites have a spatial resolution of 20 to 30 meters, making it difficult to identify wetlands smaller than this resolution (Ozesmi and Bauer 2002; Olmanson et al. 2002). In particular, vernal pools in California can range in size from one square meter to several hectares (Holland 1986). Holland (1996) mapped California's Great Central Valley vernal pool wetlands using aerial photo interpretation and concluded that available satellite images at that time were too expensive and that the image resolution was too course to reliably map features as small as vernal pools. Although Holland (1996) and Ozesmi and Bauer (2002) concluded that satellite remote sensing cannot provide the detailed information that aerial photography can, newer high resolution satellites and aerial mounted sensors provide new capabilities for remote sensing of smaller scale wetland types, such as vernal pools (Glenn and Ripple 2004).

Many of the new high resolution satellites, such as Digital Globes's® Quickbird satellite and Space Imaging's IKONOS® satellite, have spatial resolutions of 2-4 meters. Airborne sensors, such as Airborne Data Acquisition and Registration (ADAR) are able to collect even higher spatial resolution images of a few feet to inches, depending on the altitude of the aircraft. Using ADAR imagery, Hope and Coulter (2002) demonstrated that a 0.61-meter resolution is optimal for vernal pool vegetation classification.

Therefore, many of these new sensors have spatial resolutions that may be sufficient for vernal pool identification and classification.

Although wetlands have been extensively studied with remote sensing, there are no known remote sensing studies that have used high resolution satellite imagery to assess wetlands in the vernal pool grasslands of California's Central Valley. Previous vernal pool studies have primarily used aerial photo interpretation methods (Lathrop et al. 2005). Recently, however, there has been some success with the use of high resolution multispectral airborne sensors to detect vernal pools and classify their vegetation in southern California (Miller 2005; Hope and Coulter 2002).

Hope and Coulter (2002) evaluated the utility of high resolution multispectral ADAR imaging for delineating vernal pools and their specific vegetation, as well as estimating vernal pool depth. They achieved 60 to 75% accuracy in separating vernal pool flora, such as spike rush (*Eleocharis macrostachya)* and button celery (*Eryngium aristulatum)*. However, accuracy was poor in separating Otay mesa mint (*Pogogyne nudiuscula)*, adobe popcornflower (*Plagiobothrys acanthocarpus*), woolly marbles (*Psilocarphus brevissimus*), and flowering quillwort (*Lilaea scilloides*). Hope and Coulter (2002) stated that their poor accuracy may have been due to small sample size and/or inaccurate sample collection. They also found a poor relationship between spectral signature and vernal pool depth.

Similarly, Miller (2005) assessed the accuracy of various classification algorithms using ADAR imagery to detect vernal pools in San Diego, California. This study showed that a supervised maximum likelihood classification algorithm was superior to aerial photo interpretation and an unsupervised classification algorithm. Supervised classification uses an *a priori* (i.e., assignment of land cover classes prior to classification) method of training the algorithm for classification, verses an unsupervised classification that uses an *a posteriori* (i.e., assignment of land cover classes after classification) method of assigning clusters of pixels to land cover classes. Miller (2005) also found that accuracies for all classification methods were significantly higher with greater vernal pool size. Miller (2005) demonstrated that approximately 0.6-meter high resolution multispectral ADAR imaging could reliably detect vernal pools in southern California and that this approach could achieve a 61-75% accuracy. Miller (2005) assessed the accuracy of vernal pool detection based on whether classified vernal pool polygons were present or absent within the reference vernal pool polygons. Overall, Miller's (2005) study was aimed at detecting vernal pools for planning purposes and to aid in identifying locations warranting detailed ground surveys. The authors recommend that future investigations examine different remote sensors and vernal pool habitats.

The studies by Hope and Coulter (2002) and Miller (2005) suggest that high resolution multispectral satellite imagery is not likely to be a sound approach for estimating vernal pool water depth, but that these methods may be able to identify vernal pools and distinguish among vernal pool sub-communities. Since vernal pools in

Sacramento County are similar in spatial extent to those studied by Miller (2005), the accuracy for identification should be comparable using satellite imagery with spatial and spectral resolutions near that of ADAR imagery. Furthermore, the findings by Hope and Coulter (2002) that spike rush (*Eleocharis macrostachya),* a diagnostic species between deep and shallow vernal pool sub-communities, was spectrally separable from other species, provides evidence that vernal pool sub-communities can be accurately classified.

In the one study found that used high resolution imagery to identify wetlands consistent with the USACE Manual, O'Hara (2002) ranked and fused the results of ancillary data, such as hydrologic analysis and soils, and hyperspectral imagery classification to create a map that determined the likelihood of areas that would meet all three wetland parameters. In this study, O'Hara (2002) used a Euclidean (ordinary) distance grid to assess the accuracy of the likelihood map. Although a 95% accuracy of predicting the location of wetlands was reported, the accuracy assessment method did not incorporate a random sampling design or report the error of commission, which could be substantial. Because the study used a minimum 0.10 ha mapping unit, it is not applicable to studies of smaller wetlands, such as vernal pools. However, this study does suggest that ancillary data such as soils and detailed topography may improve results. It also provides evidence that remote sensing using high resolution imagery may be able to accurately identify wetlands.

Identification of wetlands and classification of vernal pools using high resolution satellite imagery may be a more efficient means to inventory and monitor these resources for regulatory and conservation purposes. The recent availability of high resolution satellite imagery provides new opportunities for the assessment of small scale wetlands, such as vernal pools. Yet, if wetland assessments and conservation decisions are to be made based on remote sensing efforts, accuracies must be within acceptable tolerances so users can determine the utility of such efforts (Baker et al. 2006; Glenn and Ripple 2004).

Although many remote sensing studies have been conducted on wetlands, there appear to be no studies that have examined the accuracy of high resolution multispectral satellite imagery to identify wetland plant communities in vernal pool grasslands. There also appear to be no studies that have used remote sensing to classify vernal pools using the classification developed by Barbour et al. (2003). Therefore, I hypothesize that wetland plant communities can be accurately identified using high resolution multispectral satellite imagery. I will test this hypothesis by comparing wetland plant communities that are identified by classification of high resolution multispectral satellite imagery with that of wetland communities identified using the USACE Wetland Delineation Manual. In addition, I hypothesize that vernal pool sub-communities can be accurately classified using high resolution multispectral satellite imagery. I will test this hypothesis by comparing vernal pool deep and vernal pool shallow sub-communities classified according to Barbour et al. (2003) with that of a high resolution multispectral satellite imagery classification.

METHODS

Study Area

The study area is located in eastern Sacramento County, California (Figure 1), within the Sacramento Valley Open Space Conservancy's (SVOSC) Sacramento Prairie Vernal Pool Preserve (SPVPP). The SPVPP is located to the east of Excelsior Road, west of Eagles Nest Road, south of Jackson Road/Highway 16, and north of Grant Line Road, within the U.S. Geologic Survey's, Elk Grove and Carmichael 7.5-minute topographic quadrangles (Figure 2). The climate of the region is Mediterranean, with hot dry summers and cool wet winters. Mean annual air temperature was 18°C for the years 2001-2005 and mean annual precipitation was 49 cm. Mean winter (December – March) air temperature was 11°C and mean winter precipitation was 35 cm, whereas mean summer (June-September) temperature was 25°C and mean summer precipitation was 2 cm (California Climate Data Archive 2006).

Three study sites totaling 368 ha were selected within the SPVPP: Gene Andal, Kassis, and Klotz (Figure 2). The study sites were chosen because they: 1) contained upland, seasonal wetland, and vernal pool habitats in sufficient numbers to allow for adequate replication across habitat types; 2) were accessible for ground surveys (i.e., property access); 3) were within a single 64 square-kilometer imagery collection area; and 4) were located on relatively undisturbed lands (i.e., not known to have experienced previous anthropogenic disturbances other than cattle grazing).

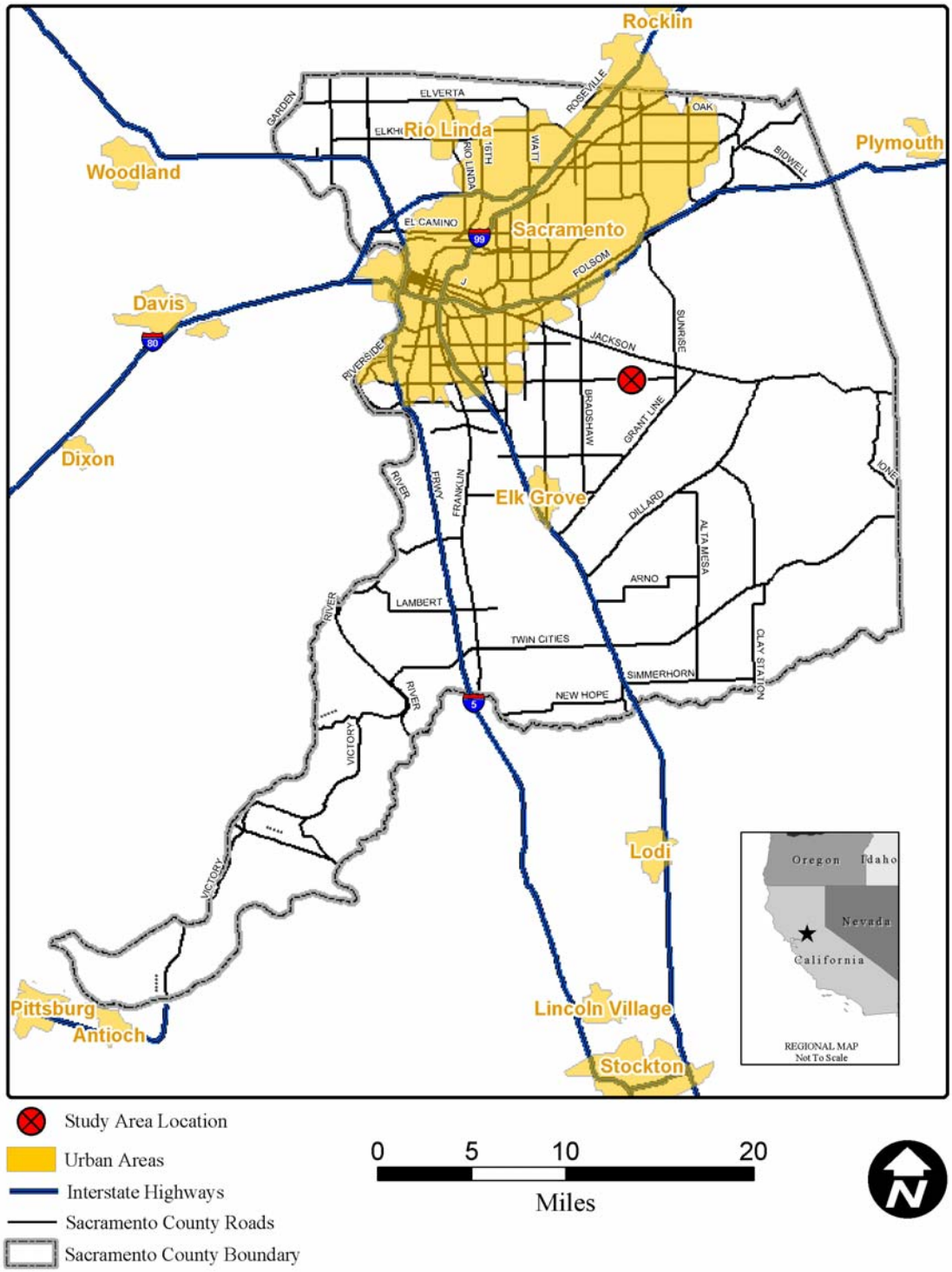

Figure 1. Vicinity map of the study area location in Sacramento County, California.

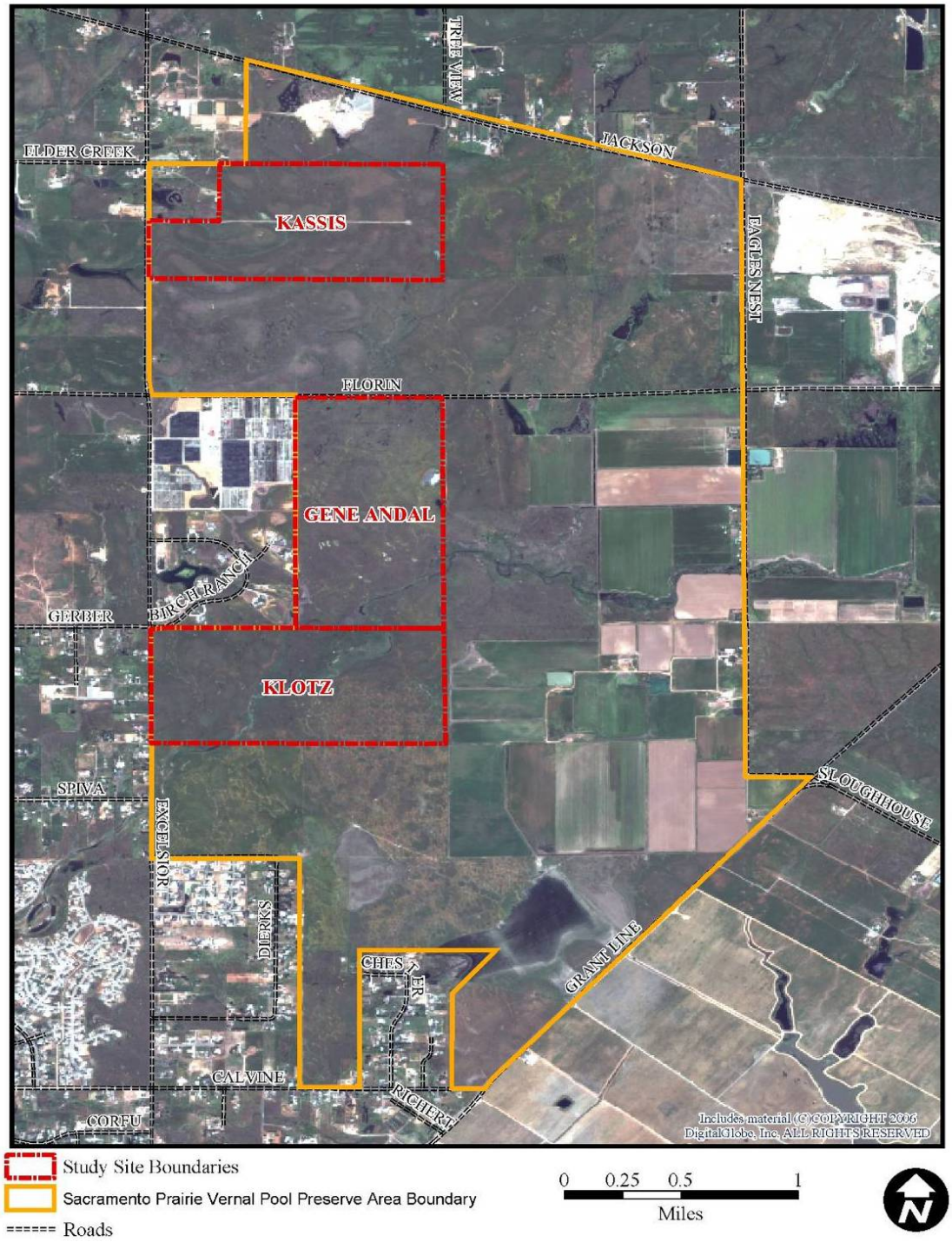

Figure 2. Map of the Gene Andal, Kassis, and Klotz study sites located within the Sacramento Prairie Vernal Pool Preserve boundary in Sacramento County, California. Satellite imagery resolution is 2.44-meter multispectral. Image was taken on May 7, 2006.

Study sites are located at approximate latitude 38.49 and longitude -121.28 (decimal degrees) and range from 26 to 38 m in elevation (Table 1). The vegetation of the study sites consists of vernal pool grassland communities occurring on a gently rolling topography and interspersed by mima-mounds. Vernal pools within the study sites are classified as northern hardpan vernal pools and are located in the southeastern Sacramento Valley vernal pool region (Keeler-Wolf et al. 1998; Witham 2005). They occur on low alluvial terraces with acidic soils and an underlying silicate-cemented hardpan (Keeler-Wolf et al. 1998; Witham 2005). Kassis soils are composed of Redding gravelly loam and Red Bluff – Redding complex soils (USDA 2006), whereas the Gene Andal study site includes these soil types plus Fiddyment fine sandy loam and a small fraction of Hedge loam (USDA 2006). The Klotz site is a mix of Redding, Hedge, Fiddyment and San Joaquin silt loam (USDA 2006). Vernal pools at the study sites typically occur on the Redding, Hedge, and San Joaquin soil types, whereas Red Bluff soils generally support upland communities (Witham 2005). Laguna Creek traverses and drains the Gene Andal and Klotz study sites to the south-west. This creek is perennial due to upstream hydrologic inputs in the summer from agricultural irrigation and a nursery on the southeast corner of Excelsior and Florin Roads. An ephemeral stream to Elder Creek also traverses and drains the Kassis study site to the south-west.

Table 1. Locations, areas, elevations, vegetation, and soils of the three study sites: Gene Andal, Kassis, and Klotz. Vegetation community series correspond to Sawyer and Keeler-Wolf's (1995) classification of California vegetation. Soil series are those described by USDA (2006) as occurring within the study sites.

Study Site	Area (ha)	Latitude, Longitude (Decimal degrees)	Elevation Range (m)	Vegetation Community Series	Soil Series
Gene Andal	128	38.490, -121.284	32-38	California Annual Grassland, Northern Hardpan Vernal Pools, Spike-rush, Valley Oak	Fiddyment fine sandy loam, Hedge loam, Redding gravelly loam, Red Bluff – Redding complex
Kassis	113	38.507, -121.288	27-37	California Annual Grassland, Northern Hardpan Vernal Pools, Spike-rush, Cattail, Bulrush, Sedge	Redding gravelly loam, Red Bluff – Redding complex
Klotz	128	38.478, -121.288	26-34	California Annual Grassland, Northern Hardpan Vernal Pools, Spike-rush, Cattail, Bulrush, Sedge	Fiddyment fine sandy loam, Redding gravelly loam, San Joaquin silt loam, Hedge loam

At the time of this study, each site was subject to different levels of grazing intensity. At the Kassis site, grazing intensity is approximately 1.375 animal unit months (AUM). An AUM is defined as the amount of forage required to support either one adult cow, one horse, one mule, five sheep, or five goats for 30 days. These two sites have been grazed at a level of 1 cow for every 4 to 5 acres over a six month grazing season or 1 cow for 5 to 6 acres for an eight month grazing season (Witham 2005). During the year in which the study was conducted, the Kassis site was grazed for eight months (January to August) (A. Rutledge, pers. comm.). The Gene Andal site was ungrazed at the time of this study (A. Rutledge, pers. comm.) and, although there is no available record, the site has probably been ungrazed for the past several years. The Klotz study area was grazed with 35 heifers between November and June, 2006 (H. Krolick, pers. comm.).

Remote Sensing Imagery

Digital Globe's® Quickbird satellite imagery was used because it has the highest spatial resolution that is commercially available. The Quickbird satellite simultaneously collects a panchromatic (i.e., black and white) and multispectral image, both of which are different in their spatial and spectral resolutions. Spatial resolution for the panchromatic image is 0.61-meter, whereas for the multispectral image it is 2.44-meter. Spectral resolution for the panchromatic image is one band (450 to 900 nm) versus four bands for the multispectral image (blue: 450 to 520 nm; green: 520 to 600 nm; red: 630 to 690 nm; and near-infrared: 760 to 900 nm).

To improve classification accuracy, images were acquired during the time period most likely to result in maximum contrast between the classes of interest (Jensen 2004). Maximum spectral contrast for vernal pools and their sub-communities typically occurs when pool levels are receding and plants are flowering and producing seed, a phase described as the drying phase (Zedler 1987). Given the brief window of opportunity during which vernal pool wetlands are in flower, the timing of imagery collection was critical (Miller 2005; Ozemsi et al. 2002). Study sites were closely monitored for optimal conditions. Optimal conditions were considered to be the time when the majority of vernal pool flora was not covered with water and minimal cloud cover was anticipated based on weather forecasts. When optimal conditions were anticipated, Digital Globe® was notified to proceed with imagery collection. On May 7, 2006, Digital Globe® collected a 64 square-kilometer imagery area using the company's Quickbird Satellite. The imagery consisted of both a 2.44-meter multispectral image and a separate 0.61-meter panchromatic image.

To minimize geometric and positional errors, the imagery was rectified to known global positioning system (GPS) coordinate locations collected in the field. Seven GPS coordinates with approximately sub-meter accuracy were collected with a Trimble® GeoXT GPS, which received real-time differential corrections via Trimble's® Beacon-on-a-Belt. Using GPS coordinates and ESRI's ArcGIS 8.3 referencing tools, the imagery was rectified to a Universal Transverse Mercator (UTM), Zone 10, North American Datum 1983, projection.

Sampling Approach

To create randomly selected sampling areas within each study site, remote sensing imagery was partitioned into spectrally homogeneous sample polygons using an object-oriented segmentation algorithm in SPRING 4.2 software (Camera et al. 1996), technical protocols adapted from USFWS (2006a and 2006b), and Hawth's Analysis Tools for ArcGIS (Beyer 2004). Sample polygons were assigned to one of 6 land cover classes, such that there were 10 sample polygons per land cover class at each site, for a total of 60 sample polygons per site and 180 sample polygons across all three sites.

Sample polygons were ground-truthed between May 15 and June 30, 2006, and assigned to land cover classes by locating them in the field with a GPS, assessing them to ensure homogeneous vegetation communities (i.e., only one land cover class), and classifying them according to the key in Table 2. A 1 m^2 plot within each of the sample polygons was used to assess dominant species of any plant community and assign it to a class. To minimize sampling error, sample polygons that were greater than 4,000 m^2, unidentifiable, or contained more that one land cover class, were deleted and new sample polygons were delineated via GPS at that location. Because vernal pool vegetation became desiccated and open water areas rapidly evaporated by mid-May, it was difficult to accurately identify vegetation and open water classes after May. To further minimize sampling error associated with desiccation, vegetation cover classes were collected first; urban and water sample polygons were classified subsequently using photo interpretation.

Table 2. Dichotomous key used to assign land cover classes to training polygons in the field. Six land cover classes were distinguished: upland, seasonal wetland, shallow vernal pool, deep vernal pool, water and urban. Key adapted from USGS (1976) remote sensing classification key and modified to include: vernal pool indicator species in Keeler-Wolf et al. (1998), USACE Manual (1987) wetland plant communities, and vernal pool sub-communities identified by Barbour et al. (2003).

---

1 Area with >5% vegetative cover and no anthropogenic features……..……..2

2 Area does not meet wetland plant community per USACE Manual…….…...**Upland**

2' Area meets wetland plant community per USACE Manual……..3

3 Area not dominated by one or more vernal pool indicator species……....**Seasonal Wetland**

3' Area dominated by one or more vernal pool indicator species…….……..4

4 Area not dominated by spike rush (*Eleocharis macrostachya*) and/or rayless goldfields (*Lasthenia glaberrima*)……..…...**Shallow Vernal Pool**

4' Area dominated by spike rush (*Eleocharis macrostachya)* and/or rayless goldfields (*Lasthenia glaberrima*) ……..…**Deep Vernal Pool**

1' Area <5% vegetative cover, anthropogenic features may be present ……...…….……5

5 Area >50% cover of ponded water……..……...…..**Water**

5' Area <50% cover of ponded water……..……....**Urban**

A dichotomous key (Table 2) was developed to assign the random sample areas to land cover classes. The key was adapted from the USGS's (1976) report on land-use classification for remote sensing and modified to include wetland plant communities identified using the USACE Manual, vernal pool indicator species from Keeler-Wolf et al. (1998), and vernal pool deep and shallow orders identified by Barbour et al. (2003). Six land-cover classes were identified: upland, seasonal wetland, shallow vernal pool, deep vernal pool, open water (i.e., ponded water with no exposed emergent vegetation), and urban (e.g., roads and residential development).

Anthropogenic features were distinguished from vegetated classes based on whether they exhibited greater than 5% vegetative cover (Table 2). Open water was distinguished from anthropogenic features by the presence of greater than 50% open water cover. Vegetated classes were classified as either uplands or wetlands using the USACE Manual criteria for determining wetlands based on the dominance of hydrophytic vegetation. Dominance was based on the USACE Manual recommended use of the "50/20" rule. Within a plot, dominant species were those that cumulatively exceeded 50% or greater cover (in descending order of abundance), and any species that individually had a 20% or greater relative cover (USACE 1987). If greater than 50% of the dominants were wetland species, as identified in the USFWS's (1988) national list of wetland plant species, the area was classified as wetland. Plant species were identified using Hickman (1993). Wetlands were classified as vernal pools if one or more of the dominants were vernal pool indicator species, as defined by Keeler-Wolf et al. (1998).

Vernal pools were further classified into deep or shallow vernal pools based on Barbour et al. (2003) and classified as deep vernal pools if they contained a dominance of spike rush (*Eleocharis macrostachya*) and/or rayless goldfields (*Lasthenia glaberrima*). Vernal pools were classified as shallow vernal pools if they did not contain a dominance of either of these species. An example of a shallow vernal pool, a deep vernal pool, an upland, and open water land cover class are shown in Figures 3 - 5.

Figure 3. Gene Andal study site on May 16, 2006. The photograph illustrates the spectral similarity between yellow-orange goldfields (*Lasthenia fremontii*), located in the bottom of the shallow vernal pool, and yellow cat's ear (*Hypochaeris glabra*) which is a dominant in the surrounding uplands.

Figure 4. Gene Andal study site on the day of satellite image collection, May 7, 2006. The photograph illustrates a deep vernal pool community dominated by spike rush (*Eleocharis macrostachya*) and open water areas containing less than 5% vegetative cover.

Figure 5. Kassis study site on the day of satellite image collection, May 7, 2006. The photograph illustrates a deep vernal pool community that is dominated by spike rush (*Eleocharis macrostachya*), and yellow cat's ear (*Hypochaeris glabra*) which is a dominant in the surrounding uplands

Accuracy Assessment

To assess the ability of high resolution remote sensing imagery to identify wetlands and classify vernal pool sub-communities, classified imagery was compared to unbiased reference areas on the ground (Congalton and Green 1999; Glenn and Ripple 2004). In addition to error matrices, which are an accepted analytical tool for assessing thematic map accuracy of remote sensing images (Lunetta and Lyon 2004; Foody 2002; Congalton and Green 1999), significance tests were also used for hypothesis testing. Replicate study sites served as controls for site to site environmental variability.

At each site, the 60 sample polygons (representing 10 in each cover class) were divided randomly by land cover class into 30 training polygons and 30 reference polygons. Training polygons were used to classify the image, whereas reference polygons were set aside for accuracy assessment. Training polygons represent the pixels used to classify the image through a classification algorithm (description below), whereas reference polygons represent the pixels against which the classified image was compared.

To classify the image at each site, the pixels within the training polygons were processed through a supervised maximum likelihood classification algorithm using Leica Geosystems Imagine Analysis™ for ArcGIS software. A comparison of the satellite imagery, training areas, and resulting classification for the Kassis site is shown in Figures 6 and 7. Once each site was classified, the total number of correctly and incorrectly

classified pixels within each reference polygon was determined using Hawth's Analysis Tools for ArcGIS (Beyer 2004).

Data Analysis

To determine whether a relationship existed between reference polygon area and classification accuracy, a regression analysis was conducted. To determine whether there were significant differences in accuracy among sites and land cover classes, a two-way analysis of variance (ANOVA) was performed with site and land cover class accuracies as the two fixed factors. Differences in reference polygon areas were standardized by calculating an accuracy ratio for each reference polygon. The accuracy ratio was calculated by dividing the correctly classified area, based on pixels, by the reference polygon area. To meet the assumptions of parametric statistical analysis, the accuracy ratio was transformed using an arcsine square-root function prior to statistical analysis. Tukey's post-hoc tests were conducted to compare mean accuracy ratios across land cover classes and sites. To compare accuracy ratios across land cover classes within sites, separate one-way ANOVAs and Tukey's post-hoc tests were conducted. One-way ANOVAs were preformed with site as the fixed factor.

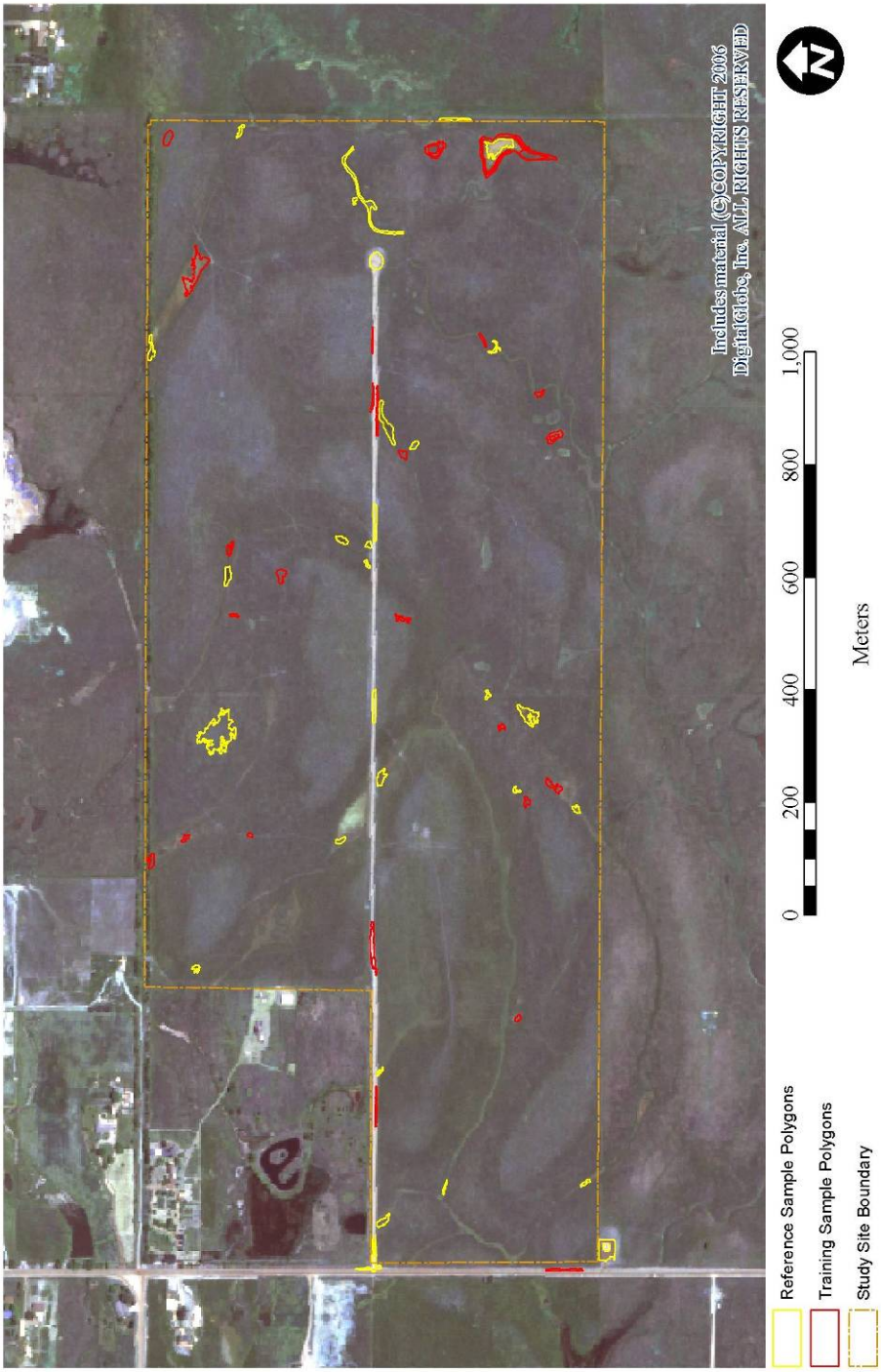

Figure 6. A 2.44-meter multispectral satellite image of the Kassis site. Shown is the study site boundary and the location of training sample polygons used for image classification and the reference sample polygons used for accuracy assessment.

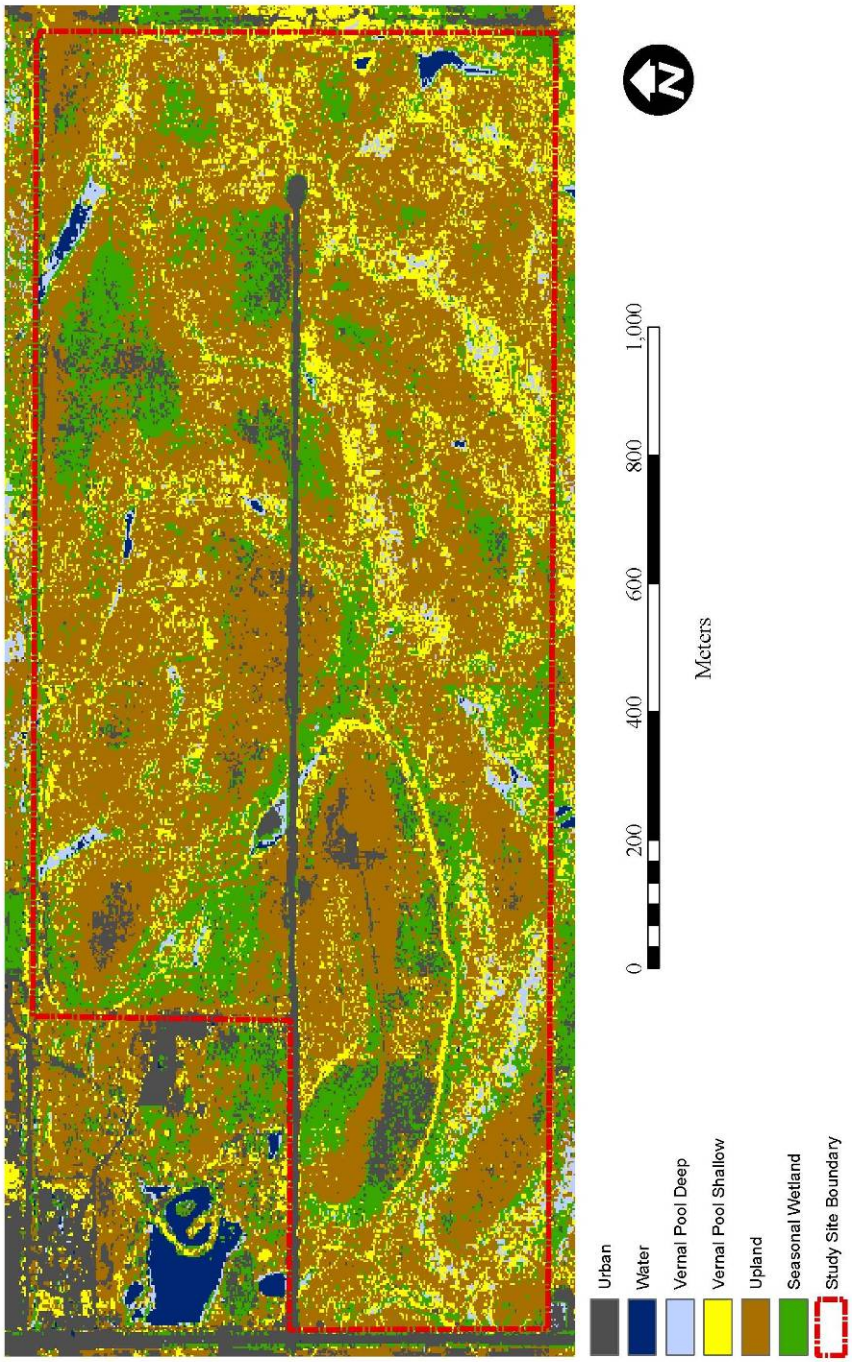

Figure 7. Classification map of the Kassis study site. Shown are the results of the imagery classification for all six classes: urban, water, vernal pool deep, vernal pool shallow, and seasonal wetland. Classification was conducted using 2.44-meter multispectral satellite imagery, training polygons, and a supervised maximum likelihood classification algorithm.

To determine whether land cover classes were accurately classified, paired t-tests were conducted by comparing the reference polygon areas and the correctly classified area within those reference polygons. For this study, a 95% accuracy level was chosen as the acceptable level of accuracy. Therefore, a 5% significance level was used to for all statistical analyses. All significance tests were calculated using Statistica software by StatSoft®.

In addition to tests of significance, error matrices were generated to aid in assessing potential sources of classification error. Both the "producers" accuracy (i.e., the accuracy relevant to the map producer) and the "users" accuracy (i.e., the accuracy relevant to the map user), were also calculated. For each study site, two error matrices were generated. Two error matrices were generated for each study site: one for wetland (i.e., seasonal wetland, vernal pool shallow, vernal pool deep and water) and non-wetland (i.e., upland and urban) land cover classes, and the other included all 6 land cover classes.

RESULTS

General Vegetation Patterns

Of the 368 ha for all three sites, image classification resulted in 13% of the sites being classified as seasonal wetland, 33% as upland, 3% as urban, 20% as vernal pool deep, 30% as vernal pool shallow, and 1% as open water. Classification areas by land cover class and by site are presented in Table 3.

Ten species were found as a dominant in one or more land cover classes (Table 4). Nutsedge (*Cyperus eragrostis*), bermuda grass (*Cynodon dactylon*), manna grass (*Glyceria declinata*), and toad rush (*Juncus bufonius*) were dominants in seasonal wetland and vernal pool deep classes. Two species were found as dominants in three land cover classes; Mediterranean barley (*Hordeum marinum*) was a dominant in seasonal wetland, upland, and vernal pool deep classes, whereas cat's ear (*Hypochaeris glabra*) was a dominant in seasonal wetland, upland, and vernal pool shallow classes. Purple loosestrife (*Lythrum hyssopifolia*) was a dominant in seasonal wetland and vernal pool shallow classes. Downingia (*Downingia bicornuta*), vernal pool buttercup (*Ranunculus bonariensis*), and coyote thistle (*Eryngium vaseyi*) were all found as dominants in both vernal pool deep and vernal pool shallow classes.

Table 3. Land cover classification areas (ha) by land cover class and by site for the three study sites. Total area of the three study sites was 368 ha.

Site	Seasonal Wetland	Upland	Urban	Vernal Pool Deep	Vernal Pool Shallow	Water	Site Totals
Gene Andal	20	26	5	41	35	1	128
Kassis	19	68	7	3	16	1	113
Klotz	11	27	0	31	58	1	128
Class Totals	49	121	12	74	109	3	

Table 4. Dominant plant species based on collection of vegetation data for assignment of sample polygons to land cover class. Species are listed by land cover class and by site.

Seasonal Wetland	Upland	Vernal Pool Deep	Vernal Pool Shallow
Gene Andal			
Cyperus eragrostis	*Avena fatua*	*Cyperus eragrostis*	*Downingia bicornuta*
Cynodon dactylon	*Briza minor*	*Downingia bicornuta*	*Downingia ornatissima*
Epilobium pallidum	*Bromus diandrus*	*Eleocharis macrostachya*	*Eryngium vaseyi*
Hordeum marinum	*Bromus hordeaceus*	*Eryngium vaseyi*	*Lasthenia fremontii*
Lolium multiflorum	*Geranium dissectum*	*Isoetes howellii*	*Layia fremontii*
Lolium perenne	*Hypochaeris glabra*	*Lasthenia glaberrima*	*Navarretia leucocephala*
Paspalum dilatatum	*Quercus lobata*	*Ranunculus bonariensis*	*Pogogyne zizyphoroides*
Rumex crispus	*Raphanus sativus*		*Ranunculus bonariensis*
Typha latifolia	*Thysanocarpus radians*		
	Vicia villosa		
Kassis			
Glyceria declinata	*Avena fatua*	*Cynodon dactylon*	*Cuscuta howelliana*
Hordeum marinum	*Briza minor*	*Eleocharis macrostachya*	*Eryngium vaseyi*
Hypochaeris glabra	*Bromus hordeaceus*	*Eryngium vaseyi*	*Glyceria declinata*
Juncus bufonius	*Hordeum murinum*		*Lythrum hyssopifolia*
Lythrum hyssopifolia	*Taeniatherum caput-madusae*		*Navarretia leucocephala*
	Trifolium hirtum		
Klotz			
Cynodon dactylon	*Achyrachaena mollis*	*Cynodon dactylon*	*Deschampsia danthonioides*
Cyperus eragrostis	*Aegilops triunciallis*	*Eleocharis macrostachya*	*Downingia bicornuta*
Hordeum marinum	*Avena fatua*	*Eryngium vaseyi*	*Eryngium vaseyi*
Juncus bufonius	*Bromus diandrus*	*Glyceria declinata*	*Hypochaeris glabra*
Lolium multiflorum	*Holocarpha virgata*	*Hordeum marinum*	*Lasthenia fremontii*
Paspalum dilatatum	*Hordeum marinum*	*Juncus bufonius*	*Navarretia leucocephala*
Polygonum amphibium	*Hypochaeris glabra*	*Lasthenia glaberrima*	
Rumex pulcher	*Taeniatherum caput-madusae*		
Scirpus acutus	*Vicia villosa*		
Typha latifolia			
Xanthium strumarium			

Error Matrices

When land cover classes were grouped into wetland and non-wetland classes, wetlands were correctly classified 85% of the time for the Gene Andal site, however 51% of the time non-wetlands were misclassified as wetlands for this site (Table 5). The Gene Andal site had the lowest overall accuracy of 74% (Table 5). The Kassis site had the highest wetland classification accuracy of 92% and non-wetlands were misclassified as wetlands 15% of the time, with the highest overall accuracy of 89% (Table 6). Wetlands were accurately classified 91% of the time at the Klotz site; however, this site had the highest misclassification of non-wetlands as wetlands at 58%, with an intermediate overall classification of 85% (Table 7).

For the Gene Andal site, individual classification accuracies are: 65% for seasonal wetland, 32% for upland, 94% for urban, 15% for vernal pool deep, 51% for vernal pool shallow, and 42% for water, with the lowest overall site accuracy for all classes of 49% (Table 8). For this site, seasonal wetlands were misclassified as urban and uplands. Vernal pool deep communities were misclassified as water, and vernal pool shallow communities were misclassified as uplands, but also urban. Water was misclassified as urban and vernal pool deep communities.

Table 5. Error matrix of the classification data for identification of wetland vs. non-wetland land cover classes at the Gene Andal study site (Numbers represent 2.44 meter pixels).

	Reference Data				
Classification Data	Non-Wetland	Wetland	Totals	Commission Error	Users Accuracy
Non-Wetland	**161**	123	284	43%	57%
Wetland	168	**686**	854	20%	80%
Totals	329	809	1138		
Omission Error	51%	15%			
Producers Accuracy	49%	85%			
Overall Accuracy	74%				

Table 6. Error matrix of the classification data for identification of wetland vs. non-wetland land cover classes at the Kassis study site (Numbers represent 2.44 meter pixels).

	Reference Data				
Classification Data	Non-Wetland	Wetland	Totals	Commission Error	Users Accuracy
Non-Wetland	**741**	71	812	9%	91%
Wetland	126	**847**	973	13%	87%
Totals	867	918	1785		
Omission Error	15%	8%			
Producers Accuracy	85%	92%			
Overall Accuracy	89%				

Table 7. Error matrix of the classification data for identification of wetland vs. non-wetland land cover classes at the Klotz study site (Numbers represent 2.44 meter pixels).

	Reference Data				
Classification Data	Non-Wetland	Wetland	Totals	Commission Error	Users Accuracy
Non-Wetland	**73**	102	175	58%	42%
Wetland	102	**1050**	1152	9%	91%
Totals	175	1152	1327		
Omission Error	58%	9%			
Producers Accuracy	42%	91%			
Overall Accuracy	85%				

Table 8. Error matrix of the classification data for all 6 land cover classes at the Gene Andal study site (Numbers represent 2.44-meter pixels).

	Reference Data								
Classification Data	Seasonal Wetland	Upland	Urban	Vernal Pool Deep	Vernal Pool Shallow	Water	Totals	Commission Error	Users Accuracy
Seasonal Wetland	**35**	46	0	1	1	9	92	62%	38%
Upland	7	**54**	5	2	33	0	101	47%	53%
Urban	10	3	**152**	1	24	299	489	69%	31%
Vernal Pool Deep	0	27	0	**7**	7	28	69	90%	10%
Vernal Pool Shallow	1	38	4	1	**67**	1	112	40%	60%
Water	1	0	0	34	0	**240**	275	13%	87%
Totals	54	168	161	46	132	577	1138		
Omission Error	35%	68%	6%	85%	49%	58%			
Producers Accuracy	65%	32%	94%	15%	51%	42%			
Overall Accuracy	49%								

Table 9. Error matrix of the classification data for all 6 land cover classes at the Kassis study site (Numbers represent 2.44-meter pixels).

	Reference Data								
Classification Data	Seasonal Wetland	Upland	Urban	Vernal Pool Deep	Vernal Pool Shallow	Water	Totals	Commission Error	Users Accuracy
Seasonal Wetland	**10**	71	13	78	46	22	240	96%	4%
Upland	39	**310**	0	13	29	3	394	21%	79%
Urban	3	85	**335**	2	0	2	427	22%	78%
Vernal Pool Deep	0	0	36	**147**	21	50	254	42%	58%
Vernal Pool Shallow	18	16	0	19	**140**	3	196	29%	71%
Water	0	0	1	47	0	**226**	274	18%	82%
Totals	70	482	385	306	236	306	1785		
Omission Error	86%	36%	13%	52%	41%	26%			
Producers Accuracy	14%	64%	87%	48%	59%	74%			
Overall Accuracy	65%								

Table 10. Error matrix of the classification data for all 6 land cover classes at the Klotz study site (Numbers represent 2.44-meter pixels).

	Reference Data								
Classification Data	Seasonal Wetland	Upland	Urban	Vernal Pool Deep	Vernal Pool Shallow	Water	Totals	Commission Error	Users Accuracy
Seasonal Wetland	**21**	43	0	35	4	2	105	80%	20%
Upland	9	**35**	0	27	10	25	106	67%	33%
Urban	0	0	**65**	0	0	0	65	0%	100%
Vernal Pool Deep	57	11	1	**25**	2	2	98	74%	26%
Vernal Pool Shallow	20	20	0	32	**62**	1	135	54%	46%
Water	2	0	0	16	0	**800**	818	2%	98%
Totals	109	109	66	135	78	830	1327		
Omission Error	81%	68%	2%	81%	21%	4%			
Producers Accuracy	19%	32%	98%	19%	79%	96%			
Overall Accuracy	76%								

Classification accuracies for the Kassis study site are 14% for seasonal wetland, 64% for upland, 87% for urban, 48% for vernal pool deep, 59% for vernal pool shallow and 79% for water, with an overall accuracy for all classes of 65%. Vernal pool deep communities were misclassified as seasonal wetland, but also as water. Vernal pool shallow communities were misclassified with uplands, but also with vernal pool deep and upland communities. Seasonal wetlands were misclassified as uplands and also as vernal pool shallow communities. Water was misclassified as vernal pool deep communities.

The Klotz study site accuracies are 19% for seasonal wetland, 32% for upland, 98% for urban, 19% for vernal pool deep, 79% for vernal pool shallow and 96% for water, with an overall accuracy for all classes of 76%. Vernal pool deep communities were misclassified as uplands, seasonal wetlands, vernal pool shallow communities and water. Vernal pool shallow communities were misclassified as uplands. Seasonal wetlands were misclassified as vernal pool deep communities and vernal pool shallow communities. Water had a high accuracy for this site, but misclassified with uplands.

Classification Accuracy

There was no significant relationship between reference sample areas and classification accuracies, as shown by regression analysis (Figure 8). Hence, there was no need to separate accuracy assessment based on reference polygon size.

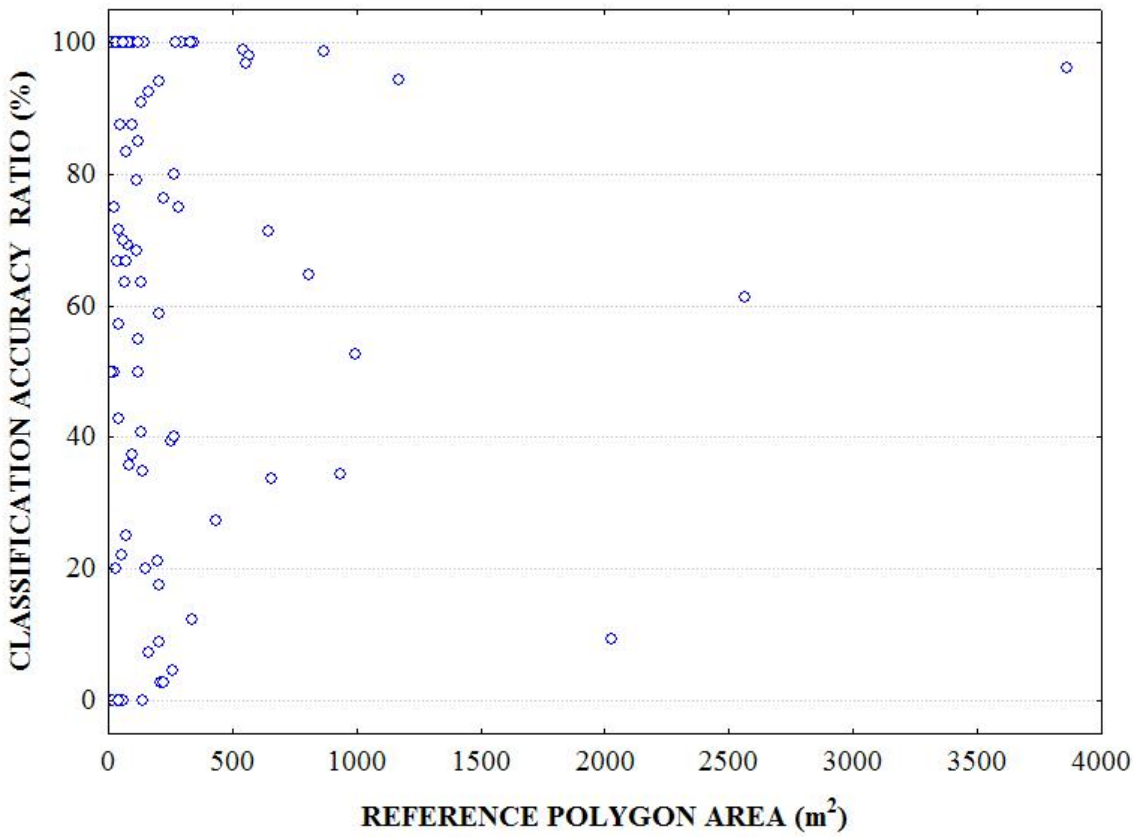

Figure 8. Regression plot of reference polygon area (m^2) and classification accuracy (%) ratio ($F_{(\alpha=0.05,\ df=88)} = 0.768$, $P = 0.383$, $R^2 = 0.009$). Accuracy ratios were calculated by dividing the correctly classified area, based on pixels, by the reference polygon area.

The overall classification accuracy ratios among sites ranged from 50 to 62% but did not differ significantly ($F_{(\alpha=0.05,\ df=2)} = 2.03,\ P = 0.138$) (Table 11). However, mean accuracy ratios of land cover classes ranged from 26 to 94% and differed significantly across sites ($F_{(\alpha=0.05,\ df=5)} = 13.45,\ P < 0.001$) (Table 11; Figure 9). Mean seasonal wetland class accuracy ratios differed significantly from urban, water and vernal pool shallow classes, but did not differ from the vernal pool deep class. Mean upland class accuracy ratios did not differ significantly from seasonal wetland, deep or shallow vernal pool classes, but did differ from water and urban class. Vernal pool deep class accuracy ratios only differed significantly from urban, whereas the vernal pool shallow class accuracy ratio differed from urban and seasonal wetland. The water class accuracy ratio differed significantly from the seasonal wetland and upland classes, whereas the urban class accuracy ratio differed significantly from all but the water class.

A significant ($F_{(\alpha=0.05,\ df=10)} = 2.81,\ P = 0.005$) interaction between site and class was also found, suggesting that class accuracies differed across sites. This was evident in that site accuracies differed significantly within the upland class but not within any other land cover class. Specifically, the Kassis site showed significantly ($F_{(\alpha=0.05,\ df=2)} = 13.54,\ P < 0.001$) higher upland classification accuracy than either the Gene Andal or Klotz sites (Table 11; Figure 9). All other cover class accuracies did not differ significantly among sites (Table 11; Figure 9).

Table 11. Mean (±SE) classification accuracy ratios (%) among sites, land cover classes and classes within sites. Accuracy ratios are calculated from the correctly classified areas within the reference areas, divided by the reference areas and converted to a percentage. Overall land cover class accuracies with the same upper case letters do not differ significantly at $P < 0.05$. Overall, within land cover classes, site accuracies with the same lower case letters do not differ significantly at $P < 0.05$. Site accuracies with the same lower case letters do not differ significantly at $P < 0.05$.

Site	Land Cover Classes						Site Accuracy
	Seasonal Wetland	Upland	Vernal Pool Deep	Vernal Pool Shallow	Water	Urban	
Gene Andal	34 [a] (0.21)	7 [a] (0.07)	55 [a] (0.20)	51 [a] (0.07)	62 [a] (0.17)	93 [a] (0.07)	50 [a] (0.07)
Kassis	14 [a] (0.07)	83 [b] (0.08)	45 [a] (0.11)	70 [a] (0.06)	59 [a] (0.17)	93 [a] (0.07)	60 [a] (0.06)
Klotz	29 [a] (0.12)	41 [a] (0.13)	32 [a] (0.17)	78 [a] (0.09)	97 [a] (0.02)	98 [a] (0.03)	62 [a] (0.07)
Class Accuracy	26 [D] (0.06)	43 [CD] (0.07)	52 [BCD] (0.06)	58 [BC] (0.04)	73 [AB] (0.06)	94 [A] (0.02)	

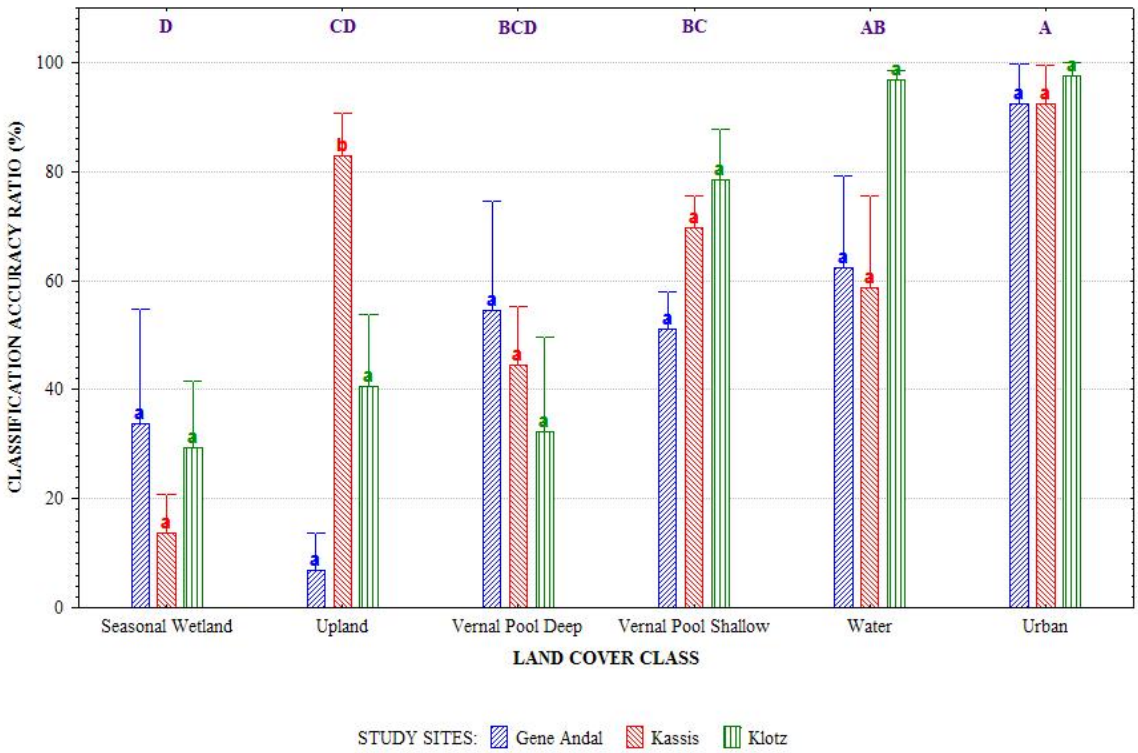

Figure 9. Mean classification accuracy ratios for the 6 land cover classes at each of the three sites. Mean land cover class accuracies with the same upper case letters do not differ significantly at $P < 0.05$. Within land cover classes, sites with the same lower case letters do not differ significantly at $P < 0.05$.

Because accuracy ratios did not differ significantly across sites within any of the wetland land cover classes or the urban land cover class, site data were pooled for each of the wetland classes and the urban cover class. Consequently, separate t-tests were conducted for each wetland class and the urban class to compare reference polygon areas with that of the correctly classified remote sensing areas within the reference polygons. Urban and water classification areas did not differ significantly ($P_{(\alpha=0.05,\ df=14)} = 0.230$ and $P_{(\alpha=0.05,\ df=14)} = 0.161$, respectively) from reference polygons, suggesting classification was accurate for these classes. However, seasonal wetland, vernal pool deep, and vernal pool shallow classification areas all differed significantly ($P_{(\alpha=0.05,\ df=14)} = 0.005$, $P_{(\alpha=0.05,\ df=14)} = 0.001$, and $P_{(\alpha=0.05,\ df=14)} = 0.042$, respectively) from reference polygons, suggesting classification was not accurate for these classes. In all cases, the correctly classified remote sensing areas were never greater than the reference polygons areas.

DISCUSSION

Overall, the results support the hypothesis that remote sensing classification of high resolution satellite imagery can accurately identify open water wetlands, but do not support the hypothesis for other wetland classes. Results also do not support the hypothesis that remote sensing classification of high resolution satellite imagery can accurately classify vernal pool deep or vernal pool shallow communities. Although the hypotheses were generally not supported, other similar studies also failed to achieve a 95% accuracy level for all land cover classes. Whereas Hope and Coulter (2002) achieved 60 to 75% accuracy in separating vernal pool species and Miller (2005) reported 61 to 75% accuracy in detecting vernal pools, this study achieved 52 to 58% accuracy for identifying and classifying vernal pool sub-communities as defined by Barbour et al. (2003). Although accuracies for vernal pools were somewhat lower than Hope and Coulter (2002) and Miller (2005), the courser spatial resolution of the imagery for this study may be the source of the differences. Regardless of these differences, management decisions based on remote sensing must be held to a high standard of accuracy. The fact that the observed accuracies in this study did not meet the 95% level points to the need to refine the approach by correcting for potential sources of error identified in this study.

A likely source of error in accurately identifying and classifying wetland plant communities under the USACE Manual is that some species are found in both uplands and wetlands. For remotely sensed imagery, this leads to spectral confusion and misclassification between the classified image and reference sample polygons. Wetland

plant species range from obligate species found >99% of the time in wetlands, to facultative species found 33 to 67% of the time in wetlands and uplands (USFWS 1988; USACE 1987). Facultative species, such as common Mediterranean barley (*Hordeum marinum*), is generally found in "marginally" (i.e., moist) wet areas but can also be found in dry upland areas (Hickman 1993). Because facultative wetland species can occur in both uplands and wetlands, this can confound separation of these communities based solely on their spectral characteristics. Likewise, errors in classification of vernal pool sub-communities includes spectral confusion from facultative species and species that are found occasionally in both shallow and deep vernal pool sub-communities [e.g., spike rush (*Eleocharis macrostachya*) and downingia (*Downingia bicornuta*), vernal pool buttercup (*Ranunculus bonariensis*), and coyote thistle (*Eryngium vaseyi*)]. Although a dominance of spike rush is an indicator of vernal pool deep communities (Barbour et al. 2003), in this study it was occasionally found as an associate species in some vernal pool shallow communities. Ancillary data layers, such as high resolution topography and soils data, should facilitate separation of these wetland and upland communities based on landscape position or soil type, and thus increase wetland classification accuracies.

Although it was assumed that maximum spectral contrast between uplands and wetlands would occur during the vernal pool drying cycle, several upland species were spectrally similar to vernal pool species during this time. For example, at the time of imagery acquisition, some uplands were dominated by cat's ear (*Hypochaeris glabra*). Cat's ear has a yellow inflorescence that is similar in spectral signature to the yellow-

orange vernal pool goldfields (*Lasthenia fremontii*) and yellow-white Fremont's tidy-tips (*Layia fremontii*) (Figure 3). Because these species happened to be in bloom during imagery collection, their coincident flowering lead to spectral confusion and errors in classification between uplands and vernal pools. Therefore, in order to maximize spectral contrast between land cover classes, species phenologies must be carefully considered when targeting appropriate time periods for imagery acquisition.

Another source of error that may have reduced wetland classification accuracies was exposed soils. Exposed soils tend to contribute to high spectral heterogeneity of grassland communities (Ustin et al. 2004) and may have been a source of error in the classification. Accuracies may be improved by including bare soil in the classification key and soil type in the stratification of sample polygons. A source of error that was not anticipated, but that became evident during field sampling, was the introduction of shadows and their spectral contribution to the sites. The satellite imagery used in this study was collected at approximately 7 pm. At this time of day, the sun's angle is low and caused unique spectral signatures to form from shadows occurring on the north sides of tall features. For example, several sample polygons were created from the unique spectral signatures of shadows that were cast by introduced trees on the Gene Andal property. Although these sample polygons were in the upland land cover class, the low spectral reflectance and signature from the shadow resulted in misclassification with other low spectral reflectance classes, such as urban asphalt and water. Imagery collection at solar noon should minimize this error and thereby increase classification

accuracies. However, if shadows cannot be avoided, then future studies should include shadows as a separate land cover class.

An interesting result of this study is that while wetland cover class accuracies were similar across sites, there was significant variability among sites in the upland class. Because the three study sites were subject to different grazing pressures, this variability may be due to site differences in grazing regimes. Indeed, the upland class accuracies for each site appear to correspond to the different levels of grazing intensity of the three sites. It is interesting to note that the Kassis site had the highest grazing intensity and had significantly higher upland cover class accuracy than the other two sites. Conversely, the Gene Andal site had no grazing and the Klotz site had an intermediate level of grazing, both of which had significantly lower upland cover class accuracy than the Kassis site. The grazing intensity at the Klotz site was intermediate and upland class accuracy was also significantly lower than the Kassis site. Although speculative, grazing pressure may influence the spectral variability and classification accuracy of upland communities but does not appear to affect the spectral variability, and consequently the accuracy, of wetland cover classes.

A small sample size may also have been a source of error in this study. Although 50 samples in each cover class is a general rule of thumb, sampling is limited by what is practical for the project (Lunetta and Lyon 2004; Jenson 2004). In this study, 5 training polygon samples were collected for each class at each site, suggesting that under-

sampling may have been a source of error. The number of samples that could be taken was limited by the brief time period during which vernal pool sub-communities were in bloom and identifiable. In addition, funding and available resources did not logistically support the acquisition of additional personnel, training of personnel, hardware (e.g., GPS units) and software. Furthermore, according to the results of this study, it may be more important to increase sample size in those classes that are less accurate or more spectrally variable, such as uplands and seasonal wetlands. Future studies should increase sample size and account for recruiting additional personnel to collect data within the limited window of time.

Probably the second most important limitation was the acquisition of accurate sample polygons (i.e., sampling error). As environmental conditions changed relative to the imagery acquisition date, it became increasingly difficult to accurately determine the correct class that was present at the time of image acquisition. Accurate identification of the water class was difficult because water levels in the vernal pools drew down rapidly with seasonal increases in temperature and concomitant evapotranspiration rate. In addition, vernal pools and grasslands are dominated by annual plants that desiccated quickly, making it a challenge to accurately identify species and correctly determine their percent cover. Species such as downingia (*Downingia spp.*) and vernal pool downingia (*Downingia bicornuta*) rapidly desiccated and nearly disappeared by the end of May. After May, species identification was mostly limited to remaining plant material, especially in shallow vernal pool areas. However, perennial species such spike rush

(*Eleocharis macrostachya*) and cattail (*Typha spp.*) were less problematic because they persisted long enough to identify and quantify their cover.

Another limitation was the acquisition of a clear satellite image within the narrow floristic "window" needed to accomplish this study. A flexible acquisition agreement with the imagery company was necessary so that imagery could be taken when conditions were optimal. Although a relatively sufficient and cloud-free image was collected for this study, acquisition of the imagery occurred when some vernal pool vegetation was obscured by ponded water. Future studies should strongly weigh the benefits of satellite imagery against the potential delays associated with it. If highly specific imagery acquisition dates are required, aerial platform acquisition may be a preferred method of imagery acquisition.

Future studies may achieve higher wetland classification accuracies if efforts are taken to minimize spectral confusion of target vegetation classes and sample size is increased to account for the spectral variability of vernal pools and their surrounding upland plant communities. Further stratification of samples based on soil types should also improve accuracies by increasing the capture of spectral variability. Inclusion of bare soils, shadows, and potentially other unique vegetation communities and urban features may also improve accuracies.

Higher spatial resolution imagery, such as pan-sharpened imagery, should be explored to determine if spatial or spectral resolutions affect accuracies. Future studies should also include analysis of wetland size on accuracies. Other satellite and aerial platform sensors should also be evaluated to determine their accuracies and cost-effectiveness in assessing wetlands within varied habitat types. Given the high variability of vernal pool grasslands, ancillary data layers and rule-based classification methods may also prove helpful in improving accuracies.

Conclusions

In conclusion, high resolution multispectral imagery classification holds promise for the identification of wetlands and classification of vernal pools if methods are refined to minimize spectral confusion and classification error. The small spatial scale and spectrally heterogeneous landscape of vernal pool grasslands creates challenges for the identification and classification of wetlands using high resolution multispectral satellite imagery. However, the results of this study show that remote sensing identification of wetlands within vernal pool grasslands in eastern Sacramento County can be done using high resolution multispectral satellite imagery, with overall accuracies between 26% and 73%, depending on wetland type. The fact that the open water wetland class was accurately identified shows that vernal pools may be accurately identified if methods target periods in which vernal pools are inundated. On average, 52% of the vernal pool deep communities were correctly classified and 58% of the vernal pool shallow communities were correctly classified.

Although the methods used in this study did not reach accuracies of 95% or greater for classification of vernal pool sub-communities or seasonal wetlands, additional refinement of methods will likely provide better results. The goal of future studies should be focused on achieving this level of accuracy for identification of wetlands and classification of vernal pool communities. Rigorous accuracy assessment and refinement of accuracy assessment methods is essential to achieving this goal. Refinement of remote sensing methods is important for developing cost-effective tools that can accurately quantify habitats for conservation purposes.

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