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Identification of invasive vegetation using hyperspectral remote sensing in the California Delta ecosystem

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ABSTRACT

Estuaries are among the most invaded ecosystems on the planet. Such invasions have led in part, to the formation of a massive $1 billion restoration effort in California's Sacramento–San Joaquin River Delta. However, invasions of weeds into riparian, floodplain, and aquatic habitats threaten the success of restoration efforts within the watershed and jeopardize economic activities. The doctrine of early detection and rapid response to invasions has been adopted by land and water resource managers, and remote sensing is the logical tool of choice for identification and detection. However meteorological, physical, and biological heterogeneity in this large system present unique challenges to successfully detecting invasive weeds. We present three hyperspectral case studies which illustrate the challenges, and potential solutions, to mapping invasive weeds in wetland systems: 1) Perennial pepperweed was mapped over one portion of the Delta using a logistic regression model to predict weed occurrence. 2) Water hyacinth and 3) submerged aquatic vegetation (SAV), primarily composed of Brazilian waterweed, were mapped over the entire Delta using a binary decision tree that incorporated spectral mixture analysis (SMA), spectral angle mapping (SAM), band indexes, and continuum removal products. Perennial pepperweed detection was moderately successful; phenological stage influenced detection rates. Water hyacinth was mapped with modest accuracies, and SAV was mapped with high accuracies. Perennial pepperweed and water hyacinth both exhibited significant spectral variation related to plant phenology. Such variation must be accounted for in order to optimally map these species, and this was done for the water hyacinth case study. Submerged aquatic vegetation was not mapped to the species level due to complex non-linear mixing problems between the water column and its constituents, which was beyond the scope of the current study. We discuss our study in the context of providing guidelines for future remote sensing studies of aquatic systems.

1. Introduction

Invasions of aquatic weeds into freshwater, estuarine, and floodplain habitats can decrease biodiversity, threaten critical habitat, alter nutrient cycles, and degrade water quality. An estimated USD $100 million per year is spent on control and eradication programs targeting aquatic weeds in the United States (Pimentel et al., 2000). Systematic, comprehensive monitoring programs are needed to detect invasions in order to effectively control aquatic weeds. Traditional methods of monitoring weed infestations are costly, time consuming, and often require direct contact with the weeds which can result in further weed dispersal (Bossard et al., 2000). Additionally, aquatic ecosystems are often inaccessible or logistically difficult for field-based monitoring methods. Remote sensing provides a synoptic solution for monitoring aquatic weed infestations over large spatial areas (Ackleson and Klemas, 1987). To be successful, a remote sensing approach must be accurate, repeatable over space and time, and account for the inherent spatial and environmental heterogeneity of a system.

We present three case studies that illustrate how these problems can be addressed to develop regional-scale monitoring of invasive aquatic and wetland weeds in the Sacramento–San Joaquin Delta: the terrestrial riparian weed, perennial pepperweed (*Lepidium latifolium*); the floating aquatic weed, water hyacinth (*Eichhornia crassipes*); and the submerged aquatic weed, Brazilian waterweed (*Egeria densa*). Each case study highlights the complexities of remote sensing of aquatic and wetland systems. They also demonstrate a range of techniques that can be used, and often integrated, to produce accurate maps for wetland and estuarine resource managers. Our examples are from a study to map these invasive species at high spatial resolution (3 m) over a regional area of 2139 km^2. The challenge of analyzing airborne hyperspectral remote sensing over a large study region notwithstanding, we demonstrate that the techniques presented can be applied consistently to all flightlines in the study

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region over multiple years, thus creating an effective and comprehensive monitoring program.

In estuarine systems, meteorological, physical, and biological heterogeneity present serious challenges that must be resolved to successfully map and monitor distributions of aquatic vegetation species. Meteorological heterogeneity is one challenge to invasive species monitoring. Factors such as weather conditions, sun, and view angle determine the bidirectional reflectance distribution function (BRDF), which complicates remote sensing of aquatic vegetation, especially submerged aquatic vegetation (SAV) such as Brazilian waterweed. Sunglint is light specularly reflected off the water surface which effectively impedes retrieval of a useable signal (Bostater et al., 2004; Mertes et al., 1993; Morel and Belanger, 2006). Variable sun angles and wind speeds contribute differing flightline effects that confound region-wide analyses. The spectral detection of SAV is also affected both by the apparent optical properties of water, such as surface reflectance and vertical diffuse attenuation, and inherent optical properties that do not depend on the ambient radiance distribution in the water column (Mobley, 1994). Water depths change with tidal stage and runoff; suspended and dissolved materials vary over geomorphological gradients, meteorological conditions, flow conditions, and land use practices. All of these effects influence remote sensing of aquatic systems by limiting the detection of SAV as light attenuates with depth, altering the water-leaving reflectance.

Another challenge to monitoring this system is its biological heterogeneity. Plant phenology varies across the large gradients present in this system. Water hyacinth and perennial pepperweed life histories must be accounted for to capture key phenological attributes such as flowering and senescence. Different phenologic states, combined with differences in leaf and canopy structure can be present over short distances, creating intra-species variation that can result in overlapping spectral features between co-occurring species. Additionally, weed species may be present in subpixel mixtures even at high spatial scales. Hyperspectral imaging may provide sufficient information to overcome these challenges, allowing the application of more complex spectral analyses and spectral unmixing techniques (Becker et al., 2007; Bostater et al., 2004; Hirano et al., 2003; Schmidt and Skidmore, 2003; Williams et al., 2003).

To summarize, detecting and monitoring invasive weed species in wetland and aquatic ecosystems at the region-wide scale is complicated by considerable physical and environmental variability. The spatial heterogeneity of these systems requires moderate to high spatial resolution (<5 m) imagery (Becker et al., 2007). High spectral resolution imaging (>100 bands with narrow bandwidths) can be used to improve discrimination of target species and resolve complex mixing problems. Flightline effects also contribute additional variability. We overcame this variability by incorporating multiple widely available techniques into novel classification schemes for water hyacinth and SAV detection, and by using a logistic regression model to map perennial pepperweed.

2. Study site

The Sacramento–San Joaquin River Delta (hereafter the "Delta") is formed by the confluence of the Sacramento and San Joaquin Rivers and drains into the Pacific Ocean via the San Francisco Bay (Fig. 1). The Bay–Delta is the largest estuary in the western United States and its watershed drains over 160,000 km^2 of California. The hydrodynamic heterogeneity of the Delta system is manifest in a wide range of salinities, tidal fluxes, water depths, and freshwater inflows with extreme seasonal and interannual variability (Jassby and Cloern, 2000). Saline waters flow upstream into the Delta on flood tides, and freshwater inflows from the Sacramento, San Joaquin, and tributary rivers flow downstream at an average of 1700±300 m^3 s^{-1} in the winter and 540±40 m^3 s^{-1} in the summer (Jassby and Cloern, 2000). The El Niño–Southern Oscillation influences precipitation patterns, resulting in extremely dry or wet years, that respectively translate into very low flow (e.g. 230 m^3 s^{-1} in 1977) or high flow (e.g. 2700 m^3 s^{-1} in 1983) water years (Jassby and Cloern, 2000). This study focuses on the Central Delta (2139 km^2), which contains the confluence of the Sacramento and San Joaquin Rivers and the network of small channels, rivers, and lakes formed by flooded agricultural tracts that connects them.

The Delta provides drinking water, agricultural water and land, recreational opportunities in the form of boating and fishing, and shipping access to the cities of Stockton and Sacramento. The Delta is a major hub for freshwater conveyance systems in the state, providing drinking water for 25 million people and important irrigation resources for California's $32 billion agricultural industry (CDFA, 2006). The estuary contains habitat for waterfowl along the Pacific flyway as well as threatened and endangered fish species such as Delta smelt, longfin smelt, and chinook salmon. Unfortunately, the Delta may have the largest number of invasive species of any estuary in the world (Cohen and Carlton, 1998) and is the focus of a massive coordinated ecosystem restoration program, with direct expenditures exceeding USD $1 billion beginning in the mid-1990s (Lund et al., 2007). Invasions of aquatic weeds into the Delta negatively impact ecosystem health, drinking and agricultural water quality, pumping, recreation, and shipping (Bossard et al., 2000), and may prevent the success of native habitat restoration projects within the Delta (Simenstad et al., 2000). The three focal invasive species (perennial pepperweed, water hyacinth, and Brazilian waterweed; Fig. 2) are all considered problems in the Delta, and have been granted high visibility and threat status according to the California Invasive Plant Council (Cal-IPC) and the California Department of Food and Agriculture (CDFA).

3. Remotely sensed data

To map perennial pepperweed, water hyacinth and SAV (dominated by Brazilian waterweed), we acquired 64 HyMap flightlines encompassing the entire Delta (Fig. 1). HyMap is an airborne hyperspectral imager that collects 128 bands in the visible and near-infrared (VNIR; 0.45–1.50 µm) through the shortwave infrared (SWIR; 1.50–2.5 µm), at bandwidths from 10 nm in the VNIR to 15–20 nm in the SWIR (Cocks et al., 1998). The spatial resolution of the data is 3 m, with a swath width of 1.5 km. The area was flown in an east–west orientation, at an altitude of approximately 1510 m. Imagery was collected during late morning and early afternoon low tides between June 22 and July 5, 2005, and June 21 and June 26, 2006. The HyMap images were converted to apparent surface reflectance using the HyCorr atmospheric correction software (Hyvista Corp., Sydney, Australia), a modified version of the Atmospheric Removal (ATREM) algorithm (Gao et al., 1993). We used an orthorectification algorithm (Analytical Imaging and Geophysics, Boulder, CO) to orthorectify the imagery using the United States Geologic Survey National Elevation Set Digital Elevation Models and a set of 1-foot (covering 30 flightlines) and 1-meter (covering 34 flightlines) color orthophotos. A minimum of 20 ground control points with a total RMSE ≤1.0 were used for each flightline. Visual inspection of image registration accuracy confirmed a registration error of ≃1 pixel. For a detailed report of image data collection and preprocessing steps please see Ustin et al. (2006).

4. Ground reference data

4.1. Perennial pepperweed

Field observations were recorded between 2002 and 2006 with a comprehensive inventory of perennial pepperweed populations on selected Cosumnes River Preserve (CRP) lands (Viers et al., 2005). Mapped botanical surveys of perennial pepperweed were conducted during flowering to aid in the identification of pepperweed patches, which were defined as areas containing a minimum of one individual and located at least 3 m from another patch. For each perennial pepperweed patch, GPS polygons delineating the patch, the number of individuals, areal percent cover, and patch area were recorded (1 m^2 minimum). A total of 345 patches over 15.5 ha were mapped by the inventory.