ABSTRACT

Mapping and predicting the spatial distribution of invasive plant species is central to habitat management; however, it is difficult to implement at regional scales. Remote sensing reduces the cost of field campaigns and can provide a regional and multi-temporal view of invasive species spread. Invasive perennial pepperweed (Lepidium latifolium) is now widespread in fragmented marshlands of the South San Francisco Bay, and is shown to degrade native vegetation in estuaries and adjacent habitats, thereby reducing forage and shelter for wildlife. The purpose of this study was to map the current distribution of pepperweed in estuarine areas of the South San Francisco Bay Salt Pond Restoration Project, and create a habitat suitability model to predict future spread. Pepperweed reflectance data were collected in-situ with a GER 1500 spectroradiometer along with 88 corresponding pepperweed presence and absence points used for building statistical models. The spectral angle mapper (SAM) classification algorithm was used to distinguish the reflectance spectrum of pepperweed and map its distribution using an EO-1 Hyperion satellite image. To map pepperweed, a supervised classification was performed on an ASTER image with a resulting classification accuracy of 71.8%. We generated a weighted overlay analysis model within a geographic information system (GIS) framework to predict areas in the study site most susceptible to pepperweed colonization. Variables for the model included disturbance, status of pond restoration, proximity to water channels, and terrain curvature. A Generalized Additive Model (GAM) was also used to generate a probability map and investigate the statistical probability that each variable contributed to predict pepperweed spread. Results from the GAM revealed distance to channels, distance to ponds and curvature were statistically significant ($p < 0.01$) in determining the locations of suitable pepperweed habitats.

KEYWORDS:
the gateway to the Bay Delta (Trumbo, 1994; Hestir et al., 2008). In addition, the invasion of pepperweed can seriously threaten the value of the tidal marshes and change important biogeochemical cycles which may disrupt the natural ability of the wetland to act as floodwater storage, a filter for runoff, and a natural carbon capture mechanism (Reynolds and Boyer, 2010; Zedler, 2000).

The key in controlling pepperweed is to limit its spread and to prevent its establishment in new areas (Andrew and Ustin, 2006). In order to do this, complete knowledge of the current and possible future extent of pepperweed is essential. Continuous and accurate data across an entire landscape are necessary to track the spread of pepperweed. Remote sensing and habitat modeling techniques present an excellent means of achieving this goal (Andrew and Ustin, 2006). Thus, mapping the extent of pepperweed in the South Bay Salt Ponds is vital to further scientific research of this ecosystem, for eradication efforts and salt pond management decisions. To predict the most susceptible areas for pepperweed invasion, we present 1) a Weighted Overlay Analysis and 2) a Generalized Additive Model (GAM) using the Marine Geospatial Ecology Tools (MGET) toolbox (Roberts et al., 2010) both within ArcGIS. Both prediction methods produce habitat suitability maps, while the GAM also analyzes the statistical probability that each variable contributes to pepperweed spread. Although many factors influence the distribution of pepperweed, our models incorporate distance to channels, status of pond restoration (encompassing pond salinity and constant inundation), terrain curvature, and proximity to disturbance (i.e. areas within and surrounding roads, buildings, electrical towers, and levees). These factors were selected because they were independently determined to be moderately or highly significant in the spread of pepperweed and were available as datasets (Spenst 2006; Grossinger et al., 1998; Zhang et al., 2006; Young et al., 1995; Hogle et al., 2006).

**Study Species**

Pepperweed is a member of the Brassicaceae (mustard) family. Its height and size are dependent on habitat, but it can grow to be 3 m tall in an ideal environment (Krueger and Sheley, 2004). Its roots can extend much further, growing down 4 m or more (Leininger and Foin, 2009). Plant phenology changes visually from June to July, when clusters of white flowers bloom throughout the upper portions of the plant (Krueger and Sheley, 2004). Pepperweed is native to Eurasia, and was most likely introduced to California in a shipment of sugar beet seeds during the 1930s (Trumbo, 1994). It began to spread widely and rapidly in the 1980s due to its high reproductive potential and high tolerance of adverse soil conditions, such as high soil moisture and salinity (Leininger and Foin, 2009; Trumbo, 1994). The California Invasive Plant Council inventory rating for pepperweed is “high”; it is a severe threat to Californian ecosystems and agriculture in terms of its impact, distribution, and invasiveness (Cal-IPC, 2011). Pepperweed spreads through prolific seed production, vegetative propagation of root fragments, and creeping roots, or rhizomes (Young et al., 1997; Leininger and Foin, 2009). Once established, it forms dense homogenous patches and out-competes other plant species (Reynolds and Boyer, 2010; Trumbo, 1994). The establishment of pepperweed can also modify soil properties, creating a positive feedback loop that may allow pepperweed to grow and spread further (Byers et al., 2006; Reynolds and Boyer, 2010). Pepperweed has proven to be difficult to eradicate because of its aggressive reproductive ability; seeds stored in soil banks or remaining root fragments may regenerate even after removing surface plants (Viers et al., 2008).

**Study Area**

This study focuses on the Alviso salt ponds complex within the south end of the San Francisco Bay in California, USA (Figure 1). The Alviso area is only one salt pond complex out of three currently undergoing the restoration by the SBSPRP. The Alviso salt ponds are adjacent to and directly northeast of Ames Research Center (ARC), Moffett Field, CA. The study area is 7959.7 hectares and encompasses Alviso, Guadalupe, and Mountain View Sloughs as well as Coyote and Stevens Creeks.
METHODOLOGY

Field Methods

Two main goals were set for field work. They were 1) collect pepperweed spectral signatures and 2) obtain pepperweed presence and absence data. The white blossoms of flowering pepperweed in the early summer give it a spectral signature distinct from that of other vegetation (Andrew and Ustin, 2006). Using a GER 1500 spectroradiometer, we acquired spectral signatures of flowering pepperweed plants in situ on June 22, 2011 to coincide with an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) overpass (Geophysical and Environmental Research, 2011). Four flowering data sets were taken in the open fields of ARC Moffett Field, within 100 m of Pond A2E. Three flowering data sets were also taken at the A19, A20, and A21 Ponds at the Don Edwards San Francisco Bay National Wildlife Refuge [Don Edwards]. Each data set included five spectra of one pepperweed patch and three spectra of a reference plate. On June 23 and 28, 2011, we obtained GPS coordinates of pepperweed presence and absence within the vicinity of the Don Edwards Wildlife Refuge and the levees near Pond A6. Before going into the field, we used an independently classified IKONOS image of pepperweed (Fulfrost, 2010) to determine areas of pepperweed presence. The distinct appearance of flowering pepperweed allowed for clear visual validation of each site upon arrival. Some predetermined points were deemed inaccurate or inaccessible, so new sites were selected based on on-site observations. The presence/absence points were collected in areas surrounding Ponds A19, A20, and A21 and the levees surrounding Pond A6. Eighty-eight presence and absence points were recorded. Additionally, over 800 presence points were acquired from the U.S. Fish and Wildlife Service. These presence/absence points, along with numerous additional points from the IKONOS image, were used in the predictive GAM analysis.

Satellite Data Processing

An ASTER image and a Hyperion image were geometrically and radiometrically corrected for analysis. The images were reprojected to the UTM WGS 84 North projection, setting the standard projection for the rest of our datasets. Both images were taken during the summer months during the pepperweed flowering stage.

<table>
<thead>
<tr>
<th>Sensor</th>
<th># of Bands</th>
<th>Wavelengths (nm)</th>
<th>Resolution</th>
<th>Date used</th>
<th>Image Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTER on TERRA</td>
<td>14</td>
<td>520-860</td>
<td>15 m</td>
<td>06/22/2011</td>
<td>WIST</td>
</tr>
<tr>
<td>Hyperion on EO-1</td>
<td>48</td>
<td>426-905</td>
<td>30 m</td>
<td>07/07/2010</td>
<td>Glovis (USGS, 2011)</td>
</tr>
</tbody>
</table>

_E0-1 Hyperion._ We used the L1R Hyperion sensor based on the NASA Earth Observing 1 platform (EO-1) for our hyperspectral classification. The Hyperion sensor features 220 spectral bands, has a spectral resolution between 0.4 and 2.5 nm and a spatial resolution of 30 m. The image used for this classification was acquired July 7, 2010. ENVI 4.7 was used to atmospherically correct and to convert radiance to surface reflectance values for the image using the FLAASH plug-in. Hyperion bands that overlapped or were subjected to striping were removed and the image was subset to 196 bands. The image was georectified using 20 ground control points on a previously rectified Hyperion image.

_TERRA ASTER._ An ASTER image acquired on June 22, 2011 was also used in the remote sensing and mapping of pepperweed. ASTER has 14 spectral bands with a resolution of 15 meters, with a swath of 60 x 60 km. Bands 1-3 were used for this analysis. ASTER’s high resolution is necessary in creating detailed maps of the extent of pepperweed in the South Bay Salt Ponds. We used the VNIR instrument subsystem due to its 0.52-0.86 nm wavelength, which is closest to pepperweed spectra.
Spectral Profiles

Blossoming pepperweed is characterized by a dense spray of white flowers, creating its distinct reflectance signal (Andrew and Ustin, 2006). To take full advantage of this, we took reflectance spectra (400–900 nm) in the field using a GER spectroradiometer during the flowering period of pepperweed. As noted previously, 5 scans of pepperweed were taken at each of the 7 locations. An average reflectance signature was taken of each set of 5 scans and used to represent each particular location. Additional pepperweed spectra were provided by the previous year’s DEVELOP team, taken in the Ravenswood complex (Elkins et al., 2010). Higher reflectance values were observed in the upper wavelengths within Moffett Field compared to Don Edwards and Ravenswood (the discrepancy for why the flowers are whiter at Moffett Field is unknown) (Figure 2). Our field observations suggest this is due to the increased whiteness of the plants flowers at Moffett Field compared to those in the other two areas. These profiles were then averaged to create a single spectrum to represent flowering pepperweed. The GER 1500 collected reflectance data at 501 wavelengths between 400 and 900 nm. ASTER and Hyperion also collect data that are between 400 and 900 nm, but only collect 3 and 48 wavelengths respectively, each of which are slightly different than those collected by the spectroradiometer. We used a MatLab function to resample the original GER data to match the wavelengths of the images, interpolating the spectral signatures of pepperweed so as to be compatible with ASTER or Hyperion.

Classification Methods

Spectral Angle Mapper (SAM) Classification. Spectral data were converted to reflectance percentages, which were compiled into a spectral library in preparation for classification of the Hyperion image using the SAM algorithm (see Satellite Data Processing). The cosine mode of the SAM algorithm (Equation 1) compares the spectrum of each pixel in an image to a reference spectrum and computes a spectral angle between them, using all the bands in the image (Shippert, 2003). The cosine of this angle is expressed as a value between -1 and 1, with pixels with values closer to 1 being more spectrally similar to the reference spectra, and those with values closer to -1 being less similar. The SAM classification of the Hyperion image was computed in the Material Mapping Wizard (MMW) within the ERDAS IMAGINE program.

Figure 2. Spectra of each of the 8 points (top) and average spectra of points (bottom).
Equation (1)

\[
\alpha = \cos^{-1} \left( \frac{\sum_{i=1}^{n} x_i y_i}{\sqrt{\sum_{i=1}^{n} x_i^2} \sqrt{\sum_{i=1}^{n} y_i^2}} \right)
\]

where:

- \( n \) = number of bands
- \( \alpha \) = angle formed between reference spectrum and image spectrum
- \( x \) = image spectrum
- \( y \) = reference or target spectrum

**Hyperion SAM Classification.** The cosine mode of the SAM algorithm was applied to the July 7, 2010 Hyperion image to classify it into areas of high and low spectral similarity to the spectral library of average pepperweed reflectances (Figure 3). Pixels with a value of 0.98 or higher were assumed to contain a significant amount of pepperweed, while pixels with lower values were classified to contain an insignificant amount. As the reference spectra were of flowering pepperweed, this classification reveals only areas of flowering pepperweed and not of dormant pepperweed.

**ASTER Supervised Classification.** The ASTER image used was acquired on June 22, 2011. First, an unsupervised SAM classification was applied to the ASTER image, but the results showed pixels classified as pepperweed in the mountainous and urban regions of the ASTER image, and almost none in the estuary and salt-pond regions. Sources of error may be the multispectral characteristic of the ASTER image or the large variance created by the non-study-area regions of the ASTER image. These areas may be excluded for improved accuracy in future studies. We determined the SAM classification to be unusable, and instead we performed a supervised classification in ENVI on the region of the ASTER image which focused on our study area (Figure 4). We used a parallelepiped classification to classify all the regions that contain pepperweed as one class. We drew regions of interest (ROI) superimposed over the areas that were previously verified in past research (Fullfrost, 2010) to contain homogenous patches of pepperweed. We used a standard deviation of 1.00 rather than 3.00 to reduce the false positive error that may occur because of the similar spectral signatures of pepperweed and other vegetation.
SUITABILITY MODELS

Suitability Variables

Four variables were selected for habitat modeling based on literature review, advise from collaborators, available datasets, and field observations.

1) **Distance to water channels.** Channels serve as a method of transportation for pepperweed seeds and root fragments. (Andrew and Ustin, 2006). Within the South San Francisco Bay, distance to channels is a very reliable predictor of pepperweed spread (Rogers et al., 2002). Distance to upland and distance to channel were overwhelmingly important to modeling pepperweed habitat (Andrew and Ustin, 2009; Vanderhoof et al., 2009), with the majority of occurrences within 10 to 30 m of a water channel (Gillham et al., 2004; Andrew and Ustin, 2009). In order to incorporate distance to channels into the models, shapefiles of marsh sloughs and Coyote Creek were extracted from soil survey data (USDA NRCS, 2011). Additional interstitial water features, such as channels inside affected ponds and tracks connecting to the sloughs and Coyote Creek, were digitized and merged with the USDA shapefiles. This ensured that all water sources within the study area were incorporated.

2) **Distance to disturbance.** Pepperweed commonly invades disturbed areas (NHDES, 2009). Disturbed areas were defined as areas subjected to construction and human activity, where seed and root fragments may be transported. Disturbed areas included roads, man-made levees, and areas surrounding buildings and electrical towers. Pepperweed usually occurs within an average of 15 m of a disturbance (Gillham et al., 2004). Field observations confirmed these occurrences of pepperweed. Road and levee datasets were obtained from the Metadata Explorer section of the SBSPRP website (SBSPRP, 2011b). Power towers and buildings were digitized using aerial imagery and represented as points and incorporated into the models.

3) **Non-restored ponds.** Non-restored or unbreached ponds and the areas in close proximity to them are unfavorable habitat for pepperweed for two reasons. First, the high salinity of unbreached ponds is unfavorable for the growth of pepperweed (Leininger and Foin, 2009). Salinity levels at the soil surface greater than approximately 23 ppt greatly reduces the viability of pepperweed seed (Spenst, 2006). While areas of high salinity can be colonized by pepperweed through vegetative reproduction, it is difficult for pepperweed to establish from seed. Provided there is no nearby area of established pepperweed, colonization of high saline soils is unlikely (Spenst, 2006; Leininger and Foin, 2009). Secondly, long term inundation also reduces the reproductive potential of pepperweed. Pepperweed can tolerate complete flooding for several months, but it cannot grow in completely saturated soil (Chen et al., 2005; Renz and Blank, 2004). Additionally, high soil moisture reduces the production of seeds in established plants (Leininger and Foin, 2009). High soil moisture adversely affects both vegetative growth and reproduction. Pepperweed prefers a soil that is nearly saturated, and is significantly hindered by soils that are completely flooded or too dry (Blank et al., 2002).

Pepperweed grows most prolifically where ideal conditions of moisture and salinity intersect, such as on levees and around sloughs (Leininger and Foin, 2009). Due to pond access restriction, we were unable to quantify the salinity of each pond. We were, however, able to distinguish breached and restored ponds that are susceptible to pepperweed spread. Breached ponds include ponds A6, A19, A20, and A21 (Mrzu, 2011). These ponds allow runoff from Coyote Creek, Guadalupe Slough, and Alviso Slough to enter. The most recently breached pond as of June 2, 2011, Pond A8 is not fully breached, but has been reconnected to the Bay. Breaching or reconnecting a pond
with the Bay lowers salinity levels, subjects them to natural tidal flows, and raise the susceptibility of pepperweed spread via Guadalupe and Alviso Sloughs. Ponds A16 and A17 are unbreached, but have been converted to habitat conservation areas and outfitted with nesting islands for migrating shorebirds (SBSPRP, 2011a). It is very likely for A16 and A17 to be invaded by pepperweed due to propagation by marsh birds and lower instances of flooding. The rest of the Alviso Ponds have been categorized as non-restored, and thus non-susceptible to pepperweed, due to their high salinity and full water inundation. These parameters were further strengthened upon visual comparisons with our classification maps, the referenced IKONOS image (Fulfrost, 2010), and United States Fish and Wildlife Service (USFWS) presence points. Pepperweed’s current distributions indicate that it does not grow near non-restored ponds.

4) Curvature. Terrain curvature may contribute to suitable habitats for pepperweed (Andrew, 2011). Slight depressions (concavities) allow accumulated runoff to form moisture-rich depressions in areas more than 30 meters away from a water source. Concavities may also decrease the distance to the water table. Seeds that germinate within concavities may have been carried by wind or wildlife factors (Andrew, 2011). Digital Elevation Model (DEM) data with a resolution of 30 m were downloaded (USDA NRCS, 2011) then converted for intended use with the curvature tool in ArcMap.

Weighted Overlay Analysis

Two Spatial Overlay analysis models were created within ArcGIS 10 model builder using the Spatial Analyst extension. They were designed to predict the pepperweed spread in the South Bay Salt ponds area based on four suitability variables described above.

The first Weighted Overlay model was built using the distance to channels and curvature variables. The Euclidean distance tool was used to calculate a 30 meter buffer for the distance from channels variable. It delineated a maximum extent in which pepperweed could grow based on previous research (Rogers et al., 2002). Once calculated, the output raster values were grouped within three different classes using the Reclass tool. Each class was determined to be suitable depending on their distance to water, levees, or salt ponds.

The curvature tool was used to calculate the convexities and concavities of the South Bay Salt Ponds terrain. The raster output was reclassified, by grouping the negative values that represent concavities and positive values that represent convexities.

The reclassified pixel values were then used in the first Weighted Overlay Analysis model. Each class previously calculated was assigned a level of importance also called “weight”. The most suitable classes were attributed the highest weight which was “9”. The other classes less suitable were given a lower weight rank that ranged from 0 to 8. 0 being a restricted class value for which pepperweed cannot grow. For instance, the classified pixels located closest to the channels were given the highest weight ("9") meaning this class was considered the most suitable for pepperweed growth.

The reclassified raster images were then given a level of influence, the highest influence being “100%” and the lowest level of influence being “0%”. Although the curvature is important, it is not as conducive to pepperweed growth as the proximity of water or levees. For this reason the reclassified curvature raster was given a lower influence rate than the reclassified distance of water and levees raster files.

A second Weighted Overlay model was built using the distance from levees and salt ponds variables. The Euclidean distance tool was used again to calculate 30 and 10 m “maximum” buffers for the distance from levees and salt ponds. Both buffers were reclassified using the Reclassify tool previously described. The reclassified values were implemented within the second Weighted Overlay Analysis model. Each reclassified raster was given a level of influence. For example, the reclassified water extent was given a higher influential rate than the reclassified levees raster because distance to water is the most important variable in this model.

Once the levels of influence were assigned to each reclassified raster and the classes weighted in both models, the two output raster of the Weighted Overlay Analysis tool were combined in ArcMap in order to create a habitat suitability map of pepperweed growth in the South Bay Salt ponds area.

Generalize Additive Model (GAM)

A Generalized Additive Model (GAM) is a useful tool in identifying the suitable habitat of a species. GAM is a semi-parametric extension of a Generalized Linear Model (GLM) that allows nonlinear functions of co-variables to be included in regression equations. A distinct advantage of GAMs is the ability to include smoothing terms taking the form of non-parametric functions of predictors in a model (Young et al., 2011). To run the GAM, it was imperative to gather presence and absence points spread evenly throughout our study area. In addition to using our presence and absence data collected in situ, presence and absence data were extrapolated from existing USFWS field

ASPRS 2012 Annual Conference
Sacramento, California ♦ March 19-23, 2012
presence points, and from a previously classified IKONOS image of pepperweed (Fulfrost, 2011). One hundred and seventy-five presence points and 175 absence points were used in the GAM. Using the IKONOS classified image for additional presence and absence points may not be ideal due to additional error. Field access constraints lead us to justify this decision. Four predictor variables were included in the model: 1) distance to channel, 2) distance to ponds, 3) distance to disturbance, and 4) terrain curvature. All distances were calculated using the Euclidean distance tool in ArcGIS. Distance to pond was used as a proxy for non-restored ponds; only ponds that were non-restored or unbreached were used to calculate this variable. Disturbance factors included levees, power towers, buildings, and other man-made structures. Curvature was used as in the GIS Overlay Analysis Model. All variables were sampled at a one meter resolution. Curvature was calculated from a DEM at a 3 m resolution and then re-sampled at a 1 m resolution. The GAM was calculated using the Marine Geospatial Ecology Toolbox (MGET) in ArcGIS. A basic spline was fit to the distance to pond and distance to disturbance variables. Using a spline to smooth these features is one of the advantages of a GAM.

RESULTS

Accuracy Assessments

Hyperion. Points of pepperweed presence and absence taken in the field were used to test the accuracy of the classified image. Initially, a classification of the Hyperion image using a 0.99 SAM algorithm result was used to map areas of pepperweed; this ensured that only areas with a very high spectral similarity to pepperweed were counted. However, this classification of the image failed to account for any presence points previously obtained in the field. For this reason, a classification of pixels with a result of 0.98 was used instead. The 77 remaining points of presence and absence were used in addition to 635 points of presence collected by USFWS to create a final accuracy assessment. Of these 712 points, 382 (56.68%) were correctly classified as pepperweed, while 38 (5.34%) were correctly classified as not pepperweed. The remaining 292 (43.32%) were false negatives. The overall classification accuracy of the SAM classification of pepperweed using a Hyperion image was 58.99%.

ASTER. Based on our field knowledge, this supervised classification was much more accurate than the SAM classification considering the classified points fell largely around the levees and did not appear in open water sources. For our manual accuracy assessment, 33 presence points previously collected in the field were superimposed onto the classification. Twenty one of these points (63.6%) were correctly classified as containing pepperweed. The other 12 points (36.3%) were false negatives. We also generated 66 random points within the classification to determine the false positive accuracy. Of these 66 random points, 36 lay outside of our study extent and were ignored for the assessment. Twenty four of the other 30 (80%) were determined to have been accurately classified; 6 of the 30 (20%) were determined to be false positives. By comparing the randomly generated points to ground-truth data the average accuracy was 71.8%.

Suitability Models

Weighted Overlay Analysis. Once the levels of influence were assigned to the reclassified raster files and the weights given to each class, the output of the Weighted Overlay Analysis tool was a habitat suitability map (Figure 5) for pepperweed growth in the South Bay Salt ponds area.
**GAM.** The results from the GAM showed that 3 of the tested variables - distance to channel, distance to pond, and curvature - were significant at the 0.01 level. Distance to disturbance was significant at the 0.1 level. The adjusted r-squared value was 0.44, which indicates a moderately strong relationship. An accuracy assessment was performed using 30 presence and 30 absence points. The accuracy of the model was calculated at 81%. This accuracy was generated at a cutoff value of 0.62. The GAM produced a map (Figure 6) that is accurate in showing areas in which pepperweed can spread. The output map is classified using a scale composed of values ranging from 0 (green) to 1 (red). A higher value indicates a higher likelihood for pepperweed to grow in that area.

**DISCUSSION**

**Outputs**

**Hyperion.** The large amount of information acquired by hyperspectral sensors allows for the species-level detection needed to map invasive weeds, an advantage Hyperion imagery has over multispectral ASTER imagery.
(Clark et al., 2005; Underwood et al., 2007). However, the accuracy of the Hyperion map never rose above 57.69%. In areas where pepperweed has not already formed dense, monospecific stands, it tends to grow in sparse patches (Hestir et al., 2008). This effect was prevalent in the Alviso salt ponds, where the combined effects of flooding and high salinity created narrow areas of pepperweed habitat suitability. This patchy distribution created heterogeneous pixels, in which pepperweed existed along with other vegetation. This reduced the spectral strength of pepperweed in each pixel, a common problem in pepperweed mapping (Hestir et al., 2008). There seemed to be a good correlation between areas classified in the image as pepperweed and areas where pepperweed was known to grow. However, when points of presence and absence were tested against the image, it became clear that the individual pixels were too large to accurately distinguish areas of pepperweed growth and non-growth. Unfortunately, this problem was especially severe in the few regions of the salt ponds we were allowed to visit and obtain ground truth data. The problem of low resolution imagery has been a major obstacle to researchers in mapping pepperweed using remote sensing techniques; imagery with a 30 meter resolution has been specifically mentioned as being inappropriate (Andrew and Ustin, 2009). The limit for accurately mapping weeds with hyperspectral imagery has been estimated at 5 meters, and most researchers have used resolutions of 3 meters or higher (Santos, 2009; Underwood et al., 2007; Andrew and Ustin, 2006).

**ASTER.** Sources of error may be the low resolution of ASTER, imprecise ground-truth data, or other vegetation with similar spectral signatures as pepperweed. Our ASTER image had a resolution of 15 m by 15 m. Relative to our study site and conditions, this resolution was low. Our study site was less than 14 km wide and 7 km long at any point. The most probable areas for pepperweed to grow were along levees, which were sometimes less than 15 m across. Although the accuracy assessment was higher when measured using the same method as the Hyperion image, the resolution remained the largest barrier for a detailed and more accurate classification. In addition, the lower spectral resolution, compared to Hyperion, may not have been able to entirely detect pepperweed spectra, hence, the lower quantity of matching pixels.

**Suitability Models.** The main cause for the low R-squared value on the GAM can be attributed to the size of the study area. In some cases the area being sampled contained levees as small as 10 m. Pepperweed was found on only one side of these levees. Many of the variable values were similar even if one was an absence point. This similarity in variables meant that it was harder for the model to delineate ranges that were suitable for habitat. Despite having a low r-squared value the model performed relatively well. The accuracy assessment cutoff value may seem low, but due to the variability of the conditions in which pepperweed can grow it is a sufficient value to use. The purpose of the model was to find the areas where there was a slight chance of pepperweed growth for possible treatment. The significance of the variables showed that they all contributed to the model. The map generated from this model shows a strong relationship between pepperweed predictions and distance to channel. This was expected since the dominant factor in pepperweed growth is proximity to water.

**CONCLUSION**

The Hyperion pepperweed map using the SAM classification produced relatively low accuracy, likely due to low spatial resolution and sparse ground truth data. Using a supervised classification of ASTER imagery (15m pixel sizes) resulted in better accuracy but does not offer the same spectral diversity as the Hyperion sensor. Although our predictive models located positions of pepperweed patches at fine scales, it did not precisely map areas to allow detection of individual plants and/or small, target populations for habitat management. Once an area has been colonized to the extent that it can be easily detected by Hyperion, or possibly even ASTER images, it has already become more difficult to control. Since the purpose of mapping is to determine areas in which pepperweed stands are small, a resolution closer to 3 meters is necessary.

Habitat suitability models showed that there are a few key decisive factors in the growth and spread of pepperweed. These include distance to or availability of water, soil salinity, and soil disturbance. While there are many other factors that contribute to pepperweed habitat suitability, as long as these requirements are met, pepperweed can grow and reproduce. In the case of the Alviso salt ponds, there are large areas of habitat that are unsuitable for pepperweed, due to a combination of these three factors. However, in the drier areas of the breached ponds and wildlife habitats, there are many opportunities for pepperweed to take root and spread. To effectively prevent pepperweed spread, resources should be focused to protect areas of high habitat suitability that are presently clear of pepperweed. Preventing its spread to these areas is highly preferable rather than attempting to control it after it has already been established. The areas of low, but not zero, pepperweed suitability should also be monitored, due to the abilities of pepperweed to modify the soil. Specifically, its potential to change the balance of salts in the surface soil horizons and to dry them out by transpiration creates the possibility for pepperweed to spread outside...
the areas of current habitat suitability. Even a small established colony of pepperweed in these areas could pave the way for larger colonies that would be more difficult to eradicate.

ACKNOWLEDGEMENTS

We thank Brian Fulfrost for providing and allowing the use of his pepperweed classification image derived from IKONOS. We also thank Cheryl Strong and Nikki Roach from the U.S. Fish and Wildlife Service for providing us with valuable information and access to our field sites. We also thank Lee Johnson of NASA Ames Research Center for accompanying us during our field days to obtain GER signatures of the study organism. Lastly, we thank Dr. Margaret Andrew of UC Davis for her guidance and direct communication with us regarding the factors of pepperweed spread.

REFERENCES

Andrew, M. E. Personal communication. July 6, 2011.
Fulfrost, B. 2010. IKONOS map of pepperweed in the south bay salt ponds. Unpublished data.


