Ecological Remote Sensing of Invasion by Perennial Pepperweed
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Abstract
Remote sensing can address a variety of ecological questions. We present three ecological applications of remote sensing to study invasion of the San Francisco Bay/Sacramento-San Joaquin River Delta by Lepidium latifolium (perennial pepperweed). Lepidium is a noxious Eurasian weed aggressively expanding in the western US; understanding the ecology and management options for this weed are priorities. Hyperspectral imagery was used to map Lepidium in several sites annually over 2004-2007. Annual distribution maps allow quantification of Lepidium spread and dispersal on Bouldin Island, existing infestations doubled in size from 2004-2007 and a new infestation grew 35-fold, dispersing up to 226m from existing patches. We generated susceptibility models for Lepidium at the Rush Ranch Open Space Preserve with data extracted from hyperspectral and LiDAR datasets. Lepidium occurrence at this site is primarily a function of the distances from channels and uplands. Finally, imagery of Rush Ranch and Cosumnes River Preserve revealed substantial spatiotemporal variation in Lepidium phenology. Remotely-sensed variables explained 33-56% of the spatial variation in phenology and interannual variation at the Cosumnes River Preserve was closely related to hydrology. Our results highlight the importance of microtopography and water availability to Lepidium distribution and phenology.

Introduction
Researchers and managers are increasingly embracing remote sensing, especially hyperspectral remote sensing, to map invasive plants (Lass et al. 2005). But although these maps can be used for ecological research, further informing management, they generally are not. We used remotely-sensed distribution maps of Lepidium latifolium (perennial pepperweed), a noxious Eurasian wetland/riparian invader that has recently become prominent in California, to predict potential habitat, quantify spread and understand variation in phenology of this species. This research can inform control efforts in space and time, identifying invisible sites prioritizes them for monitoring and eradication; knowing how weather influences spread can determine the importance of control in particular years and variation in phenology influences the effectiveness of both monitoring and control activities.

Methods
Hyperspectral imagery was acquired in June 2006 at Rush Ranch (RR) and annually in June-July 2004-2007 at Bouldin Island (BI) and Cosumnes River Preserve (CRP). Lepidium was mapped with each image date of RR and BI (Andrew and Ustin 2008) and with a comprehensive field inventory at CRP. Remote sensing accuracies were very good for four maps (~90%) and fair for one (75%). Presence/absence records were extracted from the Lepidium map of RR for distribution modeling with aggregate classification trees. Predictor variables – topography and distances to channels and uplands – were derived from a high-resolution LiDAR (light detection and ranging) DEM (digital elevation model) and the hyperspectral image. Infestation area and distance from a previous year’s patch were determined from the distribution maps of three subsites on BI. Spread was related to precipitation. At RR and CRP, a spectral phenology index was developed. Logistic regression related phenology to topography and distances from channels, uplands, trees and the...
patch edge. Temporal variation in phenology at CRP was related to precipitation and streamflow.

**Results and Discussion**

Distribution modeling identified 25% of RR (219 ha) as susceptible to invasion, only 5% of which is currently occupied by *Lepidium* (Figure 1). Distances to uplands and channels were overwhelmingly important to *Lepidium* occurrence. *Lepidium* is expected to occur within 30 m of channels or 35 m of uplands. However, there is an interaction between these terms, predicted distribution extends to 150 m from uplands when channels are relatively nearby. Topography was unimportant to *Lepidium* distribution, which is unexpected since marsh topography proxies inundation duration and frequency, and associated anoxia and salinity stresses, influencing community zonation (Pennings and Callaway 1992). Yet elevation clearly is an important correlate of *Lepidium* habitat, but is subsumed within distance to channel. Distance to channel has been found to be strongly predictive of wetland communities in a California salt marsh (Sanderson *et al.* 2000). *Lepidium* tends to colonize the natural levees along channels.

These results reveal that *Lepidium* selects habitats that minimize the stress associated with wetlands. The marshland-upland margin is expected to have a greater terrestrial influence than sites deeper within the marsh. When it occurs in the marsh, *Lepidium* tends to be found on the relatively high ground along channels, allowing it to avoid inundation.

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**Figure 1.** Current and predicted distribution of *Lepidium latifolium* at Rush Ranch
and anoxia stress. *Lepidium* possesses adaptations to both salinity (Blank and Young 2002) and inundation (Chen et al. 2005), so perhaps it is less competitive under these conditions.

*Lepidium* underwent dramatic spread from 2004-2007 on BI (Figure 2). The infestation spread linearly at sites with established populations (bridge, levee; Figure 2a & c), both of which doubled in area over the study period. At a site newly colonized during the study (western mesic; Figure 2b), *Lepidium* showed exponential growth; the area infested more than tripled each year, resulting in a 35-fold increase overall. Dispersal varied by year and site (Table 1).

The extremely rapid spread of the nascent population underscores that *Lepidium* infestations are a severe threat and can dominate a site very quickly. Eradication should focus on small satellite populations to curtail such exponential spread (Moody and Mack 1988).

Deviations from expected infestation area were negatively correlated with precipitation (Figure 2d), suggesting that spread is enhanced in dry years and slowed in wet years. However, this effect is subtle; *Lepidium* spread each year, regardless of weather conditions. More extreme conditions than experienced in 2004-2007 may have stronger impacts on spread; temperature and windiness may also be important and remain to be tested. Another consideration is that mapped distributions may correspond to previous years' spread due to sensor limitations. Positive and negative trends were found with springtime precipitation in years t-2 (p=0.08) and t-3 (p=0.06), respectively. Longer time series or data on the minimum detectable patch age are needed to determine the appropriate lag.

At RR and CRP, imagery detected spatial phenological variation. Observed stages were early flowering, peak flowering and fruiting (RR); and vegetative, flowering and senescent (CRP). At both sites, advanced phenologies were associated with the interior of patches, lower convexities, shallower slopes and higher elevations (RR: $R^2=0.33$, CRP: $R^2=0.56$), suggesting influences of intraspecific competition (Schmitt et al. 1987) and water availability (Chiariello 1989, Van der Sman et al. 1992). Interannually, phenology at CRP tracked hydrology. Five distinct trajectories
were observed, indicating that the degree to which phenology differs between years depends on site conditions as well as region-scale hydrology (Figure 3).

Phenological traits may contribute to *Lepidium*’s invasion success. Summer flowering is rare in Mediterranean climates and strongly associated with invasiveness (Lloret et al. 2005). *Lepidium*, a late-flowering species, may be taking advantage of this empty temporal niche. Additionally, phenology can control species distributions (Morin et al. 2007). Responsiveness of *Lepidium* phenology to environmental conditions may mediate the wide breadth of habitats *Lepidium* invades.

**Literature Cited**


**Table 1**

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<tr>
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<td>5±4 [25]</td>
<td>20±23 [84]</td>
</tr>
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<td>Western mesic</td>
<td>58±101 [226]</td>
<td>15±14 [86]</td>
<td>19±16 [87]</td>
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<tr>
<td>Levee</td>
<td>9±9 [57]</td>
<td>17±19 [108]</td>
<td>10±7 [51]</td>
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**Figure 3**

a) Average interannual variation in remotely-sensed *Lipidium* phenology at Cosumnes River Preserve for five distinct phenological trajectories (in colors) and for all *Lipidium* (black). For reference index values for vegetative, flowering and senescent stages are around 1.0, 1.5 and 3.0 respectively.

b) Total water year precipitation (blue) and discharge of the Cosumnes River (green), 2004-2007