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Source: Invasive Plant Science and Management, 2(3):260-269. 2009.

Published By: Weed Science Society of America

DOI: 10.1614/IPSM-09-005.1

URL: <http://www.bioone.org/doi/full/10.1614/IPSM-09-005.1>

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Predicting the Distribution of Perennial Pepperweed (*Lepidium latifolium*), San Francisco Bay Area, California

Melanie Vanderhoof, Barbara A. Holzman, and Chris Rogers*

Perennial pepperweed is an invasive plant species that occurs throughout the western United States. This study develops a predictive model for perennial pepperweed distribution for the San Francisco Bay Area, based on spatial variables. Distribution data were developed by mapping perennial pepperweed along the shoreline of the South San Francisco Bay, using geographic positioning system units. Spatial relationships between its distribution and spatial variables were tested using binomial logistic regression. Predictive models were mapped using geographic information systems (GIS), and high risk areas within the San Francisco Bay Area were identified. Perennial pepperweed was found to occur within marsh habitats with full tidal action and near open water. This study demonstrates that habitat variables from widely available GIS layers can be used to predict distribution patterns for perennial pepperweed. The model results were compared to land ownership within the study area to demonstrate a management application of the model.

Nomenclature: Perennial pepperweed, *Lepidium latifolium* L. LEPLA.

Key words: Predictive model, invasive, distribution, risk, San Francisco Bay, GIS.

The spread of invasive species is a critical ecological issue. Neville and Murphy (2001) identified invasive species as the largest threat to biodiversity after habitat destruction. Up to 46% of the plants and animals listed as endangered species in the United States have been negatively impacted by invasive species (National Invasive Species Council 2001). Such species can significantly alter the abundance, diversity, and distribution of native species (USCOP 2004). Mapping the distribution of an invasive plant species can provide the first step in managing its population. Modeling typically uses a variety of environmental and spatial variables to explain and predict the distribution of one or more species across a landscape (Guisan and Zimmerman 2000). After initial mapping efforts, modeling can be used to assess the potential spatial risk an invasive plant species poses (Collingham et al. 2000; Nielsen et al. 2008; Zhang et al. 2006).

A variety of spatial and environmental factors determine a plant's distribution (Higgins et al. 1999). Critical factors may include climatic attributes, geology, soil attributes, hydrological conditions, land cover and use, and topographic attributes (Cawsey et al. 2002; Gilham et al. 2004; Van Horsen et al. 1999). The distribution of an exotic species is also often linked to rates of disturbance (Kent et al. 1999; Zerbe et al. 2004; Zhang et al. 2006). For native marsh plants, salinity levels and tidal elevation are traditional distributional factors (Atwater et al. 1979; Grossinger et al. 1998).

The appropriate statistical model to relate distribution to spatial and environmental variables will depend on the species, type of data, scale, and goal of the model (Guisan and Thuiller 2005; Thuiller 2003). Regression analysis is a common technique that uses presence/absence data. Regression methods assume pseudoequilibrium; therefore, their use when a species is still expanding, as invasive species often are, can lead to biased results (Guisan et al. 2002). Despite this possible bias, many studies have employed forms of regression, specifically logistic regression, in ecological modeling (Bastin and Thomas 1999; Collingham et al. 2000; Higgins et al. 1999; Van Horseen et al. 1999).

Evaluating the adequacy of a model requires measuring the agreement between model predictions and field observations (Guisan and Zimmerman 2000). Types of error include (1) false negatives (species observed but not predicted to occur) and (2) false positives (species predicted

DOI: 10.1614/IPSM-09-005.1

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Interpretive Summary

This study developed a predictive model using binomial logistic regression to relate the distribution of perennial pepperweed in the San Francisco Bay Area, California, to spatial variables. Perennial pepperweed was found to occur within marsh habitats with full tidal action and near open water. The weed was also found closer to levees, on bare ground and in areas with low-intensity development. Risk was found to be unevenly distributed in the Bay Area both spatially and by land ownership. Among publicly owned lands, California Department of Fish and Game, U.S. Department of Defense, and U.S. Fish and Wildlife Service were found to have the greatest amount of land at medium, high, and very high risk of invasion by perennial pepperweed.

Modeling perennial pepperweed has both ecological and managerial benefits. The analysis of such models helps to determine critical ecosystem factors that allow for the invasion of perennial pepperweed and assist in the identification of other potential risk factors. Distance to water, for instance, appears to be a critical to the successful invasion of perennial pepperweed. Incorporating salinity or soil saturation into a model may be the next step in understanding where perennial pepperweed is most successful. Modeling perennial pepperweed on a regional scale helps natural resource managers to understand the risk the plant poses to the region, determine the amount of resources needed, and develop a strategy for managing perennial pepperweed. The models identify high-risk areas and allow field practitioners to prioritize areas to monitor and control the weed. Understanding the distribution of risk can help make weed management efforts more efficient and effective.

to occur but not observed). False-positive errors may be difficult to distinguish from suitable habitat where an invasive species has not yet been introduced (Gilham et al. 2004). The accuracy of a model is evaluated using a variety of methods. If one distribution data set is available and the data set is small, techniques such as cross-validation, jackknifing or bootstrapping are commonly used to test accuracy. If two independent distribution data sets are available, or the data set is large, the model is typically trained with one data set and tested with the remaining data set, using tests such as Cohen's *K*-statistic, kappa statistic, or another similar statistic (Guisan and Zimmerman 2000).

Perennial pepperweed (*Lepidium latifolium* L.) was originally seen as a threat to agricultural activities, but has since invaded a variety of moist habitats throughout the western United States (Renz 2001). The species has been documented expanding rapidly in the Bay Area in recent years (Howald 2000; May 1995; Renz 2002), but mapping has occurred only at a very coarse scale (Grossinger et al. 1998; May 1995). The spread of perennial pepperweed from agricultural areas into marsh and riparian systems within the San Francisco Estuary threatens habitats critical to many resident and migratory species; it also depreciates land values and degrades habitat through increased erosion and salinity (Skinner and Pavlik 1994; Spautz and Nur 2004; Trumbo 1994; Young et al. 1997).

Key to its successful expansion is the species' ability to reproduce from creeping roots, from root fragments, and by seed (California Department of Food and Agriculture 2004). Water flow and flood events have been shown to be the predominant methods of spread (Blank and Young 1997; Donaldson 1997; Hogle et al. 2006), whereas seeds and root fragments also travel by wind and soil movement via agricultural or other human activities (Young et al. 1997). Perennial pepperweed can use suitable habitats as corridors through which to spread. Perennial pepperweed established in riparian areas can follow irrigation canals and ditches to agricultural fields (Young et al. 1995) or spread from agricultural fields into previously pristine wetlands or riparian areas (Trumbo 1994).

Habitat limitations are somewhat disputed. Elevated salinity has been found by some to be detrimental to perennial pepperweed (May 1995; Spenst et al. 2004); conversely, perennial pepperweed has been found to be extremely tolerant of high water and soil salinities (Young et al. 1995, 1997). Perennial pepperweed appears to prefer moist soils, but avoids constant water inundation (Chen et al. 2002; Young and Turner 1995). Several researchers have found distance to water to be an important predictive factor for the species (Gilham et al. 2004; Hogle et al. 2006; Sanderson et al. 2001).

This paper addresses the following question: Can perennial pepperweed's distribution be explained and predicted using spatial variables? The model constructed in this study builds on two other studies. Gilham et al. (2004) relied almost exclusively on the variable distance to water to model perennial pepperweed and Sanderson et al. (2001) used a limited study area and focused on channel characteristics to predict the distribution. Developing a predictive model that encompasses a broad range of habitat characteristics is the next step in understanding the potential risk that perennial pepperweed poses to coastal ecosystems.

Although predictive models do not explain all variation in plant distribution or accurately predict all locations, predictive modeling based on GIS variable layers has proven to be an important tool in predicting the spatial distribution of plant species, and more recently, invasive plant species (Collingham et al. 2000; Higgins et al. 1999; Nielsen et al. 2008). Perennial pepperweed poses a threat because of its ability to dominate marsh and riparian habitats, quickly spread and displace native species, and elude attempts at control (Brigham 2004; Eiswerth et al. 2005). Modeling the distribution of perennial pepperweed can assist in prioritizing management strategies to curb its expansion.

Materials and Methods

Study Area. The San Francisco Estuary includes the San Francisco Bay and the upstream delta. The estuary's

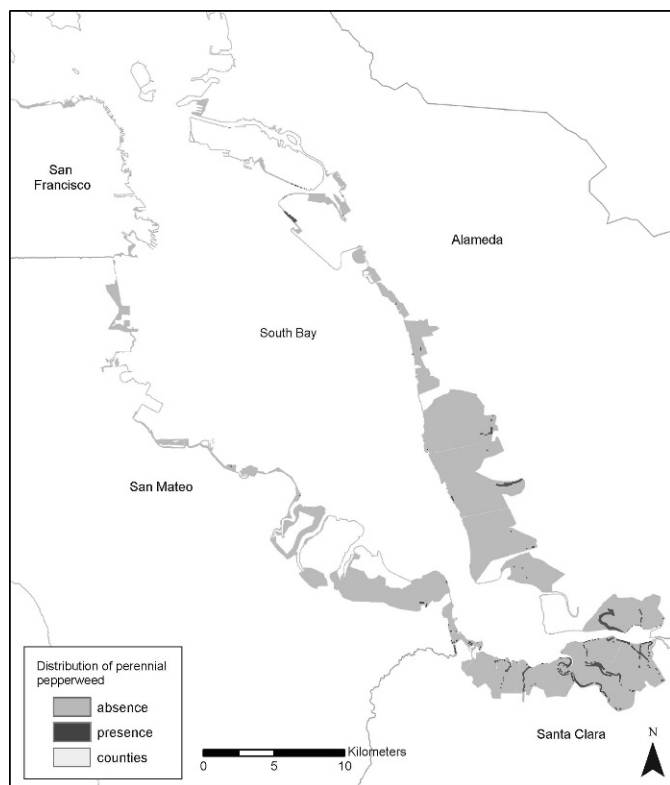


Figure 1. The distribution of perennial pepperweed within the areas surveyed around the South Bay, San Francisco Bay, California.

watershed covers an area of 60,000 square miles, roughly 40% of California (Cohen 2000). San Francisco Bay is the downstream part of the estuary. It is made up of four smaller bays: Suisun Bay and its associated diked wetlands, San Pablo Bay, the Central Bay, and the South Bay (Cohen 2000). In the past 200 yr, the conversion of marshes and mudflats into salt ponds, agriculture, and urban land have reduced the original area subject to tidal influence by more than 80% in the delta and by almost 40% in the bay (Cohen 2000). Native flora and fauna are further stressed by the more than 250 nonnative species that have been documented in the estuary (Cohen 2000).

Data Creation and Mapping. To provide distribution data upon which to build the model, perennial pepperweed was mapped using global positioning system (GPS) devices along the shoreline of the San Francisco Bay. Mapping efforts occurred on 43 d, between the months of June and December, during 2004 to 2007. Surveys consisted of covering areas by foot, bicycle, or car, and recording the perimeter of all patches of perennial pepperweed larger than 1 m² using hand-held GPS units,¹ with an expected accuracy of 1 to 3 m. In marsh areas, surveys extended approximately 200 m inland of marsh vegetation. In upland areas, surveys were restricted to approximately

200 m from the shoreline. Surveys were restricted to vegetated habitats and access was the primary limiting factor for areas surveyed.

A predictive model was developed using distribution data within the South Bay (Figure 1). Access was more comprehensive in the South Bay and habitats were seen as representative of the San Francisco Bay. Predictions of the model were applied to a larger study area that included San Pablo Bay and Suisun Bay. The extent of the predictive model was limited to an area seen as similar enough to the South Bay to minimize transferability concerns. Model transferability refers to the relevance of the model outside of the area in which it was developed.

Variables Tested. The choice of predictor variables was based on a literature review and the availability of existing data layers. To ensure that habitat types were sufficiently captured and incorporated into the model, two habitat layers were tested (layer A and layer B). The following variables were included:

- habitat type (SFEI 1997 [layer A]; USGS and NOAA 2002 [layer B])
- tidal regime (SFEI 1997)
- distance to open water (USGS and U.S. EPA 2005)
- distance to road (U.S. Census Bureau 2002)
- distance to levees (U.S. Census Bureau 2002)
- distance to agriculture (State of California, Department of Conservation, Farmland Mapping and Monitoring Program 2004)
- elevation (USGS 2003).

Variables were analyzed as raster files in GIS, a type of data structure that consists of a grid of cells. Distance-to-feature layers were created using the Euclidean distance feature in Spatial Analyst.² For categorical data, each category was converted into a binomial raster grid (each data cell contained one of two possible values), where the presence in that category equaled one and the absence equaled zero. Two habitat layers were used because the statistical significance of a habitat category may vary depending on the minimum mapping unit, classification scheme, and methodology used to derive the layer.

Analysis. Not all layers used in the analysis were available over the entire study area, so the predictive model was developed at two different spatial extents. The first spatial extent (spatial extent I) considered all of the variables, but predictions were restricted in area. The second spatial extent (spatial extent II) excluded elevation and the San Francisco Estuary Institute (SFEI) data layers (habitat [layer A] and tidal regime) but made predictions over the entire study area. To accommodate data resolution limitations, the regression analysis and model development was carried out at a raster cell size of 30 m. Principal components analysis (γ) was used to test for colinearity

between independent variables. A cut-off value of $\gamma \geq 0.75$ was used to consider the removal of variables from analysis.

Spatial autocorrelation (a measure of the degree of dependency between observations) and redundancy were reduced by selecting random, semiregularly spaced points to train the model (J. Davis, personal communication). Five hundred points within patches mapped as perennial pepperweed and 500 absent points were randomly selected. Moran's I index was calculated to assess the amount of spatial autocorrelation between the random points. The value of Moran's I index ranges from +1 (strong positive spatial autocorrelation) to 0 (a random pattern) to -1 (strong negative spatial autocorrelation).

The independent variables were first tested individually using binomial logistic regression to gauge the explanatory power (Nagelkerke R^2) of each variable.³ Based on the results of the individual variables, the variables were combined using the "enter" method, in which variables are entered into the model one at a time and related to the presence or absence of perennial pepperweed. The validity of each model was summarized using a variety of statistics. For each variable included in the model, its coefficient, standard error, and significance were calculated. The likelihood ratio test, a statistical test to decide between two hypotheses, was used to test the overall model. To test how well the model fit the data, the Hosmer and Lemeshow goodness-of-fit test was used (Garson 2006). A given model generates a regression equation that best explains the presence or absence of perennial pepperweed. This equation was converted into a probability map in GIS using raster calculator.¹ Where X_k is the coefficient of the corresponding variables, V_k , and P is the probability of occurrence (Mao 2006), the following equations are used:

$$\ln[P/(1-P)] = X_1V_1 + X_2V_2 \dots X_kV_k = \text{calculation 1} \quad [1]$$

$$[P/(1-P)] = \text{Exp}(\text{calculation 1}) = \text{calculation 2} \quad [2]$$

$$P = (\text{calculation 2}) / (1 + [\text{calculation 2}]) \quad [3]$$

The accuracy of the predictive equation built with binomial logistic regression was tested by comparing the present/absent predictions with the actual present/absent data, within a random 30% of the original data. Four types of cells were discerned when comparing predicted with actual distribution data:

- A = both actual and predicted models agreed to the absence of perennial pepperweed
- B = predicted absent, but actually present (false negative)
- C = predicted present, but actually absent (false positive)
- D = both actual and predicted models agreed to the presence of perennial pepperweed.

Four calculations were made: (1) the total percentage of cells accurately identified, (2) the percentage of absent cells correctly coded (predicted to be absent), (3) the percentage of present cells correctly coded (predicted to be present), and (4) the number of present cells correctly coded compared to the total number of cells predicted to be present (as a percentage). This fourth calculation was a measure of the overestimation of perennial pepperweed presence. The accuracy of the models using these calculations were compared at three cut-points, or probability values above which a cell is predicted to have perennial pepperweed present and below which perennial pepperweed is predicted to be absent.

We applied the model to assess perennial pepperweed risk based on land ownership. This analysis required overlaying a land ownership GIS layer (California Resources Agency Legacy Project 2005) with the probability of presence map of spatial extent II and comparing distributions using raster calculator. The goal of this application was to understand the distribution of risk compared to land ownership and the individual risk major government agencies within the San Francisco Bay Area face and to determine which agencies will be most critical to any regional control efforts.

Results and Discussion

Development of Models. The mapping efforts around South San Francisco Bay produced a distribution map for perennial pepperweed (Figure 1). The species was unevenly distributed and concentrated in the southern portion of the bay. When variables were tested individually using binomial logistic regression, distance to closest patch of perennial pepperweed explained almost all of the variation (92%). Invasive plant species tend to cluster, occurring frequently or not at all at sites. It is not surprising that this variable explained a large part of the variation in the distribution. The variable, however, is only applicable where the distribution of perennial pepperweed is known, and therefore was not included in the model. Other independent variables that had Nagelkerke R^2 values (percentage) greater than 25% included tidal zone (44%), estuarine wetland (layer B) (42%), water (layer B) (36%), diked tidal (36%), salt ponds (layer A) (32%), marsh (layer A) (31%), and distance from water (25%). The variables that had the highest explanatory power matched expectations from field observations. Perennial pepperweed occurs frequently in tidal marsh habitat, avoids salt ponds, and can be found close to, but not in, open water. Principal components analysis found five pairs of variables to be highly correlated ($\gamma > 0.75$). The variables nontidal and salt ponds (layer A) were eliminated from analysis because of high correlation with other variables. The variables distance to roads, distance to levee, and

Table 1. The variables included in each final spatial extent model, because of their statistical significance ($P < 0.05$), based on binomial logistic regression.

Spatial extent	Significant variables ^a	Coefficient	SE ^b	Significance (P)
I	Marsh (A)	1.338	0.195	< 0.001
	Other habitat (A)	1.698	0.390	< 0.001
	Distance to water	-0.003	0.001	< 0.001
	Distance to levee	-0.001	< 0.001	0.001
	Distance to road	0.001	< 0.001	< 0.001
	Diked tidal	-1.691	0.221	< 0.001
	Constant	-0.168	0.209	0.420
	II	Estuarine wetland (B)	2.400	0.370
Grassland (B)		1.960	0.416	< 0.001
Low-intensity development (B)		1.297	0.446	0.004
Bare ground (B)		1.302	0.565	0.021
Water (B)		-1.644	0.464	< 0.001
Distance to water		-0.004	0.001	< 0.001
Distance to road		0.001	< 0.001	< 0.001
Distance to agriculture		< 0.001	< 0.001	< 0.001
Constant	-0.572	0.393	0.146	

^a (A) = habitat layer created by San Francisco Estuary Institute (SFEI); (B) = habitat layer created by USGS and NOAA.

^b Abbreviation: SE, standard error.

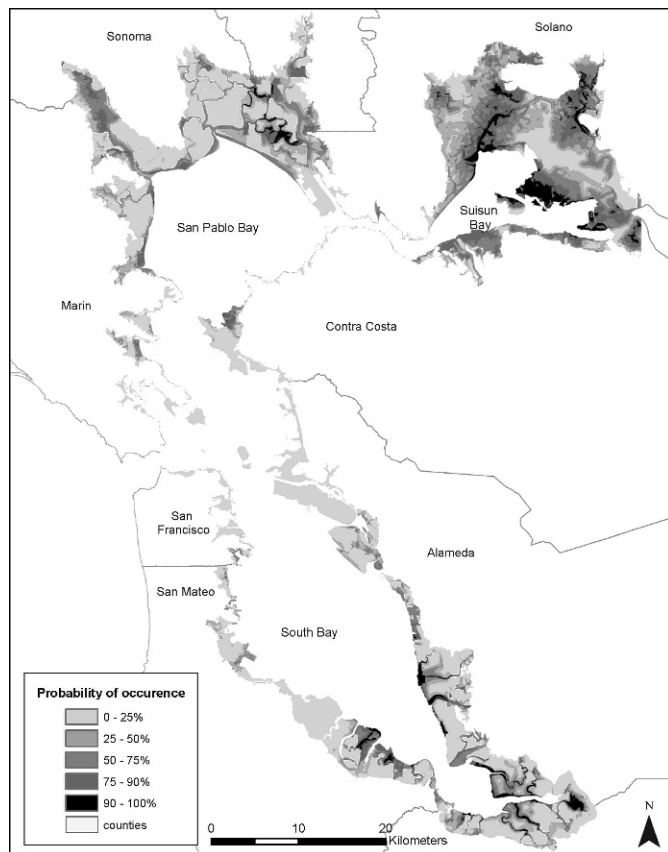


Figure 2. Probability of occurrence of perennial pepperweed within spatial extent I, San Francisco Bay, California.

distance to water were kept in the analysis because they refer to different landscape features and levels of disturbance, and appeared to explain patterns observed in the field.

Stratified sampling reduced, but did not eliminate, spatial autocorrelation (Moran's I index = 0.36; z score = 79.37 standard deviations). The variable "distance to patch of perennial pepperweed" was initially included in the analysis. The clustered distribution pattern of perennial pepperweed shown by this variable demonstrated that spatial autocorrelation plays a strong role in vegetation distributional patterns, especially weed distribution. Because of this role, although random stratified sampling did not entirely eliminate spatial autocorrelation, no other steps were taken. Incorporating a spatial autocorrelation term or information into a model can have serious disadvantages and may inadvertently mask the effect of relevant variables (Bio et al. 2002).

The significant variables included in the multivariate model for each spatial extent are listed in Table 1. For the "distance to" variables, a negative coefficient implies that a shorter distance is correlated with a higher probability of occurrence. For binomial variables, a positive coefficient signifies a higher prevalence within that category. In the model with spatial extent I (Figure 2), perennial pepperweed distribution was positively correlated with marsh, habitat classified as other, shorter distances to water and levees, and longer distances from roads, and negatively correlated with diked tidal areas (Table 1). In the model with spatial extent II (Figure 3), perennial pepperweed

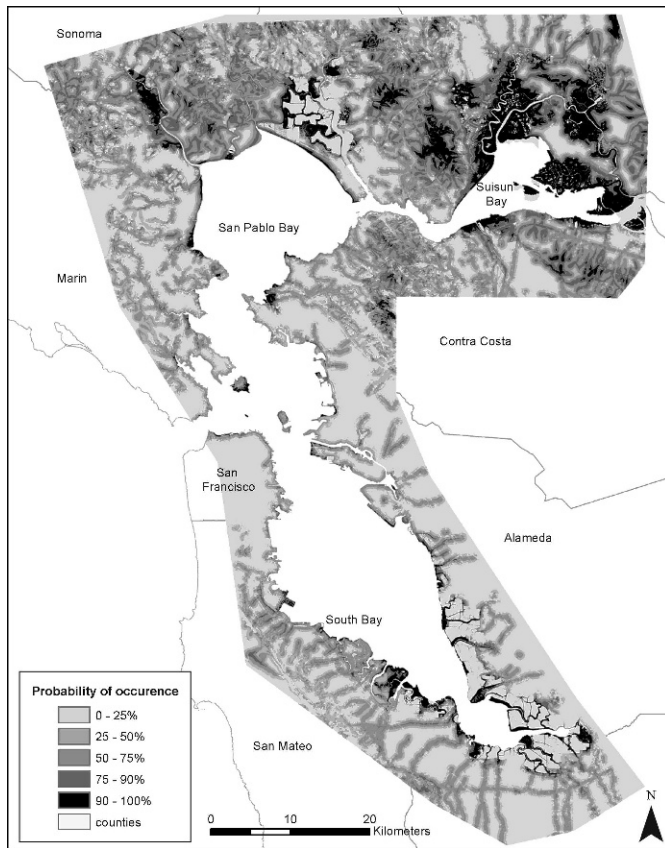


Figure 3. Probability of occurrence of perennial pepperweed within spatial extent II, San Francisco Bay, California. Spatial extent II does not consider elevation, San Francisco Estuary Institute habitat layer, and tidal regime because of layer availability.

distribution was positively correlated with marsh, bare ground, grassland and low-intensity development habitats, shorter distances to water, and longer distances to agriculture and road, and negatively correlated with water. The probabilities shown in Figures 2 and 3 are the probability of perennial pepperweed occurring at a given point.

Variables found to be statistically significant in both models included marsh habitat, shorter distances to water, and longer distances to roads. The correlation between the

species and marsh habitat and distance to water were both expected (Gilham et al. 2004; Hogle et al. 2006; Sanderson et al. 2001). The correlation with longer distances to roads may be explained by the geography of the areas surveyed. Perennial pepperweed was common along the shoreline, but because surveys occurred predominately in natural areas, roads were limited. The spatial relationship between the shoreline and roads may not be consistent in areas outside of the South Bay. Similarly, agriculture, which was significant in spatial extent II, was predominately found outside of the areas surveyed. All four “distance to” variables were significant in at least one of the models, suggesting the importance of the spatial aspect of the landscape in predicting the distribution of perennial pepperweed. The spatial relationships between agricultural activities, open water, levees, and roads may partially determine the vulnerability of an area to an infestation by perennial pepperweed. Perennial pepperweed is commonly found at the edge of marshes, as well as occasionally in ruderal areas that may have been classified as grassland, low-intensity development, or bare ground. These habitat types may have had a high explanatory power for those presence points not explained by marsh habitat, thus explaining the incorporation of somewhat unexpected habitat variables into the model.

Accuracy of Models. Both models tested well based on the training data. Spatial extent II tested slightly stronger than spatial extent I. The final models out-performed the null model (likelihood ratio table < 0.05) and the models’ estimates fit the data at an acceptable level (Hosmer and Lemeshow goodness-of-fit statistics > 0.05) (Table 2). Spatial extent II had a slightly higher explanatory value (Nagelkerke $R^2 = 0.623$) than spatial extent I (Nagelkerke $R^2 = 0.542$). Both models correctly classified both absent and present points better than 75%, and explained more than 50% of the variation in the dependent variable.

The four accuracy calculations were calculated for each model at three different cut-points: 0.5, 0.75, and 0.9. Spatial extent I had an overall accuracy of more than 85% at all three cut-points. Spatial extent II had an overall accuracy of more than 85% at the 0.9 cut-point (Table 3). The percentage of present cells correctly identified drops significantly between the 0.75 and 0.9 cut-points in both

Table 2. A statistical summary of the strength and accuracy of the three binomial logistic regression models, based on the points used to develop the model.^a

Spatial extent	Likelihood ratio table	Nagelkerke R^2	Hosmer and Lemeshow goodness of fit	% Absent classified correctly	% Present classified correctly
I	< 0.001	0.542	0.059	80.4	82.8
II	< 0.001	0.623	0.631	79.3	87.4

^a The probability cut-point to determine if perennial pepperweed was present or absent at a point was the default value of $P = 0.5$.

Table 3. Accuracy of binary logistic regression models at different cutpoints.

Spatial extent	Cut-point	1. Total correct (%)	2. Absent correct (%)	3. Present correct (%)	4. Actual/predicted (%)
I	0.5	86.01	85.90	93.28	9.23
I	0.75	92.00	92.16	91.50	15.22
I	0.9	98.00	98.74	50.20	37.97
II	.5	65.06	64.62	93.85	3.87
II	0.75	77.68	77.50	89.48	5.69
II	0.9	89.05	89.40	68.12	8.88

spatial extents. In spatial Extent II, accuracy calculation 4 was relatively small at all three cutpoints.

The statistical strength of both models helped to validate them. The higher accuracy of spatial extent I, when tested with one-third of the original data, was most likely due to the inclusion of tidal regime categories. In a perfect model, all four accuracy calculations would be 100%. For an invasive species that is still expanding, however, calculation 4 (ratio of actual/predicted presence) should be less than 100%. Consequentially, calculation 2 (the percentage of absent cells correctly coded) should also be less than 100%, indicating that some cells where perennial pepperweed is currently absent, it may not be in the future.

The recommended cut-point for both models is 0.75. At this cut-point, the accuracy calculations are best balanced between accurately identifying perennial pepperweed patches and not overpredicting its distribution. In spatial extent I, changing the cut-point from 0.5 to 0.75 cut the percentage of absent cells incorrectly coded (calculation 2) almost in half, whereas the percentage in calculation 4 almost doubled. Changing the cutpoint from 0.75 to 0.9 more than doubled calculation 4 in spatial extent I, but the percentage of present cells missed (calculation 3) increased to an unacceptable level of almost 50%. Spatial extent II experienced similar patterns, but a move from cut-point 0.75 to 0.9 resulted in a relatively small increase in calculation 4, but a large increase, to over 30%, for calculation 3.

Model Application to Land Ownership. The models were used to predict the occurrence or risk of invasion with respect to land ownership. In assessing overall risk, we found over 80% of the study area is composed of private land (Table 4). Of the publicly owned land within the study area, California Department of Fish and Game (CDFG) (19%), the Regional Park District (RPD) (19%), U.S. Fish and Wildlife Service (USFWS) (12%), local water districts (12%), and the Department of Defense (DoD) (9%) manage the majority of the public land. Of the public land predicted to be at medium, high, and very high risk for invasion by perennial pepperweed, CDFG manages the most, followed by DoD, USFWS, and local water districts (Table 4). If the risk was spread equally

throughout the study area, then the proportion of land owned by each agency should be similar to the proportion of land at risk for each agency. However, several agencies have either a noticeable increase or decrease in their expected risk level. Land owned by CDFG, DoD, and conservancies or land trusts shows a disproportionate risk, whereas land owned by the RPD and the National Park Service (NPS), show a disproportionate reduction in risk (Table 4).

When the land owned by each agency is examined separately, several agencies have a significant portion of their property at risk of invasion by perennial pepperweed, including California State Lands Commission (CASLC) (> 85% at high or very high risk of invasion), conservancies or land trusts (~ 60% at high or very high risk), and CDFG (> 40% at high or very high risk of invasion). At particularly low risk is NASA (3% at medium, high, or very high risk), NPS (< 3% at high or very high risk), and Open Space districts (4% at high or very high risk).

The model application demonstrates that the control of perennial pepperweed will not be successful if limited to publicly owned lands. Over 80% of medium- and high-risk land and approximately 70% of very high-risk land is privately owned (Table 4). Despite this challenge, organizing a management program within public lands will help protect or restore already preserved land from invasion by perennial pepperweed. Within the study area, the CDFG, DoD, USFWS, and local water districts will all be critical to include in any management efforts. Additional groups including CASLC and conservancies or land trusts may own relatively small amounts of public land within the study area, but face high levels of risk within the land they manage. Any control efforts would require coordination across agencies, and between different levels of government (local, state, and federal).

Analysis of Models. The models developed are informative at the large scale of the study, but may be too general for individual land owners and managers. The strength of the models was limited by the variables available and considered in the analysis. The scale of the layers used required a raster cell size of 30 m, but this limited the

Table 4. The distribution of medium, high, and very high risk land (land at risk of invasion by perennial pepperweed), between public landowners.^a

Agency	% of study area	Medium risk (%)	High risk (%)	Very high risk (%)
Private land	82.56	86.79 ^b	81.60 ^b	70.85 ^b
All public land	17.44	13.21	18.40	29.15
California Department of Fish and Game	19.20	23.44 (1 ^c)	35.10 (1 ^c)	48.28 (1 ^c)
Regional Park District	18.81	11.23 (4 ^c)	8.89 (4 ^c)	2.61
U.S. Fish and Wildlife Service	12.46	13.64 (3 ^c)	7.96	25.61 (2 ^c)
Local water district	11.86	8.60	9.56 (3 ^c)	2.17
Department of Defense – general	9.24	19.52 (2 ^c)	19.63 (2 ^c)	8.54 (3 ^c)
City or county park	6.58	3.56	2.40	0.95
Miscellaneous local	5.42	6.66	6.14	2.28
National Park Service	5.00	1.99	0.94	0.27
Open space district	4.20	4.63	1.75	0.14
California Department of Parks and Recreation	2.82	2.21	2.90	1.38
Conservancy or land trust	2.61	3.91	4.25	7.46 (4 ^c)
NASA	0.81	0.23	0.01	0.00
Miscellaneous state	0.61	0.28	0.05	0.00
California State Lands Commission	0.18	0.05	0.32	0.15
State academic institution	0.18	0.05	0.10	0.02
Unknown – federal	0.02	0.02	0.00	0.14
Bureau of Land Management	< 0.01	0.00	0.00	0.00

^a The percentages for “private land” and “all public land” represent the percentage of all land within the study area, whereas the percentage for each individual nonprivate landowner represent the percentage out of all public-owned land within the study area.

^b Represents the percentage of the study area at the specified risk level that is private land. For example 86.79% of the medium risk land within the study area is private land.

^c Rankings of the top four agencies in order of the amount of land at risk, for each risk level, are recorded in parentheses.

precision of relationships that could be detected. Data acquisition difficulties included finding high-resolution data that were available over the entire study area (approximately 6,000 km²). Errors and inaccuracies within the GIS data layers were likely a source of error. Also, the difference in significance and a lack of correlation between the two different habitat layers used in the analysis demonstrates that the classification method and the techniques used to create a data layer affect the significance of that variable within a model. Current and ongoing research on more specific aspects of perennial pepperweed ecology may identify additional explanatory variables that could be used to further refine a model such as the ones presented here. The utility of modeling would benefit from incorporating data from current and future research on subjects such as salinity and inundation tolerance, sediment characteristics (Spent et al. 2004), recruitment characteristics, rates and pathways of spread, methods of dispersal, and impacts on wildlife habitat, soil biota, and food webs. As finer-resolution GIS layers become available, conducting the analysis at a more detailed level may help discern subtle relationships between perennial pepperweed distribution and a variety of spatial and environmental variables.

The models, despite the concerns raised above, can assist in the management of perennial pepperweed. Management plans could be developed based on the distribution of habitat at risk and the ownership of that land. Such a plan could help focus education efforts and prioritize eradication and monitoring sites. Perennial pepperweed tends to spread to immediately adjacent areas, thus infestations should be controlled and eliminated as early in the establishment phase as possible. Habitat type can provide a basis for monitoring strategies. Marsh habitat, the transition zone between grasslands and marshes or low-density development and marshes, and areas close to open water, should all be prioritized in monitoring for perennial pepperweed.

This modeling attempt demonstrates that habitat variables from widely available GIS layers can be used to begin discerning the spatial risk of perennial pepperweed. Areas at high risk include tidal marsh and riparian habitat, particularly within large wetland systems. The significant relationships between distribution patterns and spatial and environmental variables increase our knowledge about the habitat preferences and limitations of perennial pepperweed. This modeling attempt is a first step in developing a comprehensive predictive model. Modeling the species at different study sites and incorporating additional variables

as they become available will help further the understanding of how perennial pepperweed interacts with its environment. This study indicates potential for modeling other invasive species. Such models can be applied in management activities to prioritize control efforts and increase the efficiency with which funds are spent to monitor and control invasive plant species.

Sources of Materials

¹ Trimble GeoExplorer 3.0. Trimble. 935 Stewart Drive, Sunnyvale, California 94085.

² ArcGIS 9.2., ESRI, Redlands, CA.

³ SPSS for Windows, Release 14.0, SPSS, Chicago, IL.

Acknowledgments

This project was fully funded by a grant from the California Bay Delta Authority's (CALFED) Ecosystem Restoration Program (ERP-02-P09). Materials and logistical support were provided by the consulting firm ESA and by the Geography Department at San Francisco State University. The authors would like to thank Martha Lowe, Mark Fogiel, Kelly Runyon, and Cody Reynolds for their assistance in mapping *L. latifolium*, as well as Dr. Ellen Hines, Dr. Jerry Davis, Barry Nickel, Bill Boynton, Clyde Morris (USFWS), and John Krause (CDFG) for their feedback and logistical support. The authors would also like to thank the editor and anonymous reviewers for their constructive comments.

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Received February 14, 2009, and approved June 7, 2009.