A SPATIAL MODEL OF EELGRASS (ZOSTERA MARINA) HABITAT IN HUMBOLDT BAY, CALIFORNIA

By

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A SPATIAL MODEL OF EELGRASS (*ZOSTERA MARINA*) HABITAT IN
HUMBOLDT BAY, CALIFORNIA

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ABSTRACT

A spatial model of eelgrass (Zostera marina) habitat in Humboldt Bay, California

Whelan Gilkerson

This study was conducted to model the extent of eelgrass habitat in Humboldt Bay, California through physical surveys of the maximum depths and upper limits of growth in conjunction with recently acquired high-resolution bathymetry data and supplemental imagery. A combination of chronic turbidity, frequent coastal stratus, and wind-waves, make Humboldt Bay a challenging environment to assess subtidal eelgrass (Zostera marina) habitat from remotely-sensed imagery. Additionally, eelgrass and green algae overlap extensively in shallow intertidal areas, confounding efforts to distinguish between habitat types from imagery alone. A relative exposure index (REI) was developed to identify areas of eelgrass habitat that may be prone to disturbance from wind-waves. Approximately 2200 hectares of eelgrass habitat were identified. Accuracy was assessed at 91% for modeled eelgrass habitat in South Humboldt Bay based on a comparison with hyperspectral imagery captured in October, 2004. Modeling the extent of eelgrass habitat represents an important step towards understanding the extent to which future restoration or mitigation may be possible in Humboldt Bay.
Humboldt State University faculty support and guidance was provided by Dr. Steven Steinberg, Dr. Frank Shaughnessy, and Dr. Gregory Crawford. Funding support was provided by the Center for Integrative Coastal Observation Research and Education (CICORE; NOAA award NA16OC2907) and by Pacific Coast Joint Venture. Bathymetry data used in this study were acquired, processed, archived, and distributed by the Seafloor Mapping Lab of California State University Monterey Bay.
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Eelgrass (*Zostera marina*) is widely distributed throughout temperate estuaries and protected coastal embayments of the northern Pacific and Atlantic oceans. In Humboldt Bay, California, eelgrass is the dominant macrophyte of shallow subtidal and lower intertidal zones and provides a multitude of ecosystem services. It represents a critical food source for staging Black Brant (*Branta bernicla nigricans*) (Moore and Black 2006) and supports a rich detrital food web (Phillips 1984). Eelgrass provides important structure and habitat for a broad range of fish and invertebrates (Phillips 1984). In areas where eelgrass forms extensive meadows, current flow velocity and turbulence are reduced, leading to the creation of localized depositional environments (FONSECA AND FISHER 1986). This can result in a concentration of fine particles and an increase in both organic content and sediment stabilization (Phillips 1984).

Eelgrass habitat is protected by federal and state law (Clean Water Act, 1977 and California Coastal Act, 1976). As a result, development activities conducted in areas where eelgrass is present are heavily regulated. The National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service, and California Department of Fish and Game have developed a standardized policy to mitigate harmful impacts to existing eelgrass beds as well as potential eelgrass habitat (NMFS 1991). In general, disturbance of existing eelgrass necessitates mitigation to offset any loss of the resource. Surveys are required to define the areal extent of potential as well as existing eelgrass habitat at.
risk of impact. Eelgrass habitat is determined on the basis of suitable depth, slope, light, hydrodynamic setting, water quality parameters, and history of eelgrass coverage. Analysis of these factors contributes to a determination of the scope of required mitigation (NMFS 1991).

A no net loss management policy for eelgrass dictates a need to better understand the limits of eelgrass habitat on a regional scale (Fonseca et al. 1998) in order to better estimate the capacity for mitigation. With the growing availability of high-resolution bathymetry data and software tools that facilitate portrayal of habitat parameters in a geographic information system (GIS; e.g. Allen et al. 2007), the opportunity now exists to extrapolate results of site specific surveys to model eelgrass habitat across entire estuarine landscapes. Modeling at this scale requires mapping the spatial extent of eelgrass using the most up-to-date data available.

Physical habitat attributes and environmental phenomena most relevant to the distribution of eelgrass within a study area must also be considered for inclusion in a GIS-based habitat model. Availability of existing data as well as local knowledge of the estuary should guide decision-making regarding parameters to be modeled.

Two major objectives are addressed in this study: development of a model delineating eelgrass habitat distribution in Humboldt Bay and a demonstration of how this model can be used to make site recommendations for restoration or mitigation of eelgrass based on hand transplanting methods.

A variety of techniques have been suggested to map eelgrass and other submerged aquatic vegetation (SAV). These techniques can be broken down into three general
categories: physical, off-water remote sensing, and on-water remote sensing (Sabol et al. 2002). Physical methods of mapping SAV include the use of divers to measure attributes in subtidal areas as well as walkers to conduct surveys during low-tides. Off-water remote sensing techniques involve aircraft and satellite based imaging technologies. On-water remote sensing includes the use of georeferenced underwater videography and hydroacoustic imagery. Advantages, disadvantages, and relative costs of these different approaches are summarized by Fairbanks and Norris (2004).

Across the Pacific Northwest, eelgrass has been documented to grow within a range of tidal elevations spanning –6.6 to 1.8 m relative to Mean Lower Low Water (MLLW) (Phillips 1984). The upper limit of eelgrass growth is primarily determined by plant stresses associated with desiccation and wave exposure (Koch 2001; Boese et al. 2003). Maximum depths suitable to the growth of eelgrass are heavily influenced by the attenuation of light at depth, due to the cumulative effects of turbidity (Dennison 1987).

Water quality with respect to the light environment varies significantly across multiple spatial and temporal scales within Humboldt Bay. While patterns have been observed, little is known about the light environment, especially in South Bay. Where water quality data are available (dock B along the Eureka waterfront, Fig. 1), precipitation appears to have the biggest impact on turbidity, which in turn depresses light availability for primary producers (Shaughnessy et al. 2004).
Fig. 1. Study area location, Humboldt Bay, California, USA
While seasonal phytoplankton blooms and dissolved organic material contribute to turbidity in Humboldt Bay, these factors are overwhelmed by the impacts of suspended sediment (Barnhart et al. 1992). Sediments carried by runoff from surrounding watersheds primarily during winter storms enter the bay in two ways: as discharge from tributaries that feed directly into the bay, and indirectly during winter and early spring when the Davidson current carries suspended sediment north from the Eel River and into the bay through the entrance channel on flood tides (Barnhart et al. 1992).

Eelgrass grows in a wide range of unconsolidated sediments within the spectrum of sand to clay (Phillips 1984). Virtually all of Humboldt Bay, with the exception of areas impacted by recurrent dredging operations, active aquaculture, and the physical presence of buoys, docks, and armored pilings, consists of substrate suitable to the growth of eelgrass (Borgeld and Stevens 2004).

In addition to particle size distribution, geochemical cycling of nutrients and toxins such as sulfides may play a role in limiting eelgrass distribution (Koch 2001). Though no evidence was found to suggest that eutrophication is negatively impacting eelgrass in Humboldt Bay currently, Tennant (2006) showed that eelgrass was susceptible to mortality from experimentally increased sediment phosphate concentrations.

The wave environment may also play an important role in shaping the upper limits of eelgrass habitat within certain areas of Humboldt Bay. While seagrass meadows have been shown to attenuate wave energy based on extensive field observation and recent modeling efforts (Koch 2001; Chen et al. 2007), they are also prone to physical disturbance from wind-waves generated locally during intense winter storms. Fonseca
and Bell (1998) found that the continuity of eelgrass beds on a landscape scale decreased with increasing hydrodynamic activity. Seasonally persistent winds of a lower intensity may also restrict the upper limit of potential eelgrass habitat through constant shifting and resuspension of sediment particles (Koch 2001).

A number of studies provide a conceptual framework for modeling eelgrass habitat. Bach (1993) identified water transparency, water temperature, and bathymetry as primary factors controlling the growth and distribution of eelgrass. Orth (1994) assessed environmental factors contributing to light attenuation and concluded that SAV biomass and density can increase with improvements to water quality associated with the light environment. Keddy (1982) created the Relative Exposure Index (REI) based on wind speed, fetch measurements, and the proportion of time that the wind blew from a particular bearing. REI was developed to investigate the distribution of aquatic plants in a freshwater lake. Fonseca and Bell (1998) adapted REI to model exposure in seagrass beds but found that the results overestimated the development of waves in shallow water. Fonseca and Malhotra (2006) produced an updated wave exposure model (WEMo 3.0) incorporating depth in the calculation of fetch to improve estimates of REI values in shallow water.

A generalized model for estimating habitat was proposed by Cho and Poirrier, (2005). They assessed the relationship between SAV distribution and environmental factors to develop model parameters. Water clarity was found to control maximum suitable depths, fluctuations in water level and wave mixing determined the upper limits suitable for growth, and variations in areal coverage under comparable water
quality conditions resulted from differences in shoreface slope. Model validation was accomplished by comparison of empirical values from the data to those predicted by the model. This model was developed for a freshwater system but is said to be applicable for coastal areas as well (Cho and Poirrier, 2005).

Several states along the Atlantic coast of the USA have adopted the use of site selection tools designed to predict and inform managers of the best locations to attempt restoration of eelgrass. Parham and Karrh (2001) developed a GIS-based model to evaluate Chesapeake Bay tidal areas for suitable SAV restoration sites. The model was based on a synthesis of water quality, bathymetry, current and historic SAV distribution, fisheries, and watershed level data. Kelly et al. (2001) developed a predictive mapping technique for seagrass habitat in North Carolina, based on bathymetry, REI, and seagrass coverage. Logistic multiple regression and Boolean logic models were developed from the data to generate predictive maps identifying locations susceptible to storm damage, probability of seagrass cover, and the suitability of areas for seagrass restoration. Short et al. (2002) developed a site selection model called the Transplant Suitability Index (TSI) specifically for Z. marina, integrating bathymetry, sediment type, water quality, wave exposure, and past as well as present eelgrass distribution in a multiplicative index to identify and prioritize locations for eelgrass restoration.

A review of eelgrass restoration efforts dating back to 1978 in the northeastern U.S. showed that previous efforts had resulted in an average success rate of 25% (Short et al. 2002). Surveys conducted two years after restoration efforts were completed found
a 62% success rate at sites selected by the TSI model in New Bedford Harbor, Massachusetts. In an effort to document mitigation efforts, Hoffman (1999) compiled a database of eelgrass transplanting projects in California dating back to 1976. He found that overall transplant success increased from 25% during 1976-1979 to 56% between 1990-1994. He attributed this improvement to more careful consideration of appropriate site conditions. Development of a model for optimal site selection such as the TSI might lead to further improvements in the success rate of prospective eelgrass transplanting efforts in California.

Future port expansion and shoreline development activities are likely to impact eelgrass habitat in Humboldt Bay. This makes it increasingly important to understand the extent of available habitat in order to better predict the capacity for mitigation of eelgrass within the bay. This study modeled the extent of eelgrass habitat in Humboldt Bay on the basis of physical surveys of maximum depths and upper limits of growth coupled with bathymetry and supplemental imagery. A model of relative wave exposure was developed to describe how variation in the exposure environment within the bay might influence the success of eelgrass transplanting efforts. A demonstration of how this model could be used to inform management decisions regarding site recommendations for transplanting eelgrass is also presented.
MATERIALS AND METHODS

STUDY AREA

Humboldt Bay, located in Northern California, is the second largest enclosed bay in the state, covering approximately 62.4 km$^2$ at mean high tide and 28.0 km$^2$ at mean low tide (Proctor et al. 1980 in Barnhart et al. 1992). The bay is comprised of three distinct sub-basins, North (Arcata) Bay, Entrance Bay, and South Bay (Fig.1). Both North Bay and South Bay consist of large areas of shallow mudflats interspersed with drainage channels (Barnhart et al. 1992). Entrance Bay has a maximum depth of approximately 15 m in the dredged portion of the channel and connects both North and South Bay to the Pacific Ocean. Humboldt Bay contains roughly 45% of California's eelgrass habitat.

For the purpose of this study, eelgrass habitat was defined as the area between maximum depths and upper limits suitable to the growth of eelgrass in the North and South Bay basins of Humboldt Bay. Eelgrass habitat in these basins includes both existing eelgrass as well as areas identified as being suitable for eelgrass growth not currently supporting eelgrass. Due to a lack of appropriate high-resolution imagery for the North Bay basin, a distinction between the extent of existing eelgrass and potential eelgrass habitat is beyond the scope of this study for North Bay.

The Seafloor Mapping Lab at California State University Monterey Bay produced a bathymetric digital elevation model (DEM) of Humboldt Bay (available at http://
seafloor.csumb.edu/SFMLwebDATA_n.htm#HUM) for the Center for Integrative Coastal Observation, Research, and Education (CICORE). The DEM was based on a fusion of LiDAR, hyperspectral, multibeam sonar, and singlebeam sonar imagery collected between 2002 and 2005. This dataset represents the most complete effort to map the bathymetry of Humboldt Bay to date and provides the backdrop to support a raster-based geospatial model of eelgrass habitat. The DEM consists of 25 m$^2$ grid cells. All analytical GIS procedures in this study utilized ArcGIS 9.2 (ESRI, Redlands, California) software unless otherwise noted.

The Humboldt Bay DEM required several preliminary modifications in order to effectively model eelgrass habitat across the bay. The DEM was initially referenced to the NAVD-88 vertical datum. NOAA Center for Operational Oceanographic Products and Services (CO-OPS) tidal benchmark information for Humboldt Bay (available at http://tidesandcurrents.noaa.gov/) was used to interpolate a surface by which to adjust the depth values of the DEM to reference to Mean Lower Low Water (MLLW) (Bennett et al. 2004). With the exception of the major shipping channel, much of Entrance Bay was missing depth data. Additionally, many areas of the channels in both North and South Bay beyond the limits of sonar surveys had depth values that were significantly underestimated by LiDAR and hyperspectral sensors. A rectified nautical chart (NOAA chart 18622) and 2005 National Agricultural Imagery Program (NAIP) 1m$^2$ resolution color imagery were used to supplement the DEM where depth data were either missing or inadequate. An analysis mask was also created to avoid
identifying eelgrass habitat in Entrance Bay basin due to the susceptibility of the area to disturbance from large ocean waves.

Figure 2 shows the areas of the Humboldt Bay fusion DEM covered by each of the four input datasets. Supplemental depth data for portions of Entrance Bay and North Bay Channel not included in the fusion DEM were derived from an electronic nautical chart (NOAA nautical chart 18622).

Light availability has been established as the principle factor in determining the maximum depths suitable for SAV growth (Dennison 1987). Since light availability is a function of optical properties of the water column and is associated with average water quality conditions at a given location, water quality data can be used to predict the maximum depths of SAV growth (Cho and Poirrier 2005).

Spatially extensive water quality data are lacking for most of Humboldt Bay. Data from the CICORE sonde located at Dock B along the Eureka waterfront (Fig.1) illustrate the dynamic nature of the light environment in Humboldt Bay. Turbidity values may vary as much as 100 Nephelometric Turbidity Units (NTU) across a single tidal cycle. This makes it challenging to characterize the light environment at any particular location, without having extensive water quality data from which to draw inference. Conversely, if the maximum depth of eelgrass growth is dependent upon the average light availability at a given location, then measuring the maximum depths of eelgrass growth at locations distributed across the bay was thought to provide a reasonable surrogate for water quality data for the purpose of modeling habitat.
Fig. 2. Source data footprint for the fusion digital elevation model of Humboldt Bay, California. LiDAR data (EarthData International, Gaithersburg, MD) was captured in 2002, hyperspectral imagery (Florida Environmental Research Institute) was captured in 2004, single-beam sonar (U.S. Army Corps of Engineers) and multi-beam sonar (Seafloor Mapping Lab, CSU Monterey Bay) data were captured in 2005. The Seafloor Mapping Lab performed fusion of these data for CICORE in February 2006.
EXPERIMENTAL DESIGN

In order to model the extent of eelgrass habitat in Humboldt Bay, surveys were conducted to determine the depth range suitable for the growth of eelgrass. Maximum depth data collected in November 2005 and April 2006 were used to establish the lower threshold of eelgrass growth. Scientific divers from Humboldt State University swam 100 m transects established along the lower edge of eelgrass beds adjacent to channel margins. Divers descended to the lower edge of the eelgrass at opposite ends of each transect and released small buoys to signal the beginning of the depth survey. A third buoy was released when the dive teams met at the center of the transect, signaling the end of the survey. Sensus Pro data loggers (Reefnet, Inc., West Seneca, New York) were used to record depth to the nearest 0.3048 m every second during the dives. Buoys were intercepted at the surface by a support crew and GPS coordinates were then established with a Trimble Geoexplorer GPS unit (Trimble Navigation, Sunnyvale, California). Depth data were calibrated to the tidal stage at the time of buoy release to determine maximum depths in m relative to MLLW. These efforts yielded latitude, longitude, and maximum depth at eighteen sites distributed across North and South Bay (Fig. 3).

The upper limits of eelgrass habitat were determined from extensive ground-based surveying during minus low tides between April 2006 and December 2007. During these surveys, small isolated patches of eelgrass were found growing in moisture retaining features in mudflats, situated at relatively high intertidal elevations well above the upper limits of the more extensive eelgrass beds. These features were too
small to be captured by the bathymetry DEM and therefore difficult to incorporate in a raster-based habitat model. Additionally, incorporating these small patches of (potentially ephemeral) eelgrass would have led to an overestimation of available eelgrass habitat. As a result, a distinction was made to differentiate between patchy and continuous habitat: continuous eelgrass habitat was defined on the basis of a minimum mapping unit of 25 m² to match the resolution of the bathymetry dataset. Photos were taken during upper limit surveys to illustrate the distinction between habitat types (Figs. 4, 5). Although a calculation of habitat area was not possible for patchy eelgrass habitat, the regions of the DEM where patchy eelgrass was found during surveying efforts were identified.

Upper limit elevations were determined in one of two ways based on location of the survey. In areas within close proximity to benchmarks referenced to tidal elevation, an electronic total station (Topcon Positioning Systems, Inc., Livermore, California) was used to establish the upper limits suitable to eelgrass growth. In remote areas of the bay, a Trimble Geoexplorer GPS unit was used to capture latitude and longitude coordinates along the upper edge of growth. Coordinate data were differentially corrected to achieve a horizontal accuracy of approximately 1 m. Elevation values associated with the underlying cells of the bathymetry DEM were then assigned to the coordinate data, providing latitude, longitude, and elevation for the upper limits of eelgrass habitat. A total of 226 upper limit elevation values were measured at 26 sites across Humboldt Bay (Fig.6).
Fig. 3. Eelgrass (*Zostera marina*) maximum depth survey site locations (A-R) and bathymetry (gray scale) for Humboldt Bay, California.
Fig. 3. Photo taken at a tidal stage of approximately -0.2 m MLLW in Humboldt Bay, California, showing continuous eelgrass (*Zostera marina*) in the foreground and background bisected by a small tidal channel carrying turbid water.
Fig. 4. Photo taken at low tide, showing patchy eelgrass (*Zostera marina*) (A) growing at approximately 1.4 m MLLW (foreground) in an area of mudflat receiving runoff from intertidal marsh (B).
Fig. 5. Eelgrass (*Zostera marina*) upper limit survey site locations (1-26) and bathymetry (gray scale) for Humboldt Bay, California.
Table 1 illustrates survey effort involved in determining the depth range suitable for eelgrass growth in Humboldt Bay. The number of surveys and the number of individual depth measurements recorded for maximum depth and upper limit surveys are shown.

DATA ANALYSIS

Raw values from maximum depth and upper limit surveys were summarized prior to incorporation into the depth-based habitat model. Mean and standard deviation were calculated for depths measured at each upper limit survey site. Due to the large amount of data recorded during each maximum depth survey (Table 1), mean, standard deviation, and 95% confidence intervals were generated from a random sample consisting of 40 depth values measured at each site. The mean center of each maximum and minimum depth survey site was calculated from the latitude and longitude coordinates of the individual survey points at each site. A shapefile was created and the mean elevations corresponding to each survey site were then assigned to each site location. The site point data were used to interpolate surfaces representing the upper and lower thresholds for eelgrass growth using ordinary kriging (Spatial Analyst Extension). Guan et al. (1999) identified kriging as the most suitable method for spatial interpolation of all SAV parameters measured. They also found that transect data with irregular patterns of spatial distribution were sensitive to interpolation methods. Boolean logic was used to generate a map algebra expression with the Raster Calculator (Spatial Analyst) using the continuous upper and lower eelgrass interpolated surfaces to select the region of the bathymetry DEM with depths suitable for eelgrass
Table 1. Summary of depth survey data including type, number of surveys conducted, and total number of depth values recorded for the maximum depths and upper limits of eelgrass growth in Humboldt Bay, California.

<table>
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<th>Survey type</th>
<th>number of surveys conducted</th>
<th>total number of depth values recorded</th>
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<td>maximum depth</td>
<td>18</td>
<td>13395</td>
</tr>
<tr>
<td>upper limit</td>
<td>26</td>
<td>226</td>
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growth. All geographic data analysis was performed in the WGS 1984 datum, UTM zone 10 North with linear units in meters.

Supervised classification was performed on the 2005 NAIP imagery using the Image Analyst extension. The image was clipped to the extent of Humboldt Bay and four training classes were visually interpreted. Training areas were selected in regions of the image clearly defined as consisting of eelgrass, algae, water, or mudflat. The region of the image classified as eelgrass was resampled to a horizontal resolution equal to that of the DEM for further raster analysis. Areas identified as eelgrass in the imagery were used to supplement the survey data in places where the DEM was deemed insufficient for depth-based habitat modeling to produce the final eelgrass habitat grid. Hyperspectral imagery captured in October 2004 and classified to identify the extent of eelgrass in South Bay (Judd 2006) was used to validate the modeled eelgrass habitat grid. Hyperspectral eelgrass data were projected to the WGS 1984 datum, UTM zone 10 North in meters, converted from 3m to 5m horizontal resolution, and coreferenced with the modeled eelgrass habitat grid to allow for direct comparison. An error matrix was generated to evaluate the overlapping grids as being either identical or different in either direction on a pixel-by-pixel basis.

A Relative Exposure Index (REI) was generated on the basis of exceedance winds (>10 m s⁻¹; Keddy 1982; Fonseca and Bell 1998) to model the susceptibility of eelgrass to wave-induced disturbance. The Woodley Island National Weather Service station on Woodley Island, Humboldt Bay provided local wind speed data. Sustained maximum wind speeds recorded every six hours between June 1, 2003 and July 1, 2007, were
screened to remove all values less than 10 m s\(^{-1}\) from the dataset using Microsoft Access Software (Microsoft Corp., Redmond, Washington). REI was calculated on the basis of the following equation adapted by Murphey and Fonseca (1995) from Keddy (1982):

\[
\text{REI} = \sum_{i=1}^{8} \left( V_i \times P_i \times F_i \right)
\]

where \(i\) = \(i\)th compass heading from 1 to 8 in 45° increments, \(V\) = exceedance wind (> 10 m s\(^{-1}\)), \(P\) = percentage of exceedance winds blowing from the \(i\)th heading, and \(F\) = effective fetch in meters.

Fetch is defined as the length of water over which a given wind has blown. Fetch length, wind speed, and wind duration are the principle factors that determine the size of wind-waves. Effective fetch for each wind bearing is determined by calculating fetch along 9 lines at increments of 11.25 degrees centered about and including the actual wind bearing. The product of fetch multiplied by the cosine of the angle of departure from the wind bearing is summed over the nine lines and then divided by the sum of the cosines of the nine angles. By weighting multiple fetch measurements associated with each compass heading, the calculation of effective fetch diminishes the impact of irregularities in shoreline geometry that might otherwise lead to an overestimation of the potential for wind-wave development (Fonseca and Malhotra 2006).

Due to the shallow nature of Humboldt Bay, the horizontal extent of the water varies considerably between low and high tide. At low tide, fetch lengths across most
of the bay are limited and wind-wave development is restricted to the deeper channels that remain submerged. As the water level rises, fetch lengths increase leading to the development of potentially larger and more energetic wind-waves across a larger portion of the bay. While the potential for wind-wave development continues to increase with the rising tide, the susceptibility of eelgrass to disturbance from wind-waves is likely greatest at an intermediate tidal stage. It is thought that at higher tidal stages, eelgrass beds are submerged enough to be below where wave energy flux is greatest.

To simulate an intermediate tidal stage, the Humboldt Bay DEM was adjusted to a reference of 1.5 m MLLW using the Raster Calculator (Spatial Analyst). This tidal stage was chosen because it was thought to best approximate the water level where wind-waves would have the greatest potential for causing disturbance of eelgrass. A shoreline polygon was generated through heads-up digitizing of the 2005 NAIP imagery to produce a clipping mask for the fetch algorithm. The Humboldt Bay DEM was resampled to 25m horizontal resolution using bilinear interpolation, in order to increase the processing speed of the algorithm. WEMo 3.0 software (Fonseca and Malhotra 2006) was used to calculate REI values for a point grid at 100m spacing across the bay. Depth values from the underlying DEM were interrogated by the fetch algorithm at an interval of 25m to account for the effect of bathymetry on the attenuation of wave energy. Wind bearing data originally recorded at 10° increments were simplified to the corresponding bearings reported at 45° increments to meet the
input requirements of the WEMo 3.0 software. The resulting REI values associated with the point grid were used to interpolate a REI surface at 5m horizontal resolution using ordinary kriging (Spatial Analyst).

To demonstrate how these efforts could be used to support management decisions, the REI developed for Humboldt Bay was integrated with the model of eelgrass habitat to identify potential eelgrass restoration or mitigation sites. Boolean logic was utilized to identify areas of Humboldt Bay deemed most suitable to attempt hand transplanting of eelgrass on the basis of depth and REI values using the Raster Calculator (Spatial Analyst). In South Bay, eelgrass hyperspectral imagery data was also incorporated in the analysis to further refine the prediction of areas suitable for hand transplanting. Map algebra expressions were generated to determine the extent of the Humboldt Bay DEM identified as eelgrass habitat where hand transplanting would be feasible during extreme low tides (depth less than -0.5 m MLLW), where REI values were deemed sufficiently low to preclude disturbance (REI < 2996), and where imagery data showed an absence of eelgrass within areas identified as eelgrass habitat in South Bay. The threshold REI value was determined by averaging the REI values associated with two areas where eelgrass disturbance was observed during surveys of minimum depths. The appearance of exposed eelgrass rhizomes revealed by the erosion of the underlying substrate was taken as evidence of the occurrence of wave-induced disturbance.
RESULTS

Maximum depths suitable for eelgrass growth varied across Humboldt Bay (Table 2). Sites A through J were located in North Bay, sites K through R were located in South Bay. Maximum eelgrass depths ranged from -2.11 m MLLW at the northern end of Hookton Channel (Site L) in South Bay to -0.47 m MLLW in front of Dock B (Site B) in North Bay. The 95% confidence intervals varied from 0.04 m (site G) to 0.17 m (site A).

Table 3 shows results of the surveys conducted to determine upper limits suitable to the growth of eelgrass. Sites 1-11 and 22-25 were located in North Bay. Sites 12-21 and 26 were located in South Bay. Upper limit elevations for continuous eelgrass ranged from 0.07 m MLLW on the west side of North Bay Channel (Site 11) to 0.77 m MLLW in the southwest corner of South Bay (Site 21). Patchy eelgrass was found growing as high as a mean depth of 1.42 m MLLW with a standard deviation of 0.21 at Site 22 above Samoa Channel along the western shoreline of North Bay.

The extent of the Humboldt Bay fusion DEM capable of supporting continuous and patchy eelgrass habitat on the basis of depth and supplemental imagery is shown in Fig. 7. An analysis mask was generated to avoid identification of eelgrass habitat in Entrance Bay where exposure to ocean swell prevents eelgrass growth. The fusion of eelgrass data classified from 2005 NAIP imagery, with survey data from North and South Bay led to the identification of 946 hectares of eelgrass habitat in South Bay and
1,256 hectares in North Bay, yielding a total of 2,202 hectares of modeled eelgrass habitat in Humboldt Bay.

An error matrix (Table 4) shows results of the comparison between modeled eelgrass habitat and eelgrass classified from hyperspectral imagery (Judd 2006) in South Bay. Hyperspectral eelgrass data were resampled to 5 m horizontal resolution, projected to the WGS 1984 datum, UTM zone 10 North in meters, and coreferenced to the modeled eelgrass habitat grid to perform a pixel-by-pixel comparison. Overall accuracy of modeled eelgrass habitat in South Bay was assessed at 91.0% based on this comparison.

A cartographic depiction of the accuracy assessment of modeled eelgrass habitat in South Bay is presented in Fig. 8. A two-way comparison of the mutually exclusive areas identified as eelgrass by classified hyperspectral imagery and modeled as eelgrass habitat on the basis of surveys are shown.

A wind rose diagram (Fig. 9) was generated to illustrate directional and corresponding velocity components of local exceedance wind events occurring between 2003 and 2007. Eighty-one percent of exceedance wind events occurred from wind bearings with a southerly component (110°-230°). The remaining 19% of exceedance wind events arose from wind bearings with a northwesterly component (310°-350°) (Fig. 9). Exceedance wind data were used to develop the REI model (Fig. 10) for Humboldt Bay.
Figure 11 depicts the areas of modeled continuous eelgrass habitat in Humboldt Bay thought to be most suitable to hand transplanting eelgrass on the basis of depth and susceptibility to wave-induced disturbance. Boolean logic was used to select areas of continuous eelgrass habitat with depths less than –0.5 m MLLW, REI values less than 2996, and where eelgrass hyperspectral imagery data showed an absence of eelgrass in South Bay. Based on these criteria, 771 out of 1256 hectares (approximately 61%) of modeled continuous eelgrass habitat in North Bay and 156 out of 946 hectares (approximately 16%) of modeled continuous eelgrass habitat in South Bay were identified as being suitable to hand transplanting eelgrass.
Table 2. Mean and 95% confidence intervals for maximum depths suitable to the growth of eelgrass (*Zostera marina*). Forty depth values were sampled randomly from measurements recorded at 18 sites in Humboldt Bay, California.

<table>
<thead>
<tr>
<th>Site</th>
<th>Mean Depth below MLLW (m)</th>
<th>95% Confidence Interval (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.80</td>
<td>0.17</td>
</tr>
<tr>
<td>B</td>
<td>0.47</td>
<td>0.05</td>
</tr>
<tr>
<td>C</td>
<td>1.38</td>
<td>0.06</td>
</tr>
<tr>
<td>D</td>
<td>1.31</td>
<td>0.10</td>
</tr>
<tr>
<td>E</td>
<td>0.95</td>
<td>0.06</td>
</tr>
<tr>
<td>F</td>
<td>0.80</td>
<td>0.06</td>
</tr>
<tr>
<td>G</td>
<td>0.93</td>
<td>0.04</td>
</tr>
<tr>
<td>H</td>
<td>0.54</td>
<td>0.08</td>
</tr>
<tr>
<td>I</td>
<td>1.11</td>
<td>0.05</td>
</tr>
<tr>
<td>J</td>
<td>1.14</td>
<td>0.08</td>
</tr>
<tr>
<td>K</td>
<td>1.74</td>
<td>0.13</td>
</tr>
<tr>
<td>L</td>
<td>2.11</td>
<td>0.07</td>
</tr>
<tr>
<td>M</td>
<td>2.06</td>
<td>0.07</td>
</tr>
<tr>
<td>N</td>
<td>1.64</td>
<td>0.11</td>
</tr>
<tr>
<td>O</td>
<td>1.01</td>
<td>0.07</td>
</tr>
<tr>
<td>P</td>
<td>1.71</td>
<td>0.07</td>
</tr>
<tr>
<td>Q</td>
<td>1.79</td>
<td>0.08</td>
</tr>
<tr>
<td>R</td>
<td>1.62</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Table 3. Mean and standard deviations for the upper limits suitable to the growth of eelgrass (*Zostera marina*) measured at 26 sites in Humboldt Bay, California.

<table>
<thead>
<tr>
<th>Site</th>
<th>Habitat Type</th>
<th>Mean Depth above MLLW (m)</th>
<th>Standard Deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>continuous</td>
<td>0.32</td>
<td>0.04</td>
</tr>
<tr>
<td>2</td>
<td>continuous</td>
<td>0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>continuous</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>4</td>
<td>continuous</td>
<td>0.27</td>
<td>0.04</td>
</tr>
<tr>
<td>5</td>
<td>continuous</td>
<td>0.25</td>
<td>0.02</td>
</tr>
<tr>
<td>6</td>
<td>continuous</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>7</td>
<td>continuous</td>
<td>0.31</td>
<td>0.13</td>
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<tr>
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<td>continuous</td>
<td>0.19</td>
<td>0.06</td>
</tr>
<tr>
<td>9</td>
<td>continuous</td>
<td>0.25</td>
<td>0.08</td>
</tr>
<tr>
<td>10</td>
<td>continuous</td>
<td>0.49</td>
<td>0.05</td>
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<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>12</td>
<td>continuous</td>
<td>0.31</td>
<td>0.11</td>
</tr>
<tr>
<td>13</td>
<td>continuous</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>14</td>
<td>continuous</td>
<td>0.13</td>
<td>0.15</td>
</tr>
<tr>
<td>15</td>
<td>continuous</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>16</td>
<td>continuous</td>
<td>0.27</td>
<td>0.09</td>
</tr>
<tr>
<td>17</td>
<td>continuous</td>
<td>0.29</td>
<td>0.08</td>
</tr>
<tr>
<td>18</td>
<td>continuous</td>
<td>0.18</td>
<td>0.05</td>
</tr>
<tr>
<td>19</td>
<td>continuous</td>
<td>0.22</td>
<td>0.07</td>
</tr>
<tr>
<td>20</td>
<td>continuous</td>
<td>0.38</td>
<td>0.11</td>
</tr>
<tr>
<td>21</td>
<td>continuous</td>
<td>0.77</td>
<td>0.15</td>
</tr>
<tr>
<td>22</td>
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<td>1.42</td>
<td>0.21</td>
</tr>
<tr>
<td>23</td>
<td>patchy</td>
<td>0.65</td>
<td>0.04</td>
</tr>
<tr>
<td>24</td>
<td>patchy</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>25</td>
<td>patchy</td>
<td>0.43</td>
<td>0.40</td>
</tr>
<tr>
<td>26</td>
<td>patchy</td>
<td>0.79</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Fig. 7. Extent of modeled continuous and patchy eelgrass (*Zostera marina*) habitat in Humboldt Bay, California.
Table 4. Accuracy assessment for pixel-based comparison of modeled eelgrass (*Zostera marina*) habitat versus eelgrass classified from hyperspectral imagery for South Humboldt Bay, California. Overall accuracy of original hyperspectral eelgrass classification was reported at 92.5% and 788 hectares of eelgrass were identified (Judd, 2006).

<table>
<thead>
<tr>
<th>Eelgrass Habitat (Model Data)</th>
<th>eelgrass absent</th>
<th>eelgrass present</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>eelgrass absent</td>
<td>62832</td>
<td>17785</td>
<td>80617</td>
</tr>
<tr>
<td>eelgrass present</td>
<td>17785</td>
<td>297663</td>
<td>315448</td>
</tr>
<tr>
<td>total</td>
<td>80617</td>
<td>315448</td>
<td>396065</td>
</tr>
</tbody>
</table>

- True Positive: 94.4%
- False Positive: 22.1%
- False Negative: 5.6%
- True Negative: 77.9%
- Precision: 94.4%
- Overall Accuracy: 91.0%
Fig. 8. Cartographic depiction of accuracy assessment results comparing distinctions between modeled eelgrass (*Zostera marina*) habitat and eelgrass classified from hyperspectral imagery (Judd, 2006) for South Humboldt Bay, California. Overall accuracy of modeled eelgrass habitat is 91.0% based on this comparison.
Fig. 9. Rose diagrams based on two-minute sustained wind data (> 10 m s$^{-1}$) recorded during the period 2003-2007 at the Eureka National Weather Service meteorological station located at Woodley Island, Eureka, California. Percent frequency of exceedance winds (left) and mean exceedance wind velocities in m s$^{-1}$ (right) associated with individual wind bearings are shown.
Fig. 10. Cartographic representation of the relative wave-exposure index (REI) for a tidal stage of 1.5 m MLLW in Humboldt Bay, California. REI was calculated on the basis of local exceedance wind data (velocity > 10 m s⁻¹), effective fetch, bathymetry, and the proportion of time the (exceedance) wind blew from a given bearing.
Fig. 11. Areas of modeled continuous eelgrass (*Zostera marina*) habitat identified as being either favorable or not favorable for transplanting eelgrass on the basis of suitable depths (depth < -0.5 m MLLW), susceptibility to wave-induced disturbance (REI value < 2996), and absence of eelgrass based on hyperspectral imagery data (South Bay) for Humboldt Bay, California.
DISCUSSION

This study represents the first known attempt to determine the depth range suitable for eelgrass growth in Humboldt Bay. The recent extent of eelgrass classified from 2004 hyperspectral imagery in South Bay provided the best available opportunity to evaluate this approach to habitat modeling. Although modeling available habitat is not equivalent to identifying the extent of standing eelgrass at a given time, eelgrass beds in South Bay are sufficiently extensive to provide a reasonable basis for comparison. An overall accuracy assessment of 91% supports the use of this methodology as an effective means for modeling eelgrass habitat in Humboldt Bay.

The range of depths suitable for eelgrass, as determined from surveys of maximum depths and upper limits of growth, showed variation with respect to location across Humboldt Bay. At six of the ten survey sites in North Bay, eelgrass maximum depths averaged less than 1 m below MLLW. Sites C and D in North Bay had the deepest eelgrass (Fig. 3). Sites C and D were also located along the only major channel in North Bay not directly connected to significant sources of freshwater input from surrounding watersheds (Fig. 1). Conversely, Site B along the Eureka waterfront (Fig. 3), with the shallowest maximum depths suitable to eelgrass, is likely impacted by suspended sediment originating from Freshwater Creek and to a lesser extent, Jacoby Creek and Mad River Slough (Fig. 1).
With the exception of site O, eelgrass in South Bay grows at greater depth than eelgrass in North Bay. South Bay is located closer to the ocean and receives much less freshwater runoff than North Bay due to the smaller size of the upslope watershed area. More than 85% of the freshwater entering Humboldt Bay is confined to North and Entrance Bays (Barnhart et al. 1992). Runoff entering the bay is often heavily laden with suspended sediment. Maximum depths in South Bay exceeded 1m below MLLW at all sites (Table 2). Site O was the closest site to the only significant source of freshwater runoff entering South Bay (Salmon Creek, Fig. 1) and had the shallowest maximum depths suitable to eelgrass in the basin. Eelgrass was generally found to grow at greater depths at sites that were both closer to Entrance Bay and further from freshwater sources.

The upper limits suitable to the growth of continuous eelgrass varied to a lesser degree than maximum depths across both North and South Bay (Table 3). Three of the four sites closest to Entrance Bay (Fig. 6) accounted for the lowest upper limits of eelgrass growth. The upper edges of eelgrass beds at Sites 10 and 21 (Fig. 6) were located relatively far from Entrance Bay in North and South Bay respectively, and were situated at the highest elevations among any surveyed continuous eelgrass beds (Table 3). Patchy eelgrass at site 22, located in the far northwest corner of North Bay (Fig. 6), grew at the highest elevation surveyed in either North or South Bay (Table 3).

In both North and South Bay, eelgrass tended to grow at higher tidal elevations in locations that were both farther from the mouth of the bay, and where REI values were
relatively low. Borgeld and Stevens (2004) also found that sediment grain size
generally decreased with increasing elevation and distance from the mouth of
Humboldt Bay. This suggests a possible link between hydrodynamic setting, sediment
organic content and(or) sediment grain size, and the upper limits suitable to the growth
of eelgrass (Koch 2001; Keddy 1982). However, further study is needed to evaluate
this for eelgrass habitat requirements in Humboldt Bay.

Comparing the habitat model to classified hyperspectral imagery, the biggest
discrepancy occurred in subtidal areas of channels that may have been too deep to be
fully evaluated by the hyperspectral sensor (Judd, 2006). The lack of sufficient depth
data in channel areas likely contributed to the discrepancy as well. This may have led
to a slight overestimation of areas shallow enough to provide eelgrass habitat in the
upper reaches of Arcata Channel, Samoa Channel, Eureka Channel, Eureka Slough,
Southport Channel, and Hookton Channel. Incorporating supplemental depth data
reduced the total area that would have otherwise been misidentified as eelgrass habitat
in these channels by approximately 175 hectares.

Slightly more intertidal eelgrass habitat was identified in shallow water in the
southern portion of South Bay through surveying than was classified using
hyperspectral imagery. Considerable overlap of green algae and eelgrass was observed
along the upper margins of eelgrass beds during these surveys (Fig.12). At a horizontal
resolution of 3 m, the imagery may have been overwhelmed by the spectral response of
the algae in places where these species intermingled.
Average maximum depth and upper limit elevation values from each survey site were chosen to develop the spatial model of eelgrass habitat to account for some of the uncertainty associated with individual measurements. Maximum depth survey data required interpretation to account for situations in which divers lost sight of eelgrass and had to either ascend or descend to relocate the lower edge of the beds. Divers annotated profile plots showing depth and time during each dive to help resolve most of the inconsistencies in the data.

For upper limit surveys, uncertainty associated with individual measurements was a result of deriving elevation data from the bathymetry DEM for 22 out of the 26 sites. The DEM provided a single elevation value for each 25 m² of land area. Across much of the bay, cell-to-cell variation in the DEM was minimal due to the gradual sloping nature of the mudflats. In the vicinity of channel margins, where the slope increased, confidence in the accuracy of individual elevation values decreased. Additionally, only the portion of the DEM derived from LIDAR data (Fig.2) contained sufficiently accurate elevation data (+/- 0.15m; Judd 2006) for areas underlying shallow eelgrass to be used for determining upper limits. At sites 9, 11, 23, and 24, an electronic total station was used to determine upper limit elevations due to the proximity of survey grade benchmarks to each of these sites. This method likely produced the most accurate estimates of the upper limits suitable to eelgrass growth at individual point locations but was impractical to employ across much of the bay.

Additional uncertainty associated with upper limit surveys involved the conversion of the Humboldt Bay DEM from the NAVD-88 vertical datum to MLLW. The
relationship between NAVD-88 and MLLW was only known for seven tidal benchmark locations distributed across Humboldt Bay. MLLW varies from 0.10 m to 0.31 m below NAVD-88, primarily as a function of distance from the mouth of the bay. Potential error associated with referencing upper limits to MLLW would likely be proportional to the distance of the survey site from the nearest tidal benchmark.

Due to limitations in the accuracy of the portion of the Humboldt Bay DEM derived from hyperspectral imagery (Fig.2), certain areas of eelgrass habitat could not be identified from surveying efforts alone. While the hyperspectral imagery was useful for identifying eelgrass on the basis of spectral response, it provided inconsistent estimates of depth. The hyperspectral imagery was captured during high-tide conditions when eelgrass was completely submerged and thus, suspended in the water column. Several areas of the DEM where eelgrass was known to grow appeared to be approximately 0.5 m higher than the true depth based on field observations. This was likely a result of the aerial imaging systems incorrectly identifying dense regions of suspended eelgrass canopy as the surface of the substrate. This produced gaps in the center of known continuous eelgrass habitat in both North and South Bay. These gaps in eelgrass habitat were resolved by fusing the results of supervised image classification identifying eelgrass from 2005 NAIP imagery with the results of the depth surveys.

Eelgrass population ecology often varies within different areas of the same habitat (Phillips 1984; Fonseca et al. 1998). It exhibits annual and perennial life history strategies both, which may be present in the same estuary. This could lead to seasonal differences in the apparent extent of eelgrass beds in some locations. Eelgrass beds in
Humboldt Bay remained relatively stable over the last several decades (Judd, 2006). However, portions of beds may expand and contract seasonally in response to environmental conditions.

Interannual variations in eelgrass cover may have introduced some of the differences observed between the extent of eelgrass identified from hyperspectral imagery in 2004, and eelgrass habitat identified from surveys conducted during 2006 and 2007. This suggests that one-time efforts to inventory the spatial extent of eelgrass to delineate habitat boundaries are insufficient (Fonseca et al. 1998).

Overall, the survey-based model identified a larger area of South Bay as being able to support eelgrass (946 hectares) than was classified as actual eelgrass (788 hectares) using hyperspectral imagery. Nonetheless, discrepancies between the classified imagery and the survey-based model were relatively small (8.7%) relative to the area of South Bay.

Modeled relative wave exposure varied considerably both within as well as between the three major basins of Humboldt Bay (Fig. 10). In South Bay, REI values were generally less than 3000 with the exception of the northernmost portion of the basin adjacent to Entrance Bay. REI values in the western half of North Bay were found to exceed 4000 whereas REI values in the eastern half of the basin were generally less than 2500. Entrance Bay and North Bay Channel had the highest REI values in the entire bay, exceeding 5000 in several areas corresponding to the deepest portions of the dredged shipping channel.
Humboldt Bay is a challenging location to characterize the wind-wave environment with respect to disturbance of eelgrass. It is extremely shallow relative to the horizontal extent of both North and South Bays. Eelgrass is limited to a narrow range of depths (approximately -2.11 to 1.42 meters MLLW). This overlaps with much of the tidal range in Humboldt Bay (approximately -0.7 to 2.7 meters MLLW). The water depth in the bay is in a constant state of change, leading to a continuous shifting of locations where wave energy fluxes at the substrate/water/eelgrass interface are greatest.

Eelgrass beds are largely absent from areas where REI values are greatest due to excessive depth in North Bay Channel and exposure to ocean swell in Entrance Bay. Within areas of eelgrass habitat, REI values were generally higher in regions adjacent to deep-water channels than they were over shallow mudflats. In South Bay, the highest REI values were observed in the northern portion of the basin near King Salmon in the east and along the northwestern inner shoreline of the south spit (Fig. 10). Eroded substrate and exposed eelgrass rhizomes indicating possible wave-induced disturbance were observed along the upper fringes of eelgrass beds at both locations corresponding to sites 12 and 13 (Fig. 4) during upper limit surveys. While no clear evidence of wave-induced disturbance was witnessed in North Bay during upper limit surveys, an effort to transplant eelgrass to an area of suitable depth on the southeastern side of Indian Island adjacent to the Samoa Bridge failed after a series of intense winter storms eroded the substrate during the winter of 1985 (Allen, D. 2008. unpublished data).
In North Bay, the south and west sides of Indian Island and areas adjacent to Samoa Channel received the highest REI values (Fig. 10). Eighty-one percent of exceedance winds recorded during the period 2003-2007 occurred from wind bearings with a southerly component (110°-230°). The remaining 19% arose from wind bearings with a northwesterly component (310°-350°) (Fig. 9). This explains the relatively high REI values associated with the long fetch distances in North Bay Channel and to a lesser degree, the northern and western areas of South and North Bay basins respectively (Fig. 10). In coastal Northern California, sustained southerly winds are associated with large storms that typically occur during winter and early spring. Strong northwest winds are most common in the late spring and summer months and are associated with fair weather conditions.

Modeling waves in seagrass environments is a newly evolving discipline (Koch et al. 2006). A recent model, WEMo 3.0 (Fonseca and Malhotra 2006) represents an improvement over previous methods for calculating REI by accounting for depth when measuring fetch. Previous methods of calculating fetch overestimate the exposure environment in areas such as Humboldt Bay where extensive shallow water limits development and propagation of wave energy (Fonseca and Bell 1998). Contemporary GIS software designed to model wave exposure in a two-dimensional fashion has limitations. Wave diffraction and refraction is affected by factors in three dimensions, resulting from guidance by shorelines and submerged terrain as well as wave attenuation by seagrass beds themselves. These factors still present challenges when modeling at the landscape scale (Ekebom et al. 2003). Nonetheless, geospatial software
tools can provide valuable information in the context of understanding variations in the hydrodynamic setting likely to impact patterns of eelgrass growth and disturbance.

Most of the modeled continuous eelgrass habitat in South Bay (approximately 92%) was found to be suitable for hand transplanting of eelgrass on the basis of depth and REI criteria. Incorporation of eelgrass hyperspectral imagery data depicting the recent extent of eelgrass allowed for identification of areas of suitable habitat not currently supporting eelgrass. As a result, the area identified as suitable for hand transplanting of eelgrass was reduced to 156 hectares (16%) of modeled continuous eelgrass habitat in South Bay. This represents a significant improvement over output calculated on the basis of suitable depth and REI values alone and illustrates the value of incorporating imagery in a model of eelgrass habitat.

Approximately 61% of the total area identified as continuous eelgrass habitat in North Bay was predicted to be suitable to hand transplanting of eelgrass based on depth and modeled wave-exposure. A lack of appropriate eelgrass imagery data for North Bay prevented distinguishing between areas of modeled continuous eelgrass habitat currently supporting eelgrass from areas where it was absent.

In North Bay, most of the areas identified as suitable for hand transplanting eelgrass were found over the mudflats in the eastern half of the basin. Narrow bands of suitable habitat were also found along channel margins around Woodley Island and the Eureka waterfront. The effects of geography likely limit the development of wind-waves in these areas of the bay during a majority of exceedance wind events. The smaller size of South Bay results in shorter fetch lengths and therefore, lower REI values than what is
predicted for North Bay. In general, sites most sheltered from the effects of southerly and northwesterly winds appear to provide the best locations to transplant eelgrass on the basis of exposure.

Kelly et al. (2001) found that in shallow water, lower REI values had a larger relative impact on SAV than higher REI values associated with areas in deeper water. Eelgrass beds can form in areas with high REI values if they are below the depth where wave shoaling occurs. REI values that appear high enough to cause disturbance along the upper margins of eelgrass habitat at sites 12 and 13 were also found across much of the subtidal eelgrass habitat occupying the western side of North Bay (Fig.10). These areas of eelgrass habitat occur at greater depths than the areas where wave-induced disturbance was observed during upper limit surveys. This suggests that depth as well as the presence of extensive eelgrass beds may play a role in limiting the effects of disturbance from wind waves.

In Humboldt Bay, it is difficult to observe or document evidence of disturbance occurring to subtidal eelgrass due to persistently high turbidity. Poor visibility adds an additional challenge to the prospect of attempting subtidal eelgrass restoration. These factors provide some justification for evaluating shallow water locations in Humboldt Bay with greater scrutiny for potential restoration efforts.
Fig. 12. Image taken in (South) Humboldt Bay, California, showing eelgrass (*Zostera marina*) (A) intermingling with mats of green algae (B) along the upper margin of eelgrass habitat.
The results of this study represent an important step in defining the limits of eelgrass habitat within Humboldt Bay. Seagrass beds are highly intricate and dynamic natural systems. Eelgrass often exhibits a patchy pattern of growth near the upper and lower edges of available habitat. Near the upper limits of eelgrass growth, mats of green algae often heavily overlap with eelgrass. In subtidal areas of Humboldt Bay near the lower edge of eelgrass growth, chronically turbid water limits the depth to which eelgrass may grow. It also makes it challenging to know with certainty that maximum depths have been exhaustively sampled. Divers rarely encountered visibility greater than 1 m while surveying the maximum depths of eelgrass growth.

Additionally, portions of the estuary lacked adequate bathymetry to be included in the model. Much of Mad River Slough, Elk River Slough, and Eureka Slough, provide suitable habitat for eelgrass that could not be quantified in this study.

Spatial scale is of critical importance in defining habitat as patchy or continuous. It is very challenging to define the distinction in habitat types in the absence of appropriate high-resolution imagery or other direct measures on a landscape scale. It is also difficult to establish hard boundaries that define the extent of eelgrass habitat due to the nature of estuarine environmental conditions. Water in Humboldt Bay is generally turbid and most of the eelgrass remains submerged during all but the lowest of tides. Much of the substrate in the bay is also extremely soft making it difficult and dangerous to traverse on foot.

Most efforts to mitigate eelgrass by hand transplanting in Humboldt Bay occur at relatively shallow depths near the upper edge of the eelgrass growth zone due to the
difficult nature of working in local subtidal conditions. Eelgrass is inherently patchy along the upper margin of habitat in the intertidal zone. Mitigation efforts that focus on attempting to fill-in the gaps in this portion of eelgrass habitat can be shortsighted. Recurrent and predictable plant stressors such as desiccation and wave-exposure likely have an inordinately large effect on shallow eelgrass populations.

Availability of imagery appropriate for depicting the current extent of eelgrass in Humboldt Bay would improve the ability to identify restoration or mitigation opportunities at the landscape scale. Imagery classified to identify the current extent of eelgrass could be incorporated with this habitat model to determine the amount of potential habitat not currently supporting eelgrass in North Bay. By distinguishing between actual and potential eelgrass habitat, a quantitative estimate could be made of the potential to restore or mitigate eelgrass habitat in North Bay as demonstrated here for South Bay.

Further analysis of REI values in conjunction with existing ecological and environmental data such as percentage cover, shoot density, biomass, sediment grain size, and depth, is also strongly suggested for Humboldt Bay. Synthesis of these criteria with exposure modeling would provide invaluable information for establishing realistic criteria by which to plan for and judge the success of future mitigation efforts (Fonseca et al. 2001) in Humboldt Bay.
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Sources of Unpublished Materials
