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Eelgrass Enhancement and Restoration in the Lower Columbia River Estuary

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September 2009

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Executive Summary

The purpose of this study was to evaluate the ability to enhance distribution of eelgrass (*Zostera marina*) in the Columbia River Estuary to serve as refuge and feeding habitat for juvenile salmon, Dungeness crab, and other fish and wildlife. We strongly suspected that limited eelgrass seed dispersal has resulted in the present distribution of eelgrass meadows, and that there are other suitable places for eelgrass to survive and form functional meadows.

Funded as part of the Bonneville Power Administration's call for Innovative Projects, we initiated a multistage study in 2008 that combined modeling, remote sensing, and field experimentation to:

1. Spatially predict habitat quality for eelgrass.
2. Conduct experimental plantings.
3. Evaluate restoration potential.

Baseline *in-situ* measurements and remote satellite observations were acquired for locations in the Lower Columbia River Estuary (LCRE) to determine ambient habitat conditions. These were used to create a habitat site-selection model, using data on salinity, temperature, current velocity, light availability, wave energy, and desiccation to predict the suitability of nearshore areas for eelgrass. Based on this model and observations in the field, five sites that contained no eelgrass but appeared to have suitable environmental conditions were transplanted with eelgrass in June 2008 to test the appropriateness of these sites for eelgrass growth. We returned one year after the initial planting to monitor the success rate of the transplants. During the year after transplanting, we carried out a concurrent study on crab distribution inside and outside eelgrass meadows to study crab usage of the habitat.

One year after the initial transplant, two sites, one in Baker Bay and one in Young's Bay, had good survival or expansion rates with healthy eelgrass. Two sites had poor survival rates, and one site had a total loss of the transplanted eelgrass. For submerged aquatic vegetation (SAV) restoration projects, these are reasonable success results and represent a small net gain in eelgrass in the LCRE. Crabs used both the eelgrass and unvegetated substrate, though in neither were there great abundance of the young-of-the-year crabs. During the field assessment of 12 potential transplant sites, divers discovered one site in southern Young's Bay that contained a previously undocumented eelgrass bed.

This integrated project developed the first predictive maps of sites suitable for eelgrass and other SAV in the lower estuary. In addition, techniques developed for this project to assess light levels in existing and potential submerged habitats have great potential to be used in other regions for nearshore and coastal monitoring of SAV.

Based on these preliminary results, we conclude that eelgrass distribution could likely be expanded in the estuary, though additional information on current eelgrass locations, usage by species of interest, and monitoring of current conditions would help develop a baseline and verify benefit. Our recommendations for future studies include:

1. *Site Monitoring.* Continued monitoring of restoration sites along with physical metrics of light, temperature and salinity within beds.

   Continued monitoring will both assist managers in understanding the longevity and expansion rate of planted sites and inform practical guidance on the minimum planted eelgrass required to develop a resilient meadow.

2. *Natural bed documentation and monitoring.* Document current eelgrass habitat conditions in the Columbia River by mapping eelgrass and other SAV species and monitoring physical metrics in natural beds.

   This will assist by better defining the factors that control the annual and spatial variation in eelgrass in the estuary, and thus lead to improved management. Improved information on conditions will help refine a habitat suitability model that can more accurately predict where eelgrass can be restored or areas under duress.

3. *Monitor Species Use.* Expanded monitoring of Dungeness crab and salmon use and benefit from eelgrass in the estuary to evaluate how feeding and rearing functions of eelgrass benefit the survival and growth of these species.

We have two final recommendations. First, if transplanting of eelgrass is to be expanded, donor stocks of plants should also be expanded to reduce the dependence on natural meadows. We recommend that an eelgrass culture facility be considered to supply stocks of eelgrass for planting that are developed from the eelgrass populations now in the estuary. Second, freshwater submerged aquatic vegetation (SAV) occurs in many parts of the estuary, and probably has importance to juvenile salmon (although this also needs verification). Restoration and expansion of freshwater SAV should be considered in a comprehensive effort to restore the submerged vegetation habitats through the Columbia River estuary.

Acknowledgements

This project was made possible through funding by the Bonneville Power Administration (BPA). Kate Hall and Susan Southard formed part of the dive team, which assessed sites and planted and monitored eelgrass. Mike Anderson, Ron Kauffman, Julia Ledbetter, and Ryan Ryal assisted with field work and data preparation.

Direct broadcast MODIS data used in this study were produced by the Ocean Physics and Ecology Laboratory at Oregon State University in collaboration with the National Aeronautics and Space Administration.

Acronyms and Abbreviations

3-D	three-dimensional
BPA	Bonneville Power Administration
COE	U.S. Army Corps of Engineers
CRE	Columbia River Estuary
CSC	Coastal Services Center
CTD	conductivity-temperature-depth (instrument)
GIS	geographic information system
LCRE	Lower Columbia River Estuary
LCREP	Lower Columbia River Estuary Partnership
MLLW	mean lower low water
MODIS	Moderate-resolution Imaging Spectroradiometer
NOAA	National Oceanic and Atmospheric Administration
PAR	photosynthetically active radiation
PVC	polyvinyl chloride
RM	river mile
RWE	Representative Wave Energy
SAV	submerged aquatic vegetation
SCUBA	Self-Contained Underwater Breathing Apparatus
TIN	Triangulated Irregular Network
UW	University of Washington
WEMO	Wave Energy Model

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1.0 Introduction

Eelgrass (*Zostera marina L.*) is the most widespread species among approximately 60 seagrass species worldwide (Green and Short 2003). Its critical importance to fish and wildlife species is extremely well documented in the northwest as well as many other regions (Phillips 1984, Thom 1987). Juvenile salmonids are commonly observed associated with eelgrass meadows, and prey species sought by juvenile salmon are in great abundance in these meadows (Thom et al. 1989). In addition, meadows may produce and trap detritus important for salmonid production (Sherwood et al. 1990).

Due to its critical importance to estuarine ecosystems, eelgrass receives special protection within most coastal states. Enhancement of the distribution and abundance of eelgrass is generally cited as a primary goal for restoration of large ecosystems, including the Chesapeake Bay, Puget Sound, and San Francisco Bay. Within the Columbia River basin's mainstem amendments, wetland enhancement is recommended within key strategies for habitat enhancement (Northwest Power and Conservation Council 2003).

Based on prior research, we strongly suspected that large scale disturbances (e.g., turbidity from the eruption of Mount Saint Helens) in the recent past have disrupted natural beds and strong flows from the Columbia River have limited eelgrass seed dispersal for new recruitment. Together, these occurrences limit the present distribution of eelgrass meadows. Our objective was to evaluate the ability to enhance distribution of eelgrass in the Columbia River Estuary to serve as refuge and feeding habitat for juvenile salmon, Dungeness crab, and other fish and wildlife.

We approached this problem by locating places in the estuary that appear to have environmental conditions suitable for eelgrass, but where eelgrass does not presently occur (e.g. Short et al. 2002) and evaluated the ability to transplant eelgrass into areas beyond its present distribution. To accomplish this, we integrated remote sensing, modeling, and existing GIS datasets into an innovative GIS-based assessment to examine suitable areas for restoration. From those select sites, we planted and monitored select sites within those areas. In addition, we studied use of eelgrass by Dungeness crab to provide a linkage between the habitat and a valuable economic resource.

Eelgrass Distribution May be Limited by Poor Seed Dispersal

Although present distribution of eelgrass is poorly understood, historical data suggests that prior to human influence, submerged aquatic vegetation (SAV),which include eelgrass and freshwater plant species, was much more predominant within the Columbia River Estuary (CRE) (Sherwood et al. 1990). Early nautical charts from the 1800s document the presence of SAV in the Lower Columbia (Figure 1), though there has been no comprehensive documentation of submerged vegetation in recent years. In 2007, there were only two known eelgrass meadows in the estuary, one located in Baker Bay, the other in Young's Bay.

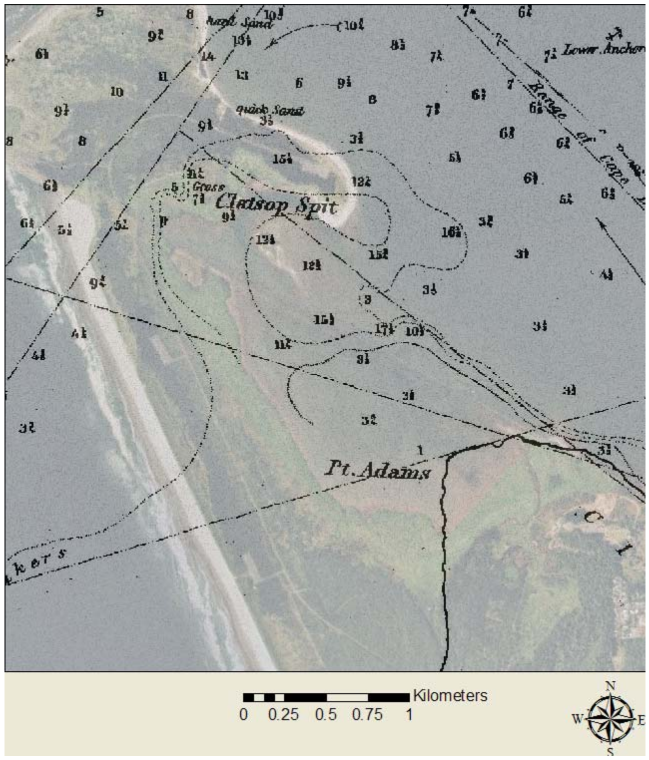


Figure 1. Georeferenced Nautical Chart of Columbia River (NOAA, Chart 640, 1851) over present imagery of Clatsop Spit, Oregon. *Grass* is noted near Clatsop spit, denoting SAV. At the time, the area was submerged.

Eelgrass distribution and health is determined by several environmental factors, such as sufficient light, wetting, current speeds, and suitable salinity ranges. Its lower depth limit is often determined by sufficient light for photosynthesis and its upper limit by desiccation (Phillips 1984; Duarte 1991; Thom et al. 1998). Salinity also limits this species. Eelgrass relies on a saline environment and usually reaches maximum abundance within estuaries where ocean water is measurably diluted with freshwater runoff from land. Finally, strong water currents may uproot eelgrass; successful eelgrass colonization usually occurs in areas without strong currents. These controlling factors vary between estuaries, thus location of eelgrass habitat depends on individual estuarine conditions. A summary of these controlling factors can be found in Table 1.

Prior research on the factors controlling the growth of eelgrass indicates that salinity, water clarity, and current velocities are likely the major environmental factors controlling the distribution in the estuary (Thom et al. 1998, 2003). In addition, rapid and frequent changes in estuarine conditions are likely to stress plants.

Anecdotal stories from scientists working in the estuary in the 1970s suggest that eelgrass was more widespread in the estuary prior to the eruption of Mt. St. Helens (*pers. conv.* Dr. Toshio Furota). Whether the subsequent discharge of massive suspended sediment loads resulting from the eruption affected eelgrass is uncertain. However, direct burial, diking, and flooding is hypothesized to have eliminated much of the original SAV meadows (Sherwood et al. 1990).

After disturbance, either anthropogenic or natural, we would expect that with time new eelgrass plants would colonize areas. However, for eelgrass colonization to occur in new sites, water currents must be capable of dispersing eelgrass seeds to new locations. Because of the river-dominated nature of the estuary, flow regulation and other activities may not have created conditions conducive to the spread of eelgrass. Substrata within the estuary is composed of unvegetated mudflats and sand flats and, although highly suitable for eelgrass, offers little refuge and sparse food resources for fish, crab, and other aquatic species compared to eelgrass.

Table 1. Habitat Suitability (Controlling Factors) Characteristics for Eelgrass

Characteristic	Eelgrass Limitation	Source
Light Availability	Above 10-20% incoming radiance Maximum use at 7 mol/m^2/day Minimum need of 3 mol/m^2/day	Duarte 2001 Thom et al. 2008 Thom et al. 2008
Desiccation Potential	Exposure based on bathymetry, tidal amplitude and wave period	Koch 2001
Maximum Temperature	Ideal maximum of 20°C	Thayer et al. 1984; Fonseca et al. 1998
Salinity	Ideal maximum of 26-30 psu. 22 psu (better than 32 psu for productivity)	van Katwijk et al. 1999 Kamermans et al. 1999
Wave Exposure	No quantitative information	Fonseca et al. 1998
Maximum Current Velocity (cm s^{-1})	~300 120-150 50 50 30	Phillips 1984 Fonseca et al. 1983 Zieman and Zieman 1989 Fonseca and Kenworthy 1987 Hasegawa et al. 2007
Minimum Current Velocity (cm s^{-1})	>16 5 <5	Fonseca and Kenworthy 1987 Hasegawa et al. 2007 Worcester 1995

Based on our own research and that of others in northwest systems, we suspect that the transport of seeds to new sites suitable for colonization and growth of eelgrass has limited eelgrass spread to all suitable locations. Seed production is typically low in Northwest estuaries (Thom et al. 2003), which severely limits spread. In addition, the dominant surface water seaward flow in the Columbia probably reduces the probability of colonization, because the floating flowering shoots with ripe seeds are, on average, transported out of the estuary rather than into it. Thus, we strongly suspected that up-estuary colonization has been limited by low seed production because of low eelgrass abundance and low seed production per plant.

Seasonal Turbidity Values can be Acquired Through Remotely Sensed Data

The CRE often contains high concentrations of suspended organic and inorganic material due to river discharge and wind and wave resuspension (Sherwood et al. 1990). This can directly affect many water-column properties and processes, including the productivity of SAV such as eelgrass (Dennison et al. 1993). The distribution of suspended sediments, however, can be highly variable in coastal environments, varying over time and space (Miller and McKee 2004). While *in-situ* sampling can resolve specific questions at a unique place and time, it is time-consuming and costly to address these questions over the broader spectrum continuum.

A number of studies have demonstrated that remotely sensed data can provide synoptic coverage over various time scales (Stumpf and Pennock 1989; Woodruff et al. 1999; Miller and McKee 2004; Warrick et al. 2004). However, the routine use of remotely sensed imagery for monitoring sediment dynamics has been limited due to inaccessibility of data, and the lower spatial resolution (1 km) of most sensors that have a relatively frequent repeat coverage (daily). In addition, to obtain the most accurate relationship between satellite reflectance data and some measure of turbidity, *in-situ* samples of turbidity need to be collected from a specific region of interest to develop a robust relationship of remotely acquired turbidity information. An experimental turbidity product has been available from remotely sensed data acquisitions for the west coast for several years. It is based on an algorithm of the diffuse attenuation coefficient of light, K_{490}, developed for the SeaWiFS satellite sensor (Mueller 2000), and modified for the Moderate-resolution Imaging Spectroradiometer (MODIS) instrument on board the EOS spacecraft, Aqua. The product is available from http://coastwatch.pfel.noaa.gov/ coastwatch/CWBrowser.jsp for the Columbia River region. It is available on a daily basis (cloud-free-dependent), and as a 3, 8, or 14-day composite. An example of a 14-day composite product is shown in Figure 2.

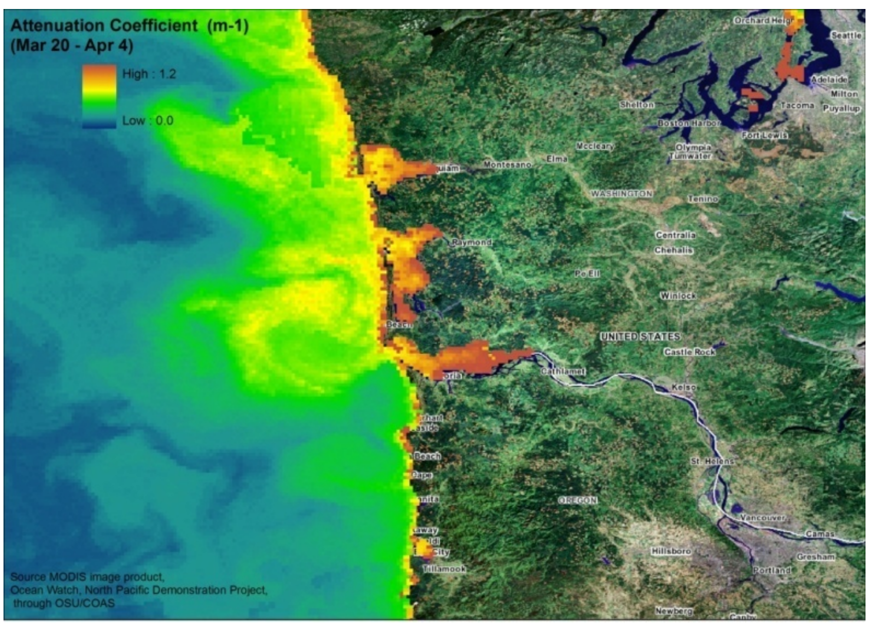


Figure 2. A 14-Day Composite of a MODIS Turbidity Product, K490, for the CRE in April 2008

Coupling *in-situ* and remotely sensed data can provide the information necessary to determine whether sufficient light is available in selected areas of the CRE to support eelgrass growth.

Salinity and Water Currents Affecting Eelgrass Production can be Modeled

Physical processes in estuaries are dynamic and complex due to variation in temporal and spatial scales of multiple factors that drive these processes. In addition to biological factors, growth and distribution of eelgrass is strongly affected by physical processes in the estuaries. Understanding and obtaining detailed information on these quantities at potential restoration sites are critical to the success of this project.

The Columbia River freshwater plume travels over a long distance off the coast during high-flow conditions during ebb tides. During the flood tide and low-flow conditions, salinity intrusion can occur as far as 60 km upstream. As a result, salinity varies over a wide range in the CRE. Tidal elevations and currents in the estuary are complex because of the presence of multiple intertidal channels and islands. It is difficult to extrapolate the distribution these physical quantities from measured datasets from a limited number of points in the estuary.

The three-dimensional (3-D) hydrodynamic model, developed by OGI, is a component of a pilot environmental observation and forecasting system for the Columbia River (CORIE). The model domain covers a large area from Bonneville Dam to the continental shelf. It predicts surface-water elevations, 3-D salinity, and velocities, as well as wetting and drying processes in the Columbia River.

Site Selection for Eelgrass Enhancement can be Conducted with GIS

In the past decade, geographic information systems (GISs) have gained popularity with natural resource managers, not only as a systematic way to document physical and biological features, but to examine the spatial relationships and trends among them. GIS-based analysis can assist in assessing habitat characteristics and habitat quality over a wide area. Datasets representing these separate habitat elements can be evaluated spatially to identify areas meeting all habitat requirements.

Examination of Crab Use in Enhanced Sites is Possible

Functional benefits of an enhanced or restored eelgrass meadow include nursery, feeding, and refuge space, not only for juvenile salmonids but other aquatic species as well. An assessment of the functional improvement of habitat will be carried out by examining Dungeness crab (*Cancer magister*) use of the sites. The CRE serves as an important nursery for this commercially important species, (Emmett and Durgin 1985; Armstrong et al. 2003). However, estuarine habitat types provide unequal benefit for vulnerable crab life stages. Settling larvae and juvenile crabs strongly prefer areas of structural complexity, such as eelgrass meadows and shell hash, over unstructured substrate (Fernandez et al. 1993; McMillan et al. 1995). Predation by a variety of fish and invertebrates, including conspecifics, is extremely high in habitats that lack adequate cover (Fernandez et al. 1993). As crabs grow larger, they tend to leave areas of structural complexity and reside in shallow subtidal areas, from which they forage in intertidal zones during nighttime high-water periods (Holsman et al. 2006). Many crabs eventually migrate from the estuary to the ocean and can form an important component of the regional crab fishery (Armstrong et al. 2003). In the Columbia River, salinity also affects crab distribution and behavior, because crabs become inactive at salinities <15 ppt (McGraw et al. 1999). This link between ontogeny and habitat preference indicates that critical habitat for young crab may be limiting in the in the CRE, because bivalve shell deposits are rare and eelgrass meadows are limited. Thus, one potential benefit of an eelgrass enhancement project is an increase in crab larval settlement and juvenile survival in eelgrass over the surrounding unvegetated substrate.

2.0 Study Area

The study area for this project was located in the LCRE, extending from the Astoria bridge, westward to the mouth of the river. Two bays, Baker Bay to the north and Young's Bay to the south, fall within this study area (Figure 3).

Figure 3. Study Area is Located Near the Mouth of the Columbia River.

3.0 Methods

We approached this project in three stages. An overview of the project workflow can be seen in Figure 4.

- In the first stage of the project, the quality of eelgrass habitat was assessed across the study area. This assessment integrated spatial datasets for salinity, temperature, current velocity, light availability, wave energy, and desiccation. From areas identified as good potential eelgrass habitat, 12 sites were selected for field assessment.
- In the second stage of the project, the 12 sites were assessed and 5 were selected for test planting. Divers planted 7 m x 7 m plots in these selected areas.
- In the last stage of the project, we evaluated the effectiveness of the eelgrass transplants. Divers re-visited the sites a year after the initial planting to monitor success. Simultaneously, crab usage of eelgrass and non-eelgrass areas were studied to determine how crabs used these areas.

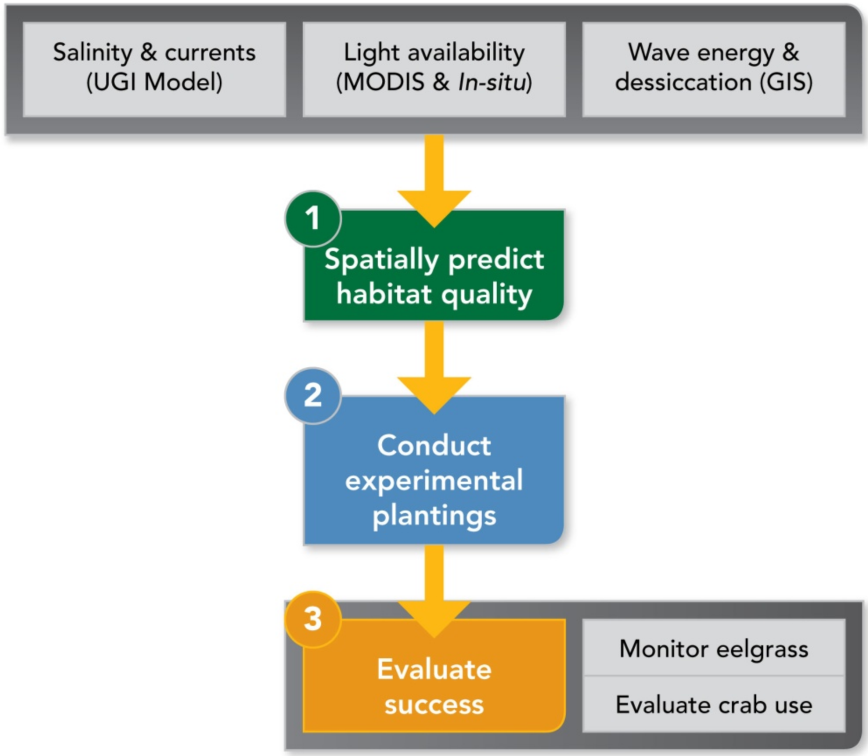


Figure 4. Project Workflow. In 2008, we (1) produced a habitat model to predict quality and (2) conducted experimental plantings. In 2009, we returned to monitor the restoration site. Crab use was evaluated from 2008-2009

3.1 Instruments, Products, and Datasets

A variety of *in-situ* sensors provided information used in this project (Figure 5). We relied primarily on light sensors, but we also used conductivity-temperature-depth (CTD) instruments, which provided ancillary information.

Three methods of acquiring light data were used:

- *In-situ* photosynthetically active radiation (PAR) levels along depth profiles were measured on 4-2-2008 from a boat field excursion, allowing researchers to travel to deeper water and mid-channel to examine potential differences in water type across the estuary.
- Two LICOR 4PI sensors, one at -0.6m and the other at -1.6m NAVD88, continuously gathered PAR levels at the Fort Canby Coast Guard dock.
- Five HOBO sensors (broadband irradiance) were placed at approximately -1m depth within potential restoration bays and inlets.

The first method of PAR acquisition provided the *in-situ* information to develop the regression equation for the rates of attenuation of PAR in the water column. The second and third methods provided ancillary data, which helped validate spatial modeling and solar constants used in later modeling.

In addition, CORIE CTD sensors were used as a second source of information to validate salinity and temperature values.

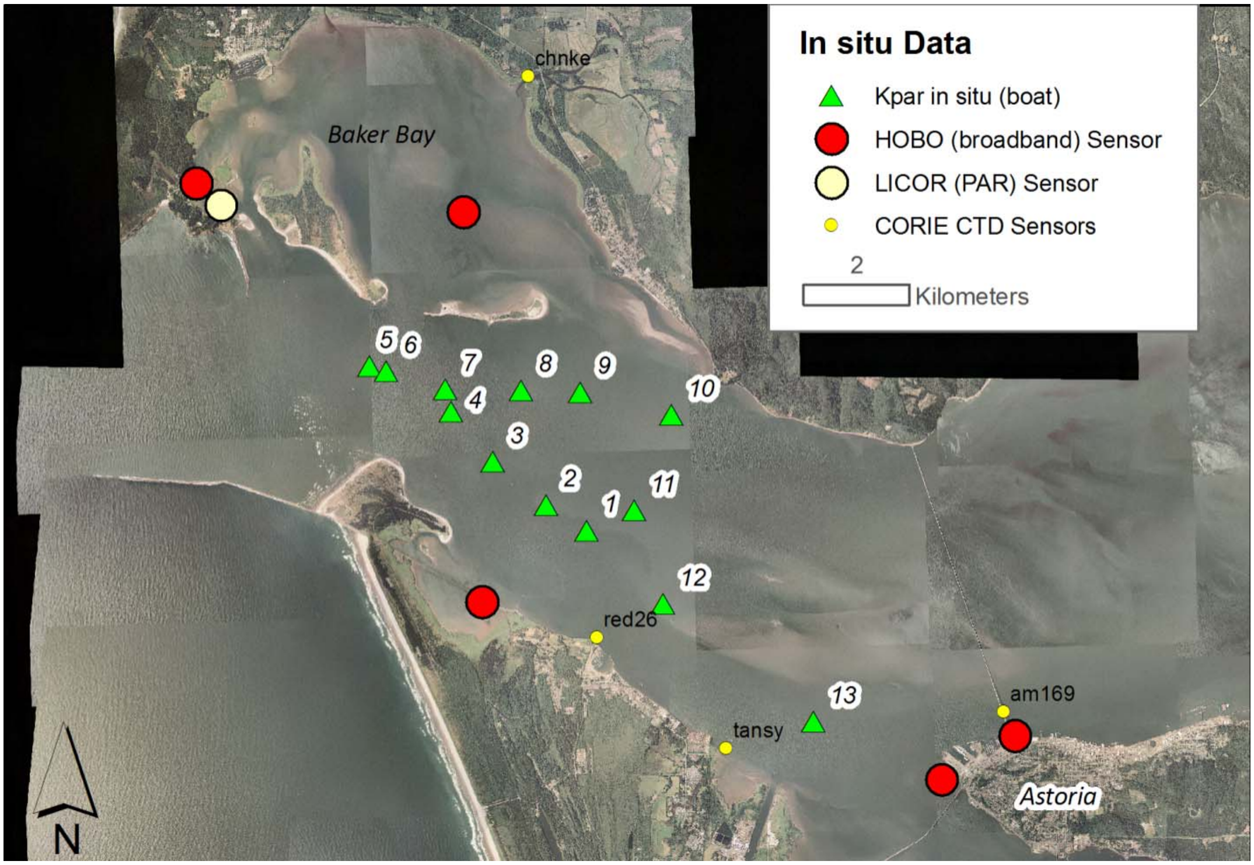


Figure 5. Sensor Locations. Light attenuation readings were taken in the Lower Columbia River from Tongue Point, Oregon, to the mouth. Additional HOBO and LICOR sensors gathered data while stationary.

3.2 Stage 1: Spatially Predict Habitat Quality

To predict habitat quality, we evaluated the following factors: light availability at depth (bathymetry and attenuation), desiccation/exposure, salinity, wave energies, currents, and water temperature. In the following section, we will discuss the approach and results from each component of the analysis, and address how the results were integrated for Habitat Quality Assessment. Table 2 provides a list of initial data sources.

Table 2. Physical Parameters and Datasets for Defining Eelgrass Habitat

Characteristic	Description	Primary Data Source(s)
Bathymetry	Preliminary fused product was acquired from the University of Washington (UW), an interpolation from bathymetry of a variety of U.S. Army Corps of Engineers (COE) surveys. To better capture shallow water areas, the dataset was decomposed into points. LiDAR point interpolations were added, channel centerlines were re-interpolated, and additional points from the National Oceanic and Atmospheric Administration (NOAA 2004) Coastal Services Center (CSC) were added.	UW - Fused Bathymetry COE (Jen Burke/LCREP 2004) NOAA (2004) CSC Bathymetry Puget Sound LiDAR Consortium
Light Attenuation Coefficient (Satellite)	MODIS K_{490} 14-day composite; 1-km resolution. The MODIS satellite acquires one image daily. In a composite, pixels are averaged over the acquisition dates, eliminating those of poor quality.	NOAA Coast Watch/Oregon State University Dates of image products 2007 | 2008 4-13-2007 | 4-3-2008 4-27-2007 | 4-10-2008 5-14-2007 | 5-15-2008 5-29-2007 6-14-2007 6-30-2007 7-15-2007 7-27-2007
Incoming Light	Average monthly direct normal radiation by hour; Gladstone, Oregon (1999-2007)	University of Oregon, Solar Radiation Monitoring
Wind Speed & Direction	Wind speed and direction (2005-2008) for Astoria, Oregon (AST03)	National Data Buoy Center
Current Known Eelgrass Distribution	Field survey and preliminary classification from 2007	LCREP 2004/Battelle
Salinity	Salinity (psu)	Oregon Graduate Institute
Temperature	Temperature (T)	Oregon Graduate Institute
Water Velocity	Velocity (m/s)	Oregon Graduate Institute

3.2.1 Light Availability Assessment

Eelgrass, as with other plant species, relies on PAR for growth and survival. Light is often the most important driving factor for sustaining eelgrass, and identifying areas that receive sufficient light is crucial for restoration.

The amount of incoming light that reaches the plant can be approximated by Lambert-Beer's Law:

$$I_z / I_o = e^{-(Kpar)(Z)} \qquad (1)$$

where:

z	=	Depth (m)
I_z	=	Irradiance at depth (z)
I_o	=	Irradiance at water's surface
K_{par}	=	Attenuation coefficient for PAR

The relationship between water quality and eelgrass depth limits becomes apparent as studies investigate the quantity of light that eelgrass needs to survive and the apparent lower depth limits of seagrasses (Duarte 1991). As the rate of attenuation increases in turbid waters, the amount of light that eelgrass receives at the same depth decreases. Thus, in turbid waters, eelgrass does not grow as deep as in clearer waters. While other studies have used a depth contour as a proxy to define a threshold for suitable light, in the Columbia River Estuary, we expect variance in depths depending on turbidity in different areas of the estuary. In terms of the Equation 1, we would expect different attenuation rates (K_{par}). Thus, examining the amount of light, I_z, rather than just depth is crucial.

To evaluate which areas have sufficient light for eelgrass growth, we calculated PAR levels throughout the estuary during the growing season. We approached this problem in a three-step process through which we created a relationship between an *in-situ* measurement and a remotely observed measurement to be able to spatially forecast light availability across the estuary:

1. **Determine the relationship between K_{490} and K_{PAR}.** While PAR (400nm-700nm) is crucial for the plant, satellite products provide calculations of attenuation rates at 490nm. To use the satellite products, we derived an equation that permitted us to transform the satellite K_{490} products into K_{PAR}

2. **Determine PAR levels over growing season.** Once we developed an equation, we used it to calculate the average amount of light that plants receive.

3. **Validation.** Using ancillary sources of PAR information, we validated our initial estimates.

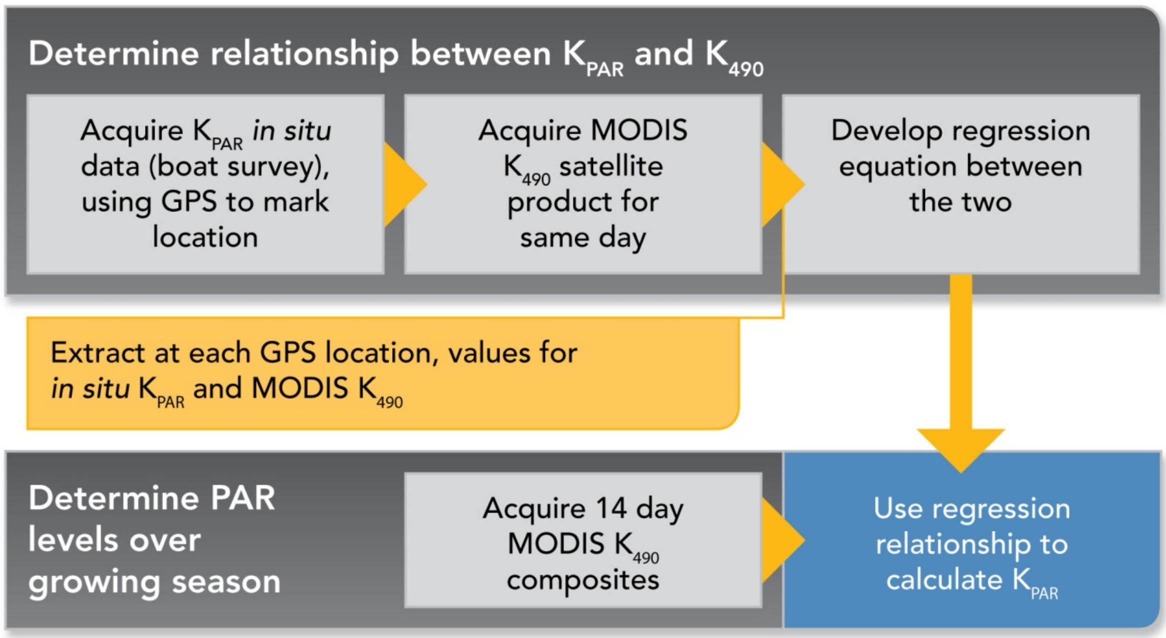


Figure 6. Steps to Develop K_{PAR} Estimates in Estuary. In step 1, we determined the relationship between K_{490} and K_{PAR}. In step 2, PAR levels over growing season was determined.

Determine the Relationship Between K_{490} and K_{PAR}

On 4-2-2008, we acquired instantaneous PAR values (µmol/m^2/sec^{-1}) at 13 locations throughout the estuary (Figure 5), using a LI-COR Biosciences Underwater Quantum sensor. At each station, readings were taken at from just below the surface down to 4m depth at 0.5m increments, depending on the water depth. Based on Lambert-Beer's law, a natural log regression between the light levels at different depths provided an attenuation rate, or K_{PAR} coefficient (m^{-1}), for each station. Station 11 was eliminated due to poor coefficient of concordance (R^2) values in the final equation. Later comparison with bathymetry showed that site 12 was very shallow, and that site was eliminated as well.

A corresponding MODIS K_{490} image composite for 4-2-2008 was acquired from NOAA Coast Watch, West Coast node in ArcGIS-compatible format, though image processing was completed by COAS at Oregon State University. Pixel values from the image were extracted for each *in-situ* station. A linear regression equation was created between the *in-situ* K_{PAR} coefficient and remotely sensed K_{490} (Figure 7).

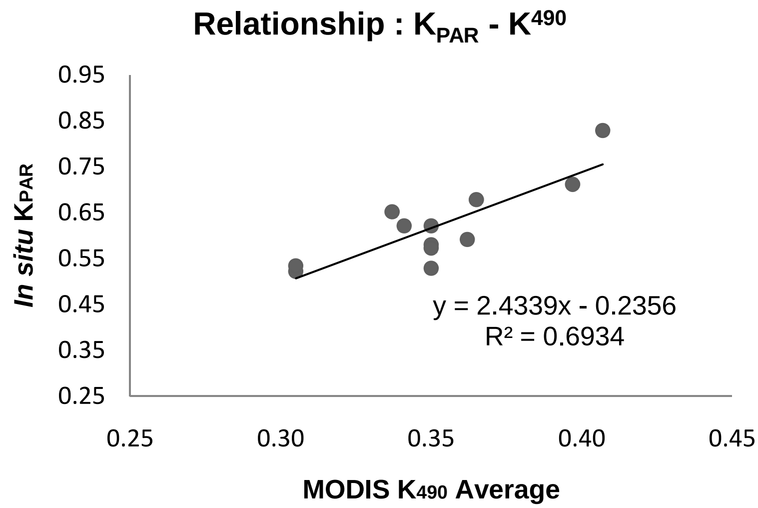


Figure 7. Regression Between K_{PAR} and K_{490}. K_{PAR} Values Are Higher Than Those of K_{490}.

Determine PAR Levels Over Growing Season

Fourteen-day composites for K_{490} were acquired for April-July 2007 and 2008, the months of greatest growth rates for eelgrass. As clouds interfere with satellite acquisition, products were not available on some dates. Table 2 provides a list of products used.

Data was imported into ArcGIS and each image was converted into K_{PAR} using the equation derived previously, where:

$$K_{PAR} = 2.4339*K_{490} – 0.2356$$

A constant for each month's incoming radiance was input, using monthly global radiance values from the University of Oregon's Solar Radiation Monitoring Laboratory in Gladstone, Oregon. Values were converted from KWH/day to mol/light/day, based on an average wavelength of 550nm. (See Appendix A for calculation). Average integrated daily PAR ($mol/m^2/day$) was calculated over the study area following Lambert-Beer's Law for each image product (Figure 8).

Prior field and laboratory studies indicate that 3 $mol/m^2/day$ is the light requirement for eelgrass survival, increasing growth to up to 7 $mol/m^2/day$ (Thom et al. 2008). However, conditions measured remotely differ from those measured *in situ,* so caution should be used in using a threshold determined on a much different scale. In addition, there are uncertainties in our calculations. Assuming an average 550nm wavelength, not accounting for scattering or transmission loss in the boundary layer, and our conversion algorithm from K_{490} to K_{PAR} undoubtedly add some error in the calculations. However, that error should be consistent throughout the datasets, allowing comparison between the datasets. To better determine a threshold for use in this study, we compared the spatial variation in PAR within known eelgrass areas we calculated to previously derived daily integrated PAR requirements.

Examining the time series for PAR from known eelgrass areas (Figure 9), showed that in 2007, average integrated daily PAR levels received by eelgrass beds did not often go below 6 mol/m^2/day and most of the population experienced light levels above 4 mol/m^2/day for every date in the time series.

In this case, we defined areas that received more than 4 mol/m^2/day at all time steps (image composites) during the growing season (April-July) as meeting the light requirement for long term survival, combining prior field study limits with observed light distribution in present-day meadows (Figure 10).

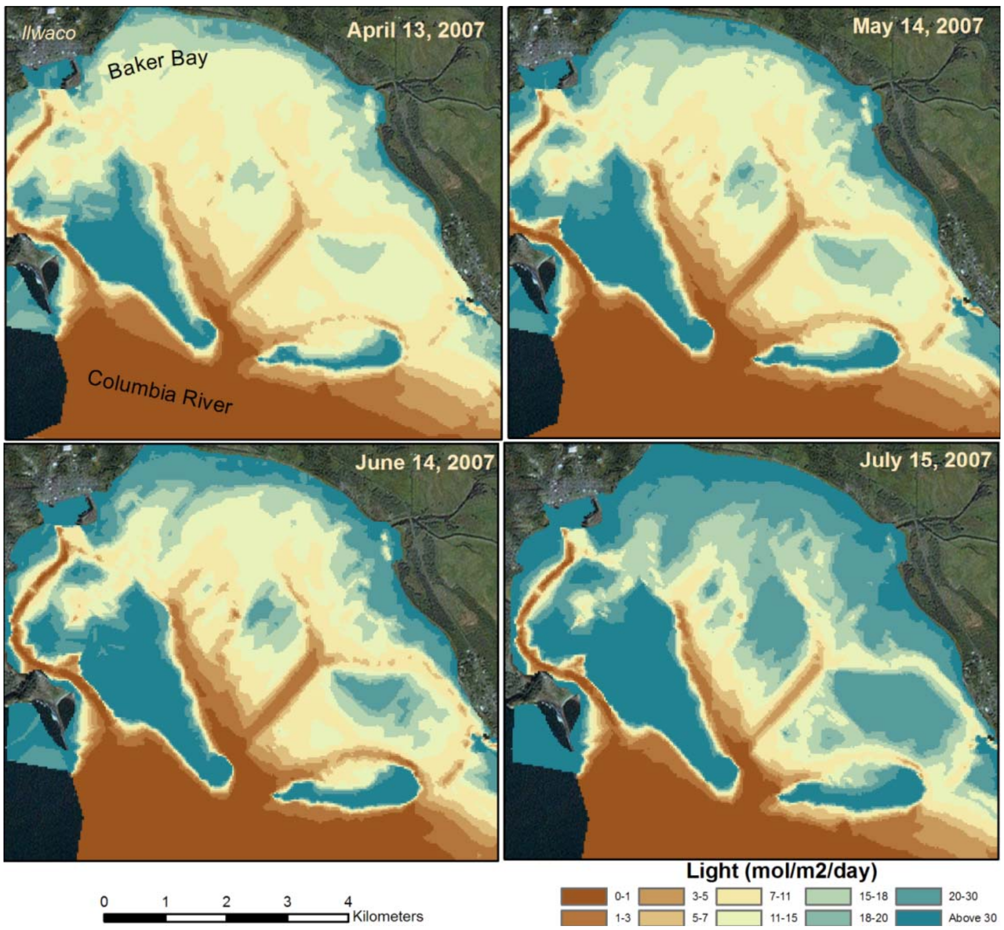


Figure 8. Time Series of Underwater Light in Baker Bay. These four dates show the total amount of light at bottom increases throughout the summer.

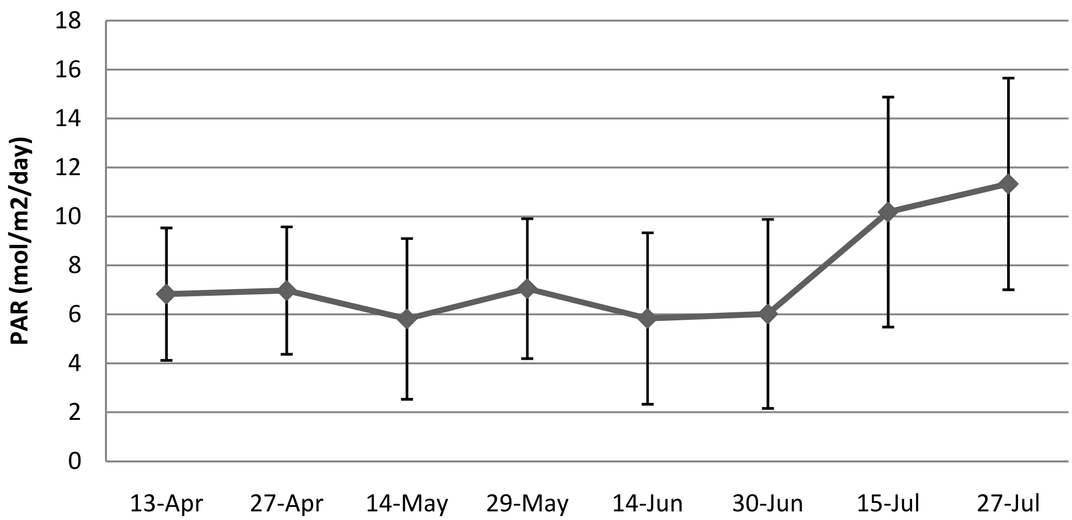


Figure 9. Time Series of Mean PAR and Standard Deviation within Eelgrass Meadows. Light levels are derived from remotely sensed observations. Known eelgrass meadows were identified in the 2007 eelgrass assessment.

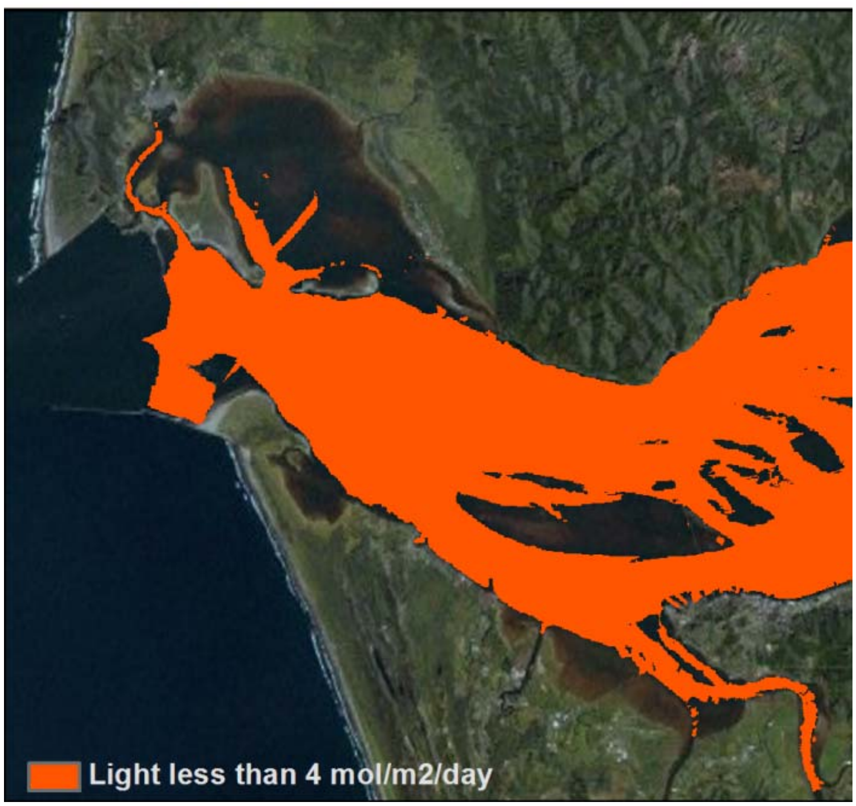


Figure 10. Areas That Receive Less Than 4 Mol PAR/m^2/day

3.2.2 Desiccation/Exposure Assessment

The upper edge of eelgrass distribution is driven by elevation and exposure. While this is a function of depth relative to mean sea level, wave period, and tidal amplitude (Koch 2001), in this assessment, we focused solely on depth. Therefore, exposure and desiccation potential was assessed as solely a function of depth, and calculated across the study area.

Limited information about eelgrass distribution is available across the CRE. The most recent assessment in 2007 mapped some areas of known eelgrass presence in Baker Bay (Borde 2008). Other adjacent areas were mapped as probable eelgrass or potential eelgrass. Using the mapped polygons as guides, we extracted information on depth for those areas of known or probable eelgrass. These areas had a mean depth of -0.98 m MLLW with a standard deviation (σ) of 0.73 m. Initial field surveys in Young's Bay showed a similar distribution. Therefore, -0.3 m (roughly +1 σ) was used as the upper limit for desiccation.

A new desiccation dataset was created by reclassifying the bathymetry dataset as either below (1) or above (0) the upper limit of -0.3 m MLLW. Figure 11 shows areas only above the upper limit. As can be seen in the close-up in Baker Bay, the extent of probable eelgrass extends beyond this upper limit. However, for the purpose of identifying suitable restoration areas, this conservative estimate was used in this analysis.

Figure 11. Desiccation. Areas judged to be too high for eelgrass are identified in the left image (tan). A close-up in Baker Bay (right) shows that known areas of eelgrass adjoin the desiccation prone areas, though the probable eelgrass classification, denoted with a yellow line, extends into the desiccation area.

3.2.3 Salinity, Temperature, and Current Velocity: Hydrodynamic Model

High temperatures and high or low salinities can stress eelgrass plants. The Columbia River freshwater plume travels over a long distance off the coast during high-flow conditions and various wind conditions, but during low-flow conditions, salinity intrusion can occur as upstream as far as RM 37. As a result, salinity varies over a wide range in the CRE. Tidal elevations and currents in the estuary are complex because of the presence of multiple intertidal channels and islands. It is difficult to extrapolate the distribution these physical quantities from measured datasets without an extensive field observation network.

Current velocity may affect the establishment of individual shoots, plant distribution, growth, and structure of seagrass meadows (Fonseca and Kenworthy 1987; Zieman and Zieman 1989). Strong currents may uproot seagrasses, while stagnant water may provide insufficient oxygen to plants. Field study results vary on specific values for maximum and minimum velocities the plants need for survival (Table 1)

The hydrodynamic model SELFE, developed by Oregon Health Science University (Zhang and Baptista 2008), is a 3-D unstructured finite-element cross-scale ocean model using semi-implicit Eulerian–Lagrangian finite-volume method. SELFE, along with other models such as ELCIRC, is a key component of the pilot environmental observation and forecasting system for the Columbia River (CORIE) (Baptista 2006). It has been producing hindcasts and forecasts since 1998. Currently, it predicts surface-water elevations, 3-D velocities, salinity, temperatures, and wetting and drying processes in the Columbia River.

To use the hydrodynamic modeled data, we followed four basic steps. (Figure 12).

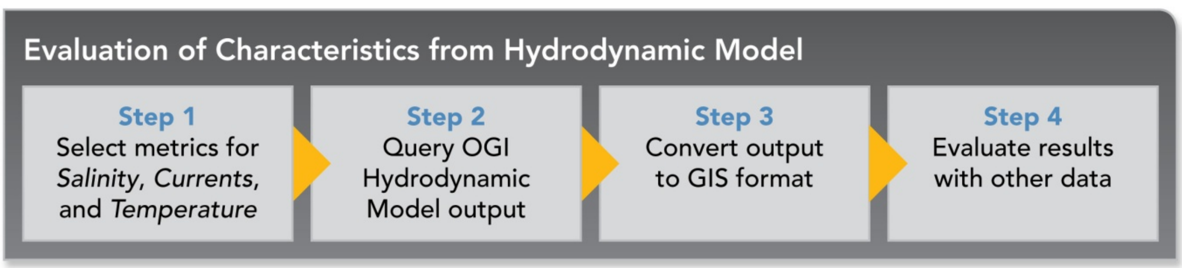


Figure 12. Steps to evaluate hydrodynamic modeling results with other data.

Selection of Metrics

We evaluated six metrics (Table 3) within 12 different scenarios of river and seasonal conditions. The 12 scenarios covered one of each of the following combinations of FLOW YEAR (high-flow year, low-flow year, and average year), SEASON (growing season (May-September), or high-flow season), and TIDE (spring/neap). Each of the six metrics from the model runs identified by the scenarios provides frequency of the metric occurrence. Frequency is based on data calculated at 15-minute intervals over a 3-day period centered at spring and neap tides, for the bottom, the surface and an integrated average over the water column (Table 4).

Table 3. Frequency Metrics for Controlling Factors Measured through Hydrodynamic Model

Metric	Criteria
Salinity - Low	Frequency of values < = 5 psu over a 3-day period
Salinity - Optimal	Frequency of values >=10 and <=30 psu over a 3-day period
Maximum Current	Frequency of values >= 1 m/s over a 3-day period

Minimum Current	Frequency of values <= 0.05 m/s over a 3-day period (only for inundated areas)
Temperature	Frequency of values >= 20°C over a 3-day period (during growing season)
Water Level	Frequency of inundation over 3-day period

Table 4. Metric calculations conducted for each of the 12 scenarios. Frequency metrics, designated with an X, were calculated for each of 12 scenarios for flow, season, and tide. Some metrics, like temperature, were only calculated for the growing season.

	Year (Flow)	Season	Tide						
Scenario	*High, Med, Low*	*High-Flow /Growing*	*Spring/Neap*	Salinity Low	Salinity Optimal	Max Current	Min Current	Temp	Water Level
1	High	High	Spring	X	X	X			X
2	High	High	Neap	X	X	X			X
3	High	Growing	Spring	X	X	X	X	X	X
4	High	Growing	Neap	X	X	X	X	X	X
5	Med	High	Spring	X	X	X			X
6	Med	High	Neap	X	X	X			X
7	Med	Growing	Spring	X	X	X	X	X	X
8	Med	Growing	Neap	X	X	X	X	X	X
9	Low	High	Spring	X	X	X			X
10	Low	High	Neap	X	X	X			X
11	Low	Growing	Spring	X	X	X	X	X	X
12	Low	Growing	Neap	X	X	X	X	X	X

We used a subset of the model results in the lower Columbia River to analyze metrics under low, high, and normal river flow conditions. Based on the annual mean distribution of flow from 1999 to 2005 (Figure 13), years 1999, 2000, and 2001 were selected for analysis to represent high, normal, and low-flow conditions. High-flow seasons in these 3 years were determined based on the monthly river distributions (Figure 13). January was selected as high-flow month for 1999 and 2000 while December was selected for 2001.

Query OGI Model

Model results were acquired at every node grid point in the horizontal plane and 26 sigma-stretched uniformed vertical layers at every 15-minute time interval. There are a total of 9027 nodes in the sub-model domain. Model results include tidal elevation, inundation, 3-D velocity, salinity, and temperature fields. Frequencies for all six metrics, listed in Table 3, were produced for spring and neap tidal cycles for each year during the growing season.

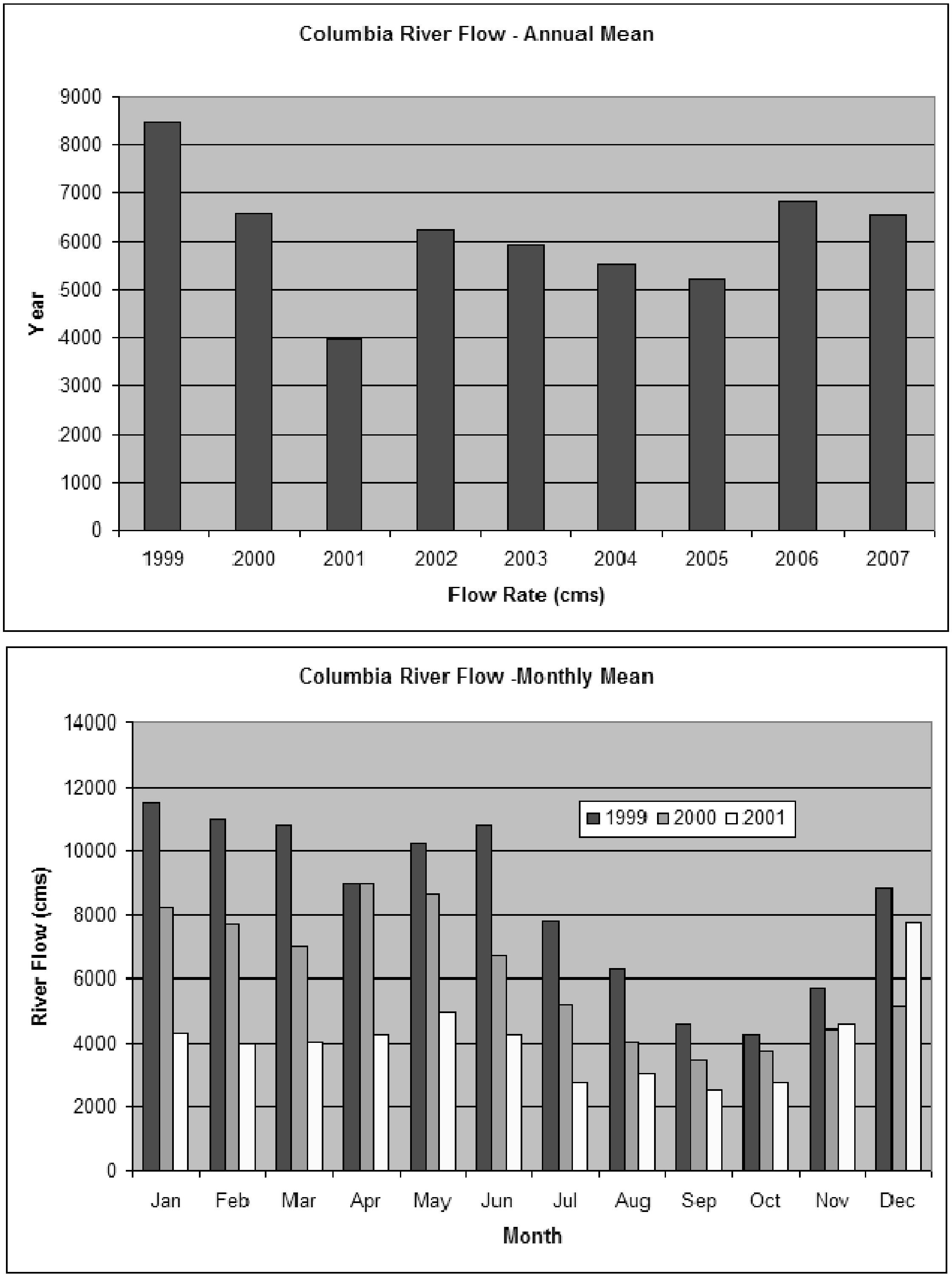


Figure 13. Mean Monthly Flows for High-Flow (1999), Medium-Flow (2000), and Low-Flow (2001) Years (top). Monthly means (bottom) help define high and low-flow seasons.

Import into GIS

Model results were imported as points into GIS, converted to Triangulated Irregular Natwork (TIN) format, then exported to 30m raster product. Temperature, salinity, and current datasets were divided by the corresponding water-level dataset (frequency of inundation) to adjust frequency to reflect only frequency when inundated.

Temperature and Current Velocity

Areas that exceeded the maximum current during the year based on the bottom current velocity or the temperature during the growing season were assessed as unacceptable habitat conditions and eliminated from the analysis. No areas in the study area fell under the minimum current requirements (Figure 14).

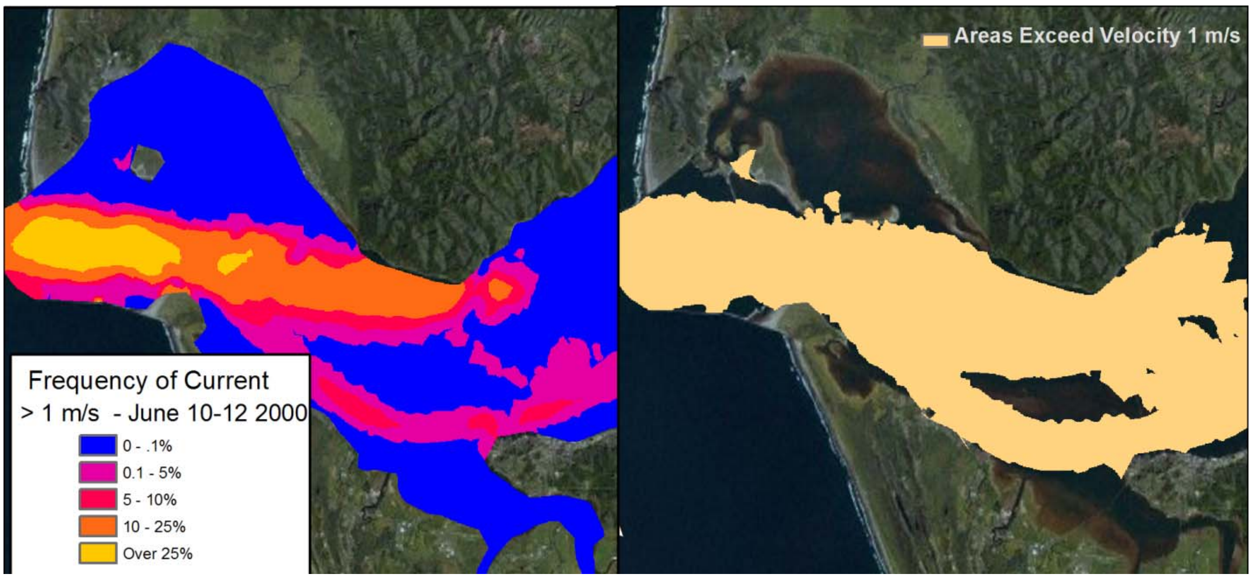


Figure 14. Current Velocity. Areas that fell above 1 m/s at any time step were eliminated. Sample frequency (left) with final mask (right).

Salinity

Salinity was more difficult to assess. None of the areas where eelgrass is present were identified as having optimal salinity values more than 50% of the time (see example in Figure 15), with the majority of areas having salinity values in the optimal range less than 5% of the time. Similar issues were found with the second salinity product−frequency of time below the low-salinity threshold.

We turned to *in-situ* CTD readings for further information, which showed highly variable conditions with vertical stratification. Both CTD stations recorded salinities which fall below published salinity tolerances. However, there were high daily fluctuations, and salinity appeared to increase in the summer during the eelgrass growing season (Figure 16).

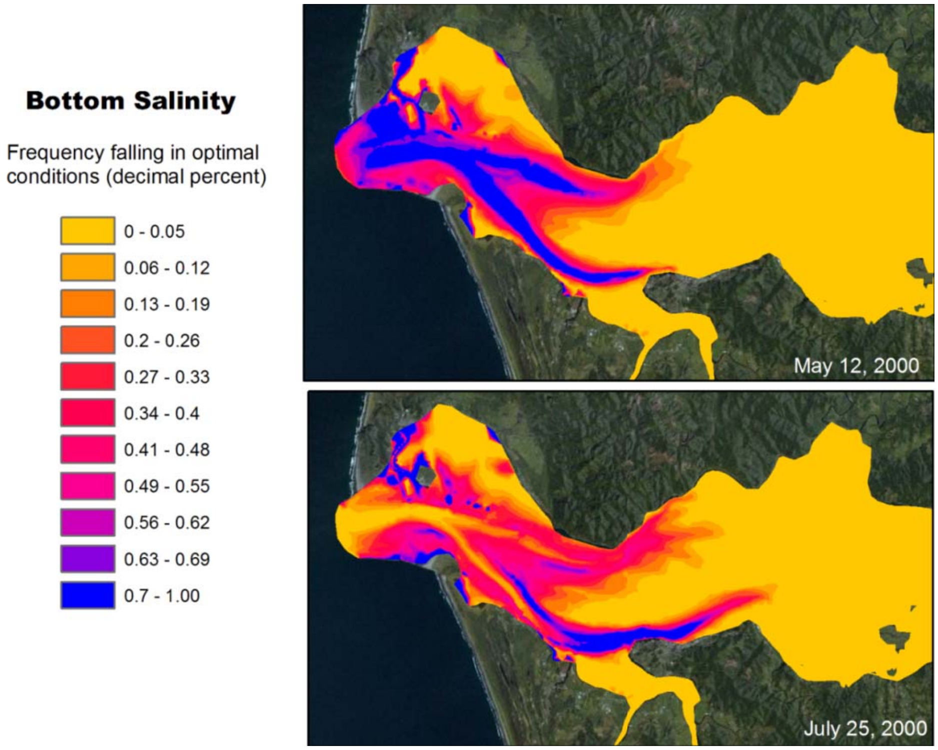


Figure 15. Sample Salinity Product for Frequency of Salinity in Optimal Ranges (10psu - 30psu). Note that in the areas where eelgrass is currently present, the salinity is 'optimal' from 0 to 12% of the time.

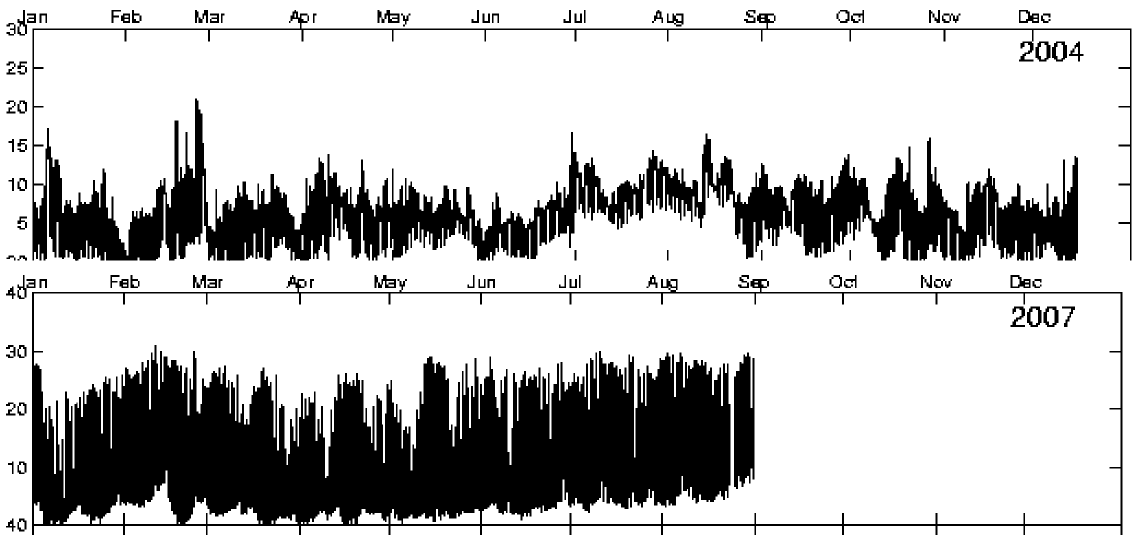


Figure 16. Salinity Measurements at Chinook (top) and Fort Stevens (lower) from CTD readings. Wide fluctuations in salinity with tidal cycles are apparent. (Refer to Figure 5 for locations).

Though salinity is likely to be a significant limiting factor in the Columbia River, not enough information was available to accurately predict where eelgrass would found based on salinity. In addition, to unknowns for biological thresholds, there has been little validation of modeled forecasts and hindcasts of salinity within Young's Bay and Baker Bay. Limited *in situ* stations hinder adaptation of the model or validation of it. A map was created that identified areas having suitable salinity ranges at least 1% of the time and at least 5% of the time (Figure 17). This was used qualitatively along with the results from the habitat assessment model for final placement of potential restoration sites.

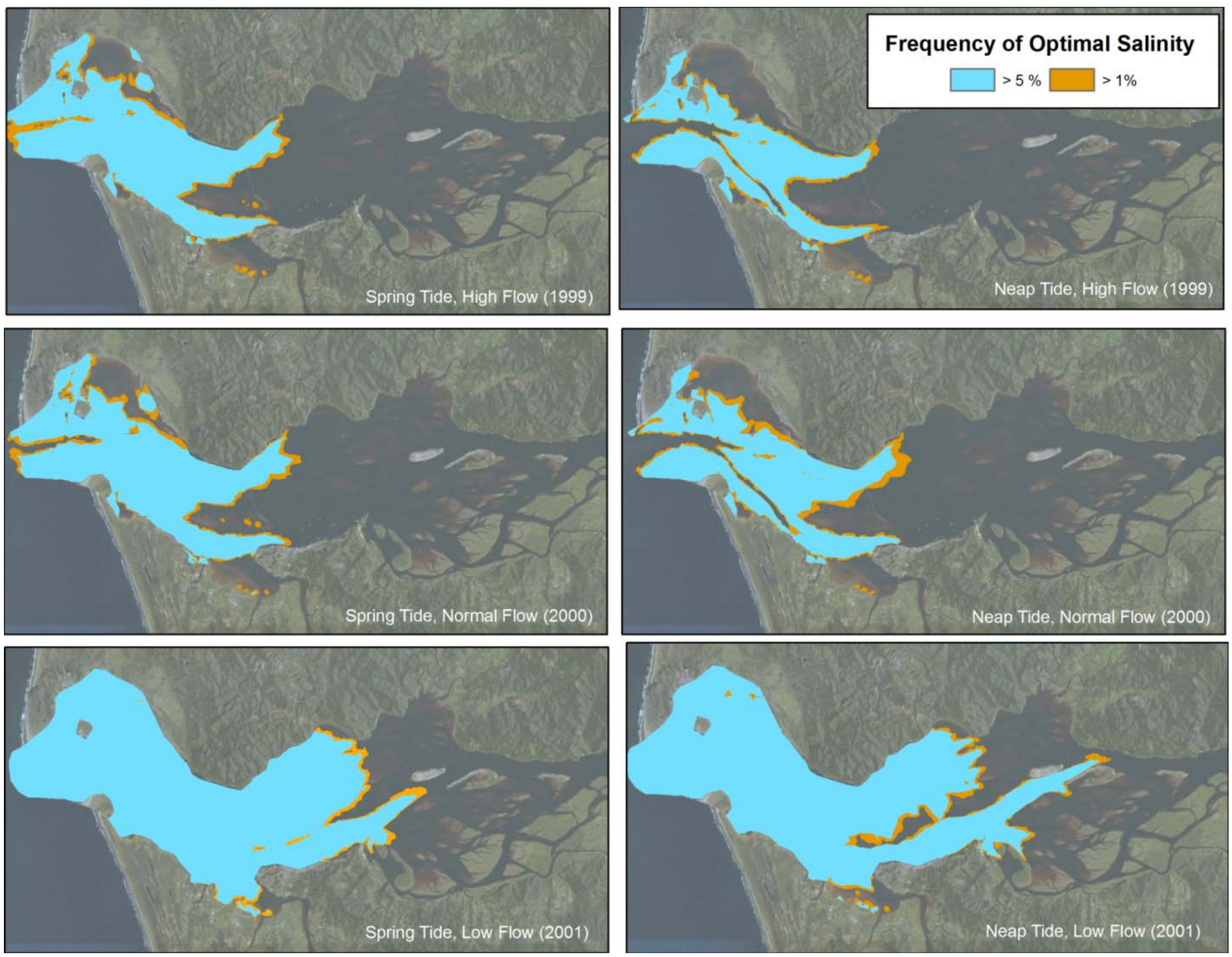


Figure 17. Frequency of Salinity in Optimal Ranges (10psu - 30psu). Note that in high or normal flow conditions, salinity is low in known eelgrass meadows

3.2.4 Disturbance Factor: Wave Energies

Wind waves are believed to be a major factor limiting seagrass distribution on many east coast estuaries, leading to erosion and plant breakage (Fonseca 1998, Koch 2001). To determine the potential impacts of wave energy within the LCRE, we used the Wave Energy Model (WEMo 3.0, Maholtra and Fonseca 2007). Representative Wave Energy (RWE) was calculated, based on fetch, bathymetry, wind speed and direction for select points in an estuary. This provides predictions of wave exposure due to local wind generated waves, using linear wave theory to calculate wave energy and height.

A list of data sources can be found in Table 2. For our analysis, we used bathymetry (30m grid resolution) and selected the strongest 5% of wind energy occurrences. Wave energy was assessed with a grid resolution of 100m over the study area

Because little information is available on eelgrass's resistance to wave energy, RWE was compared to known locations for eelgrass, though it appeared that eelgrass exists in all categories (Figure 18). Based on distribution of eelgrass, three zones of wave energy disturbance were created: (1) Low, 0-200 J/m, (2) Medium, 200-300 J/m and (3) High, > 300 J/m. Because of the uncertainty in the actual limits of eelgrass and the apparent occurrence in a wide range of energies, only the High category was judged unsuitable. However, this entire dataset was used qualitatively after the habitat suitability model was complete to refine placement of restoration sites.

Due to lack of information, other studies have used a Relative Exposure Index, which ranks sites on their wave exposure relative to other sites (Fonseca and Bell 1998; Hovel at al. 2002; Gilkerson 2008). However, we believe that a quantitative approach could still be used to rank areas because quantitative values can be compared directly and can be used to better understand the effects of wave energy in other areas.

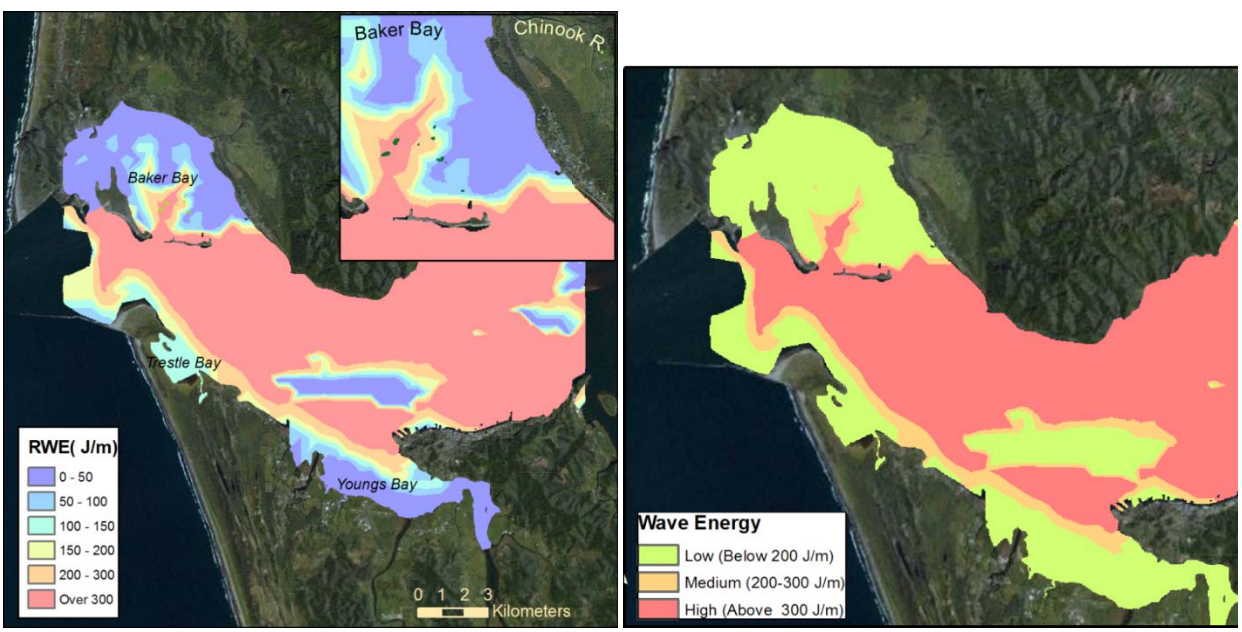


Figure 18. Relative Wave Energy in Lower Columbia River (left) with Eelgrass Meadows in Inset. Reclassified map (right).

3.2.5 Disturbance Factors: Anthropogenic Activities

Eelgrass meadows may be stressed by other in-water activities. For example, heavy boating activity will increase wave energy and increase the chance of damage due to either waves or propellers. In addition, dredging operations in channels may uproot grasses, cause greater turbidity, or deposition may bury eelgrass. Over-water structures, such as piers and bridges, may shade eelgrass, or cause localized changes in hydrodynamics. To assess the potential for stressors to affect eelgrass transplants, we compile available information on these stressors in the estuary (Figure 19).

In-water activities and structures were obtained from NOAA's Electronic Navigation Charts. Areas that contained potential disturbances to eelgrass were eliminated as potential restoration sites.

Figure 19. Sources for Direct Disturbance on the Lower Columbia River

3.2.6 Habitat Suitability Assessment

Based on the analysis of six controlling factors, we scored habitat suitability over the study area. First, the binary classifications of desiccation/exposure, wave energy, temperature, and light were overlaid to identify areas where all three criteria met eelgrass requirements. The image was reclassified into two classes: (1) Meets all three criteria (0) Does not meet all three criteria (Table 5). Salinity and wave-energy maps were also used qualitatively to help guide placement of potential restoration sites.

Table 5. Controlling Factor for Eelgrass. Model criteria and classification scheme

Factor	Criteria	Classification
Light	Area receives an average of > 4 mol light/day for all dates between April and July	1 - Meets criteria 0 - Does not meet criteria
Desiccation	Area is below .3 m MLLW	1 - Meets criteria 0 - Does not meet criteria
Temperature	Area does not exceed maximum temperature of 20°C more than 10% of the time	1 - Meets criteria 0 - Does not meet criteria
Current Velocity	Velocity is always less than 1 m/s	1 - Meets criteria 0 - Does not meet criteria
Salinity	Used as ancillary sources of information	--*Qualitative Assessment*--
Wave Energy	Extreme wave energy (5 %) < 300 J/W	1 - Meets criteria 0 - Does not meet criteria
	Medium wave energy (200-300 J/W) used qualitatively after initial model	*Medium category used qualitatively*
Disturbance Factors	Dredge channels, disposal sites, and in-water structures	1 - Factor absent 0 - Factor present

3.2.7 Identification of Potential Sites

Based on the results from the habitat suitability model, twelve potential sites for planting were identified. Other selection factors included distance from current eelgrass meadows, access by divers, and location to represent five potential areas: Baker Bay (B), Young's Bay (Y), tributaries to Young's Bay (T), the Main Channel (M) and the shallow islands (I) in the center of the river (Figure 20).

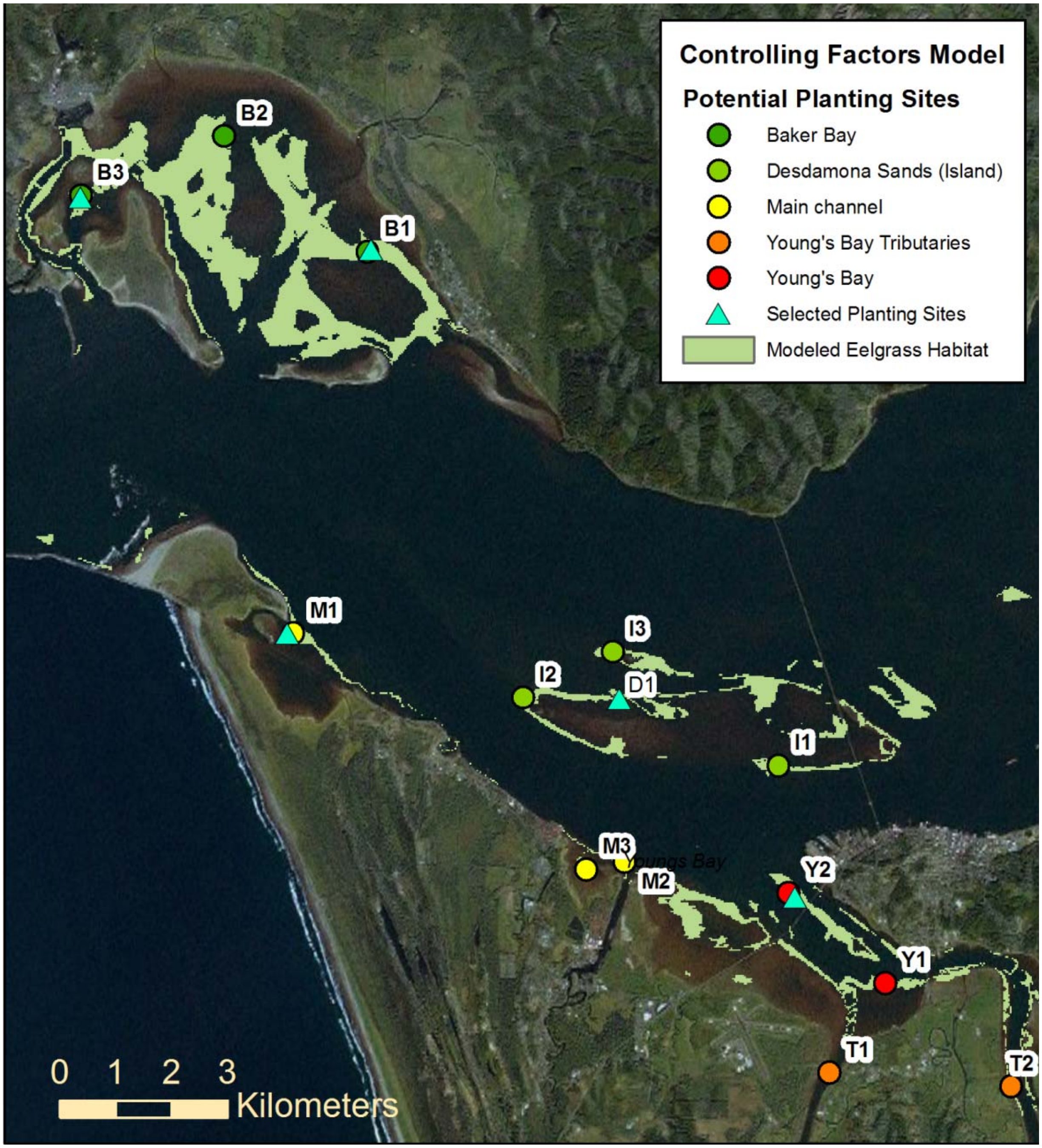


Figure 20. Eelgrass Habitat (light green) with Potential Restoration Sites. Final selected sites for planting are marked with a triangle.

3.3 Stage 2: Field Assessment and Planting

3.3.1 Field Assessment

Divers and a field crew assessed the 12 sites identified in the prior stage. From these potential sites, areas B1 and B3 in Baker Bay and area Y2 in Young's Bay were selected for planting. On visiting M1, the site looked like a good potential site, but it was too shallow, so it was moved to a lower location in the channel. Similarly, sites I1, I2, and I3 on Desdemona Sands showed signs of high wave energy and some sparse eelgrass. Therefore, the planting site was moved to D1, which appeared to have more favorable wave energy conditions and no eelgrass present. Divers discovered an eelgrass meadow at site Y1. Near this eelgrass bed, but at higher elevations, freshwater SAV species were also present.

At this stage, HOBO sensor light level results were also examined for Young's Bay, Trestle Bay and Baker Bay. Light levels appeared to be similar to those found in the natural eelgrass bed. A more complete synopsis of field notes can be found in Appendix B.

3.3.2 Planting

From June 21-27, 2008, five test sites were planted in the Lower Columbia Estuary with eelgrass harvested from donor meadows. A dive team and land-based crew worked together to 1) harvest plants and prepare them for transplant, and 2) transplant them into the experimental site.

Figure 21. Eelgrass Planting Preparation Station. Eelgrass is harvested and brought to the area in coolers. Eelgrass is sorted and bundled using twist ties and staples. Finally, it is placed on boards for divers to plant.

Harvest and Prepare Plants

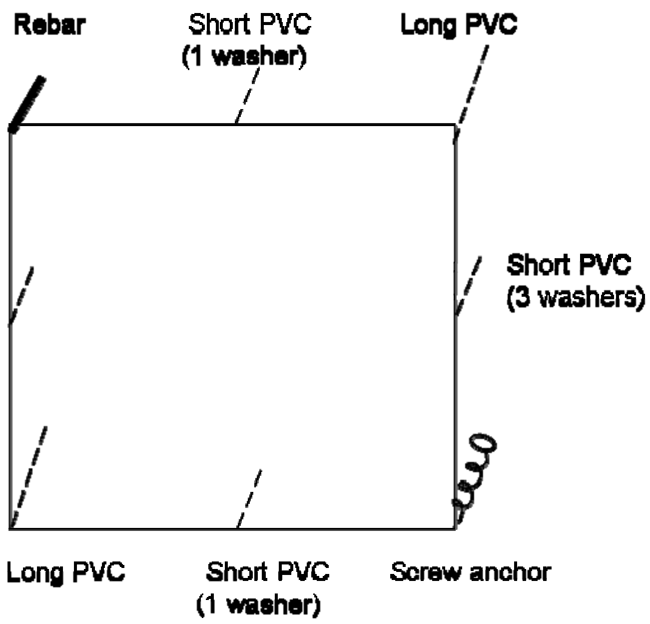
Eelgrass was harvested from three sites in the Lower Columbia: Sites H1 and H2 in Baker Bay and H3 in Young's Bay (Figure 23). Sites H1 and H2 were used for donor material for Baker Bay transplants, and plants from site H3 were used for sites Y1, M1, and D1 in Young's Bay, the Trestle Bay and Desdemona Sands. Most of the work was completed with SCUBA gear, though at low tide some activities were conducted with snorkeling equipment. An additional dive was conducted at a site away from the harvesting zone to survey the existing eelgrass densities as a control for monitoring natural densities in eelgrass meadows.

After harvest, plants were stored in coolers with ambient sea water, and transported to a ground crew. Plants were bundled into groups of 4 plants and attached to a metal staple with a twist tie. Bundles were attached to PVC boards using surgical tubing. These boards were placed in tubs of cold sea water during the entire process, with holding time from harvest to planting never exceeding 48 hours.

Transplant into Experimental Sites

While we originally proposed to plant 10 m x 10 m plots, eelgrass abundance in the natural/donor meadows was low. Therefore, the size of experimental plots was reduced to 7 m x 7 m so as not to overharvest natural meadows. Because of the steep slope and narrow depth range for planting at the Trestle Bay site M1, this planting plot was changed to 5 m x 10 m to conform to the narrow depth contour.

One corner of each plot was marked with a screw-in sand anchor with a small toggle surface float. The opposite corner was marked with a piece of rebar. Remaining corners were marked with a long piece of PVC, and midpoints on each side were marked with a short piece of PVC (Figure 22). The markers and float facilitated ease of locating the test plots at a later date. Eelgrass was planted in a one-quarter-square meter of each square meter with 5 bundles containing 4-5 shoots each. Six bundles were used per one square meter at Young's Bay. Planting resulted in an initial planting abundance of 1225 shoots per site, and 1250 at Trestle Bay.



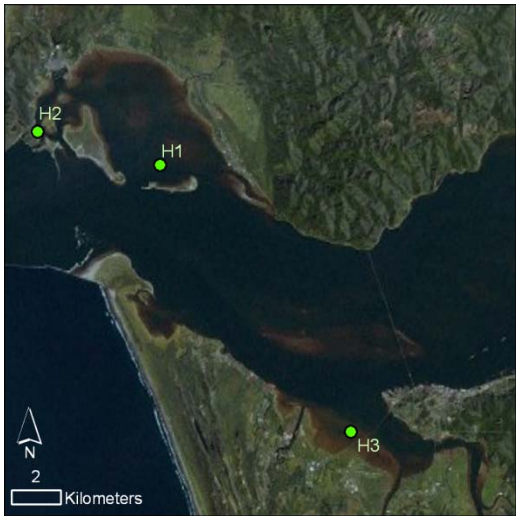


Figure 22. Schema of Experimental Planting Plot (Left), and Eelgrass Harvest Areas (Right).

3.4 Stage 3: Evaluate Success

3.4.1 Eelgrass Plantings

Dive surveys were conducted the week of July 12, 2009, one year after the initial restoration, to assess the success of the eelgrass transplants.

Conditions were poor for diving due to low visibility. To count eelgrass, divers worked in teams to count eelgrass shoots by touch. Initially, we had wanted to document meadows by taking underwater photos; unfortunately, no photographs were possible because of the high turbidity of the waters. In West Baker Bay and Young's Bay, the divers used one-square-meter quadrats to perform the survey and capture the patchy nature of the initial planting pattern, counting every other square meter. Abundance in these quadrats was extrapolated to the skipped quadrat, while shoot density values per m^2 were recorded. In areas where eelgrass was not abundant, divers conducted comprehensive surveys of the entire plot using on-meter wide belt transects throughout the plot to look for any eelgrass.

3.4.2 Crab Usage

The link between ontogeny and habitat preference indicates critical habitat for juvenile crabs may be limiting in the in the CRE, since bivalve shell deposits are rare and eelgrass meadows are not extensive. The abundance of these habitats in the intertidal appears sparse, which may limit the utility of the littoral zone as a predation refuge for the smallest crabs. As a consequence, McCabe et al. (1988) found few juvenile crabs in unstructured intertidal zones of the CRE. Subtidal eelgrass meadows may offer an important alternative habitat for young crabs. Thus, one potential benefit of an eelgrass enhancement project is an increase in the survival of 0+ aged crabs in subtidal eelgrass over the surrounding unvegetated substrate.

The intended experimental design compared utilization by crabs (measured by catch per unit effort, CPUE) and size of crabs at unvegetated, natural eelgrass, and transplanted eelgrass habitats. However, the eelgrass transplant treatments proved too small for adequate replication. We therefore primarily compared natural eelgrass and unvegetated treatments with traps in and surrounding one transplant site. We studied two sites in Baker Bay, near the mouth of the Columbia River (Figure 23). Three replicate traps were deployed within each habitat type. Vertical profiles of temperature (^{o}C), salinity (psu), and dissolved oxygen concentration (mg/L) were measured upon trap retrieval.

Baited crabs traps were used to sample for Cancer magister abundance and size which are effective at retaining crabs > 15 mm (J3 stage). Traps were deployed at high water and fished for 23-25 h. Samples were collected at 2 week to 1 month intervals from June through October 2008 and from February through July 2009. Crabs were counted, measured (carapace width at the 10th anterior spine), sexed, appraised for appendage loss, and returned to the site of capture.

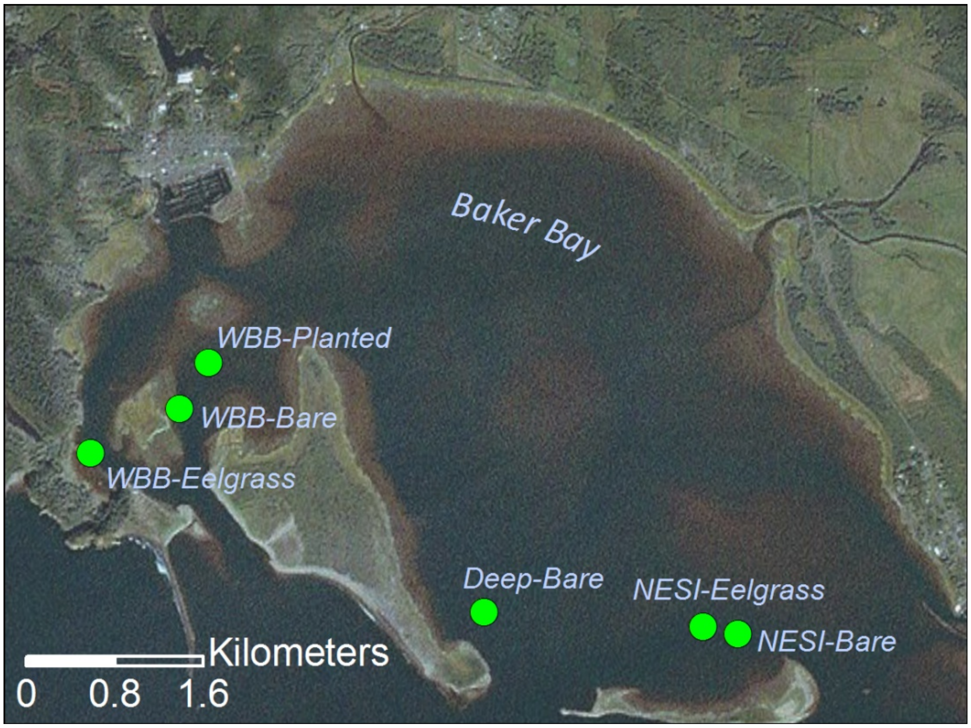


Figure 23. Stations for Crab Utilization Monitoring

We computed time series of mean CPUE and mean size per deployment for each treatment at both sites. ANOVA was used to test for differences in mean CPUE between habitat types. Regressions of mean size by day of year were made to compare relative growth rates. Crab year class (cohort age) can be estimated by carapace width (Armstrong et al. 1987). We used the size- frequency of crabs to determine cohort age for each of the six treatment plots, first for the entire sample and then as a time series for crabs pooled into two-month bins. We evaluated the sex distribution, percent limb loss, and incidence of multiple limb loss of crabs categorized into 50 mm size intervals. Finally, to investigate trends of habitat use with physical variables, we calculated regression statistics for mean crab CPUE and size by day of year, and temperature, salinity, and dissolved oxygen concentration measured at the benthos.

4.0 Results

4.1 Evaluation of Eelgrass Plantings

Overall, sites B1 in Baker Bay and Y2 in Young's Bay had good survival rates for the first year, while the other three had poor survival rates (Table 1). There was, however, a net gain in the amount of eelgrass present. Results and observations for the individual sites are provided in Table 6. Further observational field notes can be found in Appendix C.

Table 6. Monitoring Results for Planted Experimental Eelgrass Plots

Location	Estimated Total Shoots	Percent Shoot Survival	Shoot Density (m^{-2})	Shoot Length (cm)
West Baker Bay (B3)	8	0.65	< 1	10
East Baker Bay (B1)	535	43.64	10.9 $\pm$ 8.75	10-20
Trestle Bay (M1)	0	0	--	---
Desdemona Sands (D1)	3	0.24	<1	10
Young's Bay (Y2)	6524	532.55	133.1 $\pm$ 42.8	20-50

4.2 Evaluation of Crab Usage

Shallow subtidal areas in Baker Bay were primarily occupied by 1 and 2 year old crabs (Figure 24). Only 85 crab < 50 mm were present at our shallow water sampling sites, and ANOVA did not detect a significant difference in the number of small crabs between treatment sites. The low numbers of young-of- the -year crabs found during our data does not support the hypothesis of increased abundance of 0+ crab in subtidal eelgrass meadows compared to unvegetated sites. Further details on abundance and comparison with environmental variables can be found in Appendix E.

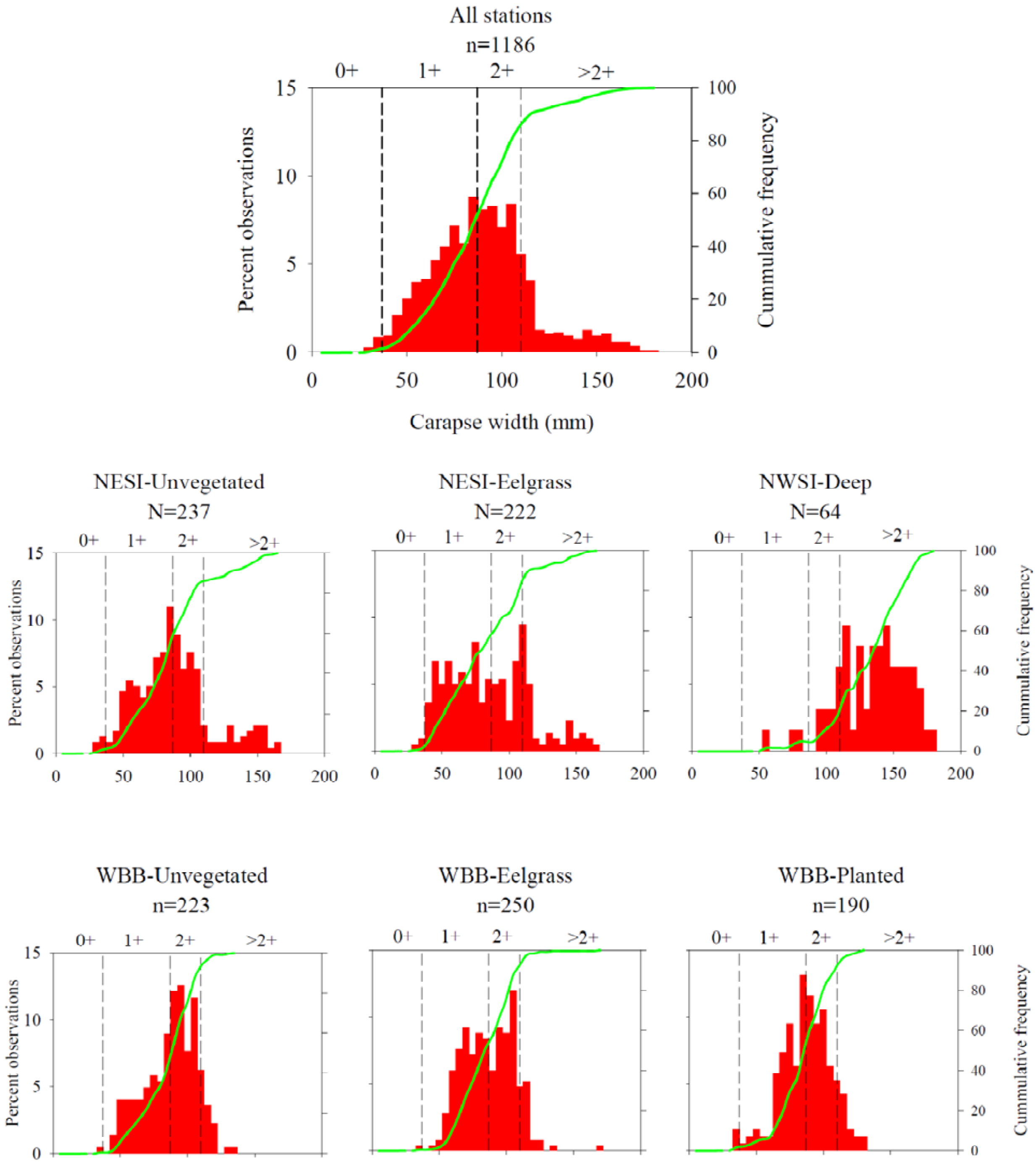


Figure 24. Histogram (bars) And Cumulative Frequency of Estimated Age Class of Crabs Caught. Top: All crabs. Middle row: Treatment plots at NESI. Bottom row: Treatment plots at WBB.

5.0 Discussion

Our initial findings suggest that there is a potential to enhance distribution of eelgrass in the estuary, and we cannot yet reject the hypothesis that distribution is recruitment limited. In addition, several sources of temporal disturbance or stress became evident, including low salinities and variation in light levels.

Through this project, we identified areas of previously undocumented eelgrass, and through our experimental transplants, a small net gain of eelgrass in the estuary was realized. Though only two out of five sites did well, overall results are promissing when compared to other eelgrass restoration projects. Out of 14 other eelgrass restoration projects found in the literature covering 25 test sites, average year-one survival rate was 45% compared to our average of 115% (see Appendix D, Thom et al 1990). In addition, Fonseca (1998) found a mean survival rate of 42% out of 53 seagrass restoration projects. However, our results in this study were highly variable, ranging from total loss to a 500% increase in eelgrass.

Comparison with modeled habitat parameters shows three commonalities. First, sites that did well had the highest light levels in 2007, though this is the year prior to the actual transplant (Figure 25). Second, salinity conditions were not ideal in any of the sites with most sites showing only a percentage of the time when the salinity was above 5 psu. Finally, both sites that had the greatest success, B1 and Y2 were located relatively near to other established eelgrass meadows (within 500-1000m). Light is important in the development of the below-ground rhizome and root system of eelgrass. It may be that additional light may help plants deal with other stresses in the site, such as establishing roots to anchor the plant.

Survival and expansion of Young's Bay (Y2) eelgrass plantings was higher than other areas. There is a large meadow across the main channel and sparse eelgrass patches were located around the restoration area. Planting additional eelgrass could have slowed the current flow or trapped seeds. In addition, planting methods were different. Six bundles were used per square meter in Young's Bay instead of 5. Planting in patches could encourage plant growth between patches, but it also leaves more edge area. A denser patch may be more stable than a sparser patch.

While other controlling factors are similar across all sites, Young's Bay also had a higher predicted wave energy and the highest light levels in 2007, as seen in Figure 25. It is possible that the higher shoot densities are related to the higher light levels. With greater wave exposure, there may be interannual variability in the eelgrass population in Young's Bay before and after large storm events.

Each plant bundle was initially attached with a long staple. In plots where we observed staples without plants, suggests to us that conditions of light or salinity were not adequate for eelgrass. In areas where the staples were missing as well, suggests that currents and waves may have been strong enough to extract the staples from the site or that the eelgrass and staples were buried. Missing staples in site B3 may indicate strong currents in these areas, and erosion of sediment (0.5 cm) in site Desdemona site D1 may indicate current as well. Surviving plants in the area after one year indicate that there is some suitable aspect to both sites, though plants were stunted in both areas.

Site M1 in Trestle Bay had no surviving plants. Comparison of the site with historical conditions (Figure 1) and divers' notes indicate a highly dynamic sediment regime in the area. In addition, when the field crew assessed the site, they moved it lower because it appeared that the bathymetry was incorrect in

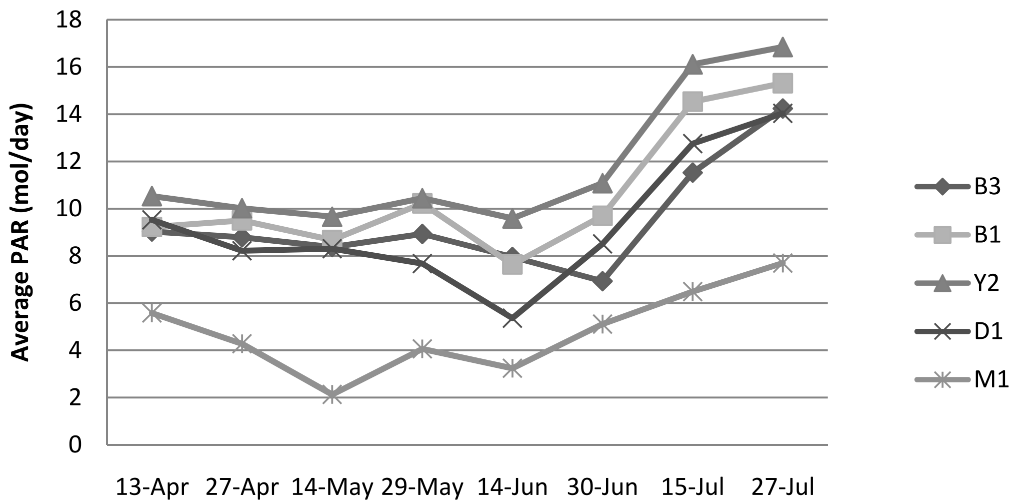


Figure 25. 2007 PAR Levels for Restoration Sites Based on Remotely Sensed Data

that area. All of these factors indicate a highly dynamic area where plants could be buried by sediment deposition. However, it is possible that the planting was located too deep to receive sufficient light. In addition, Thom (1990) compilation of eelgrass restoration projects noted another project in the Pacific Northwest where survival rates were markedly lower along channels than on tidal flats.

Salinity represented the most complex factor to evaluate and may be the critical factor affecting the survival of transplanted eelgrass. The rapid change of salinities with tidal exchange and river flow can create very dynamic and stressful conditions for seagrasses. We conducted an extensive search for information on examples of systems where eelgrass occurs but that have the dynamic variations in salinity exhibited in the Columbia estuary and found none. The value of 5psu we chose as a lower limit for viable eelgrass was based on our review. However, the wild fluctuations in this factor and its influence on eelgrass physiology, growth and survival have not been studied. Salinity remains perhaps the greatest uncertainty in predicting eelgrass dynamics and survival in the Columbia estuary. Restoration and enhancement projects can bolster eelgrass populations in the Columbia River, but further monitoring is needed to understand the stability/instability of these population relative the dynamics of salinity and other controlling factors including light and temperature.

While the shallow water habitat we investigated is recognized to be important rearing areas for subadult Dungeness crab (Rooper et al. 2003; Armstrong et al. 2003), we failed to locate the young-of-the-year Dungeness crab hypothesized to be utilizing subtidal eelgrass meadows. Several possible reasons could account for this. First, McCabe et al. (1984) found low crab usage of intertidal habitat in Baker Bay intertidal transects, albeit sampling effort was minimal. In addition, larval settlement is a highly variable process (Roegner et al. 2007), and there may have been low recruitment to Baker Bay during 2007 and 2008. Brown & Terwilliger (1992) found the first crab instars had less osmoregulatory capacity than megalopae or adults, and the low salinity levels in Baker Bay may have reduced juvenile survival. Alternatively, during our study small crabs may have avoided the traps, although we did not evaluate this possibility.

We did find both eelgrass and non-vegetated sites have relatively high abundances of 1+ and 2+ crabs with a lower number of older individuals. These shallow areas in our study appear to be important nursery areas, and may comprise staging grounds for crabs to ascend to intertidal feeding areas during nocturnal high tides (Stevens & Armstrong 1983; Holsman et al. 2007). Identifying the habitat of these new recruits in Baker Bay will require further study.

6.0 Recommendations

In conclusion, this preliminary study presents promising results. A healthy matrix of submerged and intertidal habitats likely helps maintain feeding, refuge, and forage opportunities for species in the estuary. Highly variable salinity and light conditions are probably the key limiting factors for eelgrass in the estuary. In addition, it appears that crab may temporally use submerged habitats driven by the wide salinity variations and water levels

Based on these preliminary results, we conclude that eelgrass distribution could likely be expanded in the estuary, though additional information on current eelgrass locations, usage by species of interest, and monitoring of current conditions would help document a baseline and verify benefit. Our recommendations for future studies include:

1) *Site Monitoring.*
    - It is recommended that eelgrass restoration sites be monitored for at least 5 years. If density and biomass are monitored in restored areas, sampling density and biomass in natural meadows will provide a more complete picture of eelgrass variation. In three of the restoration plots, we have hypotheses as to why the restoration site succeeded or failed after one year, but we do not know for certain. To gain a better understanding of salinity, currents, and light regimes, *in-situ* sensors could likely provide answers. This information could help further refine the habitat model and selection process to improve further restoration success rates.
    - Continued monitoring will both assist managers in understanding the longevity and expansion rate of planted sites and inform practical guidance on the minimum planted eelgrass required to develop a resilient meadow.
2) *Documentation of current conditions of eelgrass and freshwater SAV in the estuary.*
    - Eelgrass and other freshwater SAV meadows provide critical habitat, forage, and nursery areas, but there has been no system-wide effort for mapping these species in the estuary or documenting density or biomass. With changing conditions and increased anthropogenic activities, understanding the baseline conditions for these resources will be crucial for managing aquatic resources.
    - Monitoring controlling factors in natural beds will assist by better defining the factors that control the annual and spatial variation in eelgrass in the estuary, and thus lead to improved management. In addition, we recommend using the habitat model with field work to develop a map of SAV on the Columbia River.

- Restoration and expansion of freshwater SAV should be considered in a comprehensive effort to restore the submerged vegetation habitats through the Columbia River estuary.

3) *Improve assessment techniques*
    - Using adaptive modeling for eelgrass habitat, or including new information and refined parameters as data becomes available will improve the selection process.
4) *Research Species Use*
    - Further research on how fish, such as salmonids or crabs, use eelgrass meadows locally could help refine restoration priorities and decisions. Expanded monitoring of Dungeness crab and salmon use and benefit from eelgrass in the estuary to evaluate how feeding and rearing functions of eelgrass benefit the survival and growth of these species.

We have two final recommendations. First, if transplanting of eelgrass is to be expanded, donor stocks of plants should be expanded to reduce the dependence on natural meadows. We recommend that an eelgrass culture facility be considered to supply stocks of eelgrass for planting that are developed from the eelgrass populations now in the estuary. Second, freshwater submerged aquatic vegetation (SAV) occurs in many parts of the estuary, and probably has importance to juvenile salmon (although this also needs verification). Restoration and expansion of freshwater SAV should be considered in a comprehensive effort to restore the submerged vegetation habitats through the Columbia River estuary.

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Appendix A: Light Calculations and Data

Hourly monthly means in Direct Normal Radiation from Oregon State University's Solar Monitoring Station at Gladstone, OR was converted from KWH/m^2 to average mol PAR m^2/day, using the following conversation.

- In the first step, we calculated the energy (J) of a photon at 550nm (eg Gallegos 2001), as a representation of average energy of a photon in the PAR wavelengths.

  E = h * (c/lambda), where

  E = energy (J) of 1 photon
  c = 2.998×10^8 m/s
  Lambda = 550 nm ($550E10^{-9}$ m)
  h= 6.626×10^{-34} J·s

  At 550nm, the Energy of 1 Photon is $3.61177*10^{-19}$ J

- Second, values for Direct Normal Radiance in KWH/m^2 were converted to Joules, using the following conversion factor: 1Kwh = $3.6*10^6$ Joules, and divided by 2.2 to consider only PAR instead of broadband radiance (Rou, 1984) to solve for Radiance

- Using the following equation,

  Radiance (J) = Energy of 1 Photon (J) * number of photons

  We solved for total number of photos.

- Finally, using Avogadro's constant ($6.02 * 10^{23}$ mol^{-1}), we converted the number of photons into mol of photons (quanta)

Table A-1. Conversion of Energy in KWH to mol of light

Month	KWH/m2 10 AM -2PM	Broadband mol/m2/day	PAR mol/m2/day
Jan	0.849	14.05702215	6.389555523
Feb	1.487	24.6204852	11.19112964
Mar	1.428	23.64361323	10.74709692
Apr	1.689	27.96502993	12.71137724
May	1.834	30.36581699	13.80264409
Jun	1.942	32.15398942	14.61544974
Jul	2.762	45.73085416	20.78675189
Aug	2.609	43.19760988	19.63527722
Sep	2.486	41.16108017	18.7095819
Oct	1.551	25.68014294	11.67279225
Nov	1.002	16.59026643	7.541030193
Dec	0.66	10.9277204	4.967145636

In-situ PAR data collected at Fort Canby Coast Guard Station had an April monthly average of 11.89 mol PAR/m^2/day, and 13.23 mol PAR/m^2/day for early May, close to the averages measured at Gladstone, OR.

After direct light hits the water surface, some is reflected back into the atmosphere. The rate of this reflectance depends on the angle of the sun, and is roughly 2% for a vertical ray (Kirk, 2006). The loss rate is non-linear and relatively small until the sun reaches a 50 degree angle. The hours used to calculate PAR are when the sun is at its peak, and thus the angle the smallest. For the purpose of this study, this loss was not evaluated, and the incoming light was used as the level of irradiance under the water surface (I_o).

Derived K_{PAR} values from the field excursion are listed in Table A-2 below.

Table A-2. Light attenuation stations -(collected 4-2-08)

Station	UTM Easting	UTM Northing	K_{PAR} (m^{-1})
1	426416	5119570	0.678
2	425642	5120058	0.621
3	424638	5120878	0.580
4	423883	5121875	0.529
5	422302	5122700	0.522
6	422617	5122604	0.534
7	423735	5122263	0.573
8	425175	5122244	0.652
9	426288	5122210	0.621
10	428018	5121777	0.605
11	427315	5119956	0.592
12	427852	5118179	0.829
13	430698	5115947	0.712

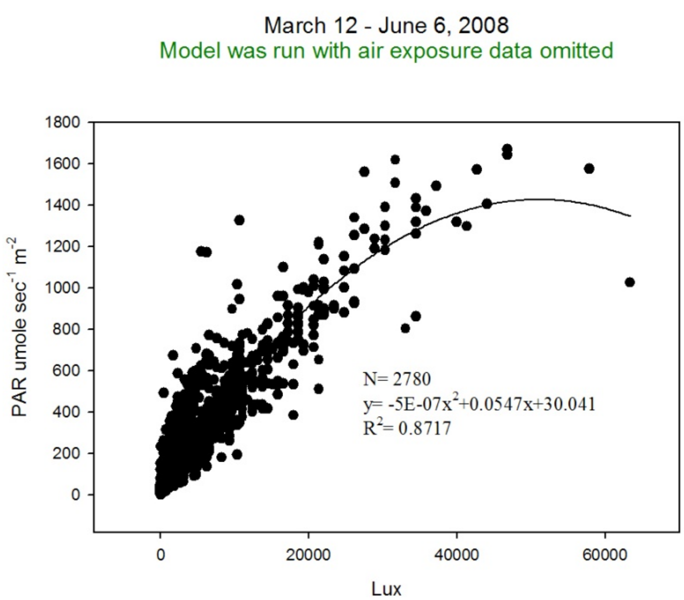


Figure A-1. Algorithm development to convert HOBO light data to PAR at Fort Canby Coast Guard Station.

Appendix B: Notes on Field Selection for Restoration

During the field assessment in mid July 2008, twelve sites were visited to assess their potential for restoration. Each of the twelve sites fell within one of the following location types:

- Baker Bay - Baker Bay sites are located in Baker Bay. These include sites B1, B2, and B3.
- Mainstem – Mainstem sites are located along the main channel of the Columbia River. Mainstem sites are M1, M2 and M3.
- Island – Island sites are located near Desdemona Sands mid-channel. These sites include I1, I2, and I3.
- Young's Bay – Young's Bay sites are located in Young's Bay and include sites Y1 and Y2.
- Tributary – Tributary sites are located on tributaries to Young's Bay, including T1 and T2.

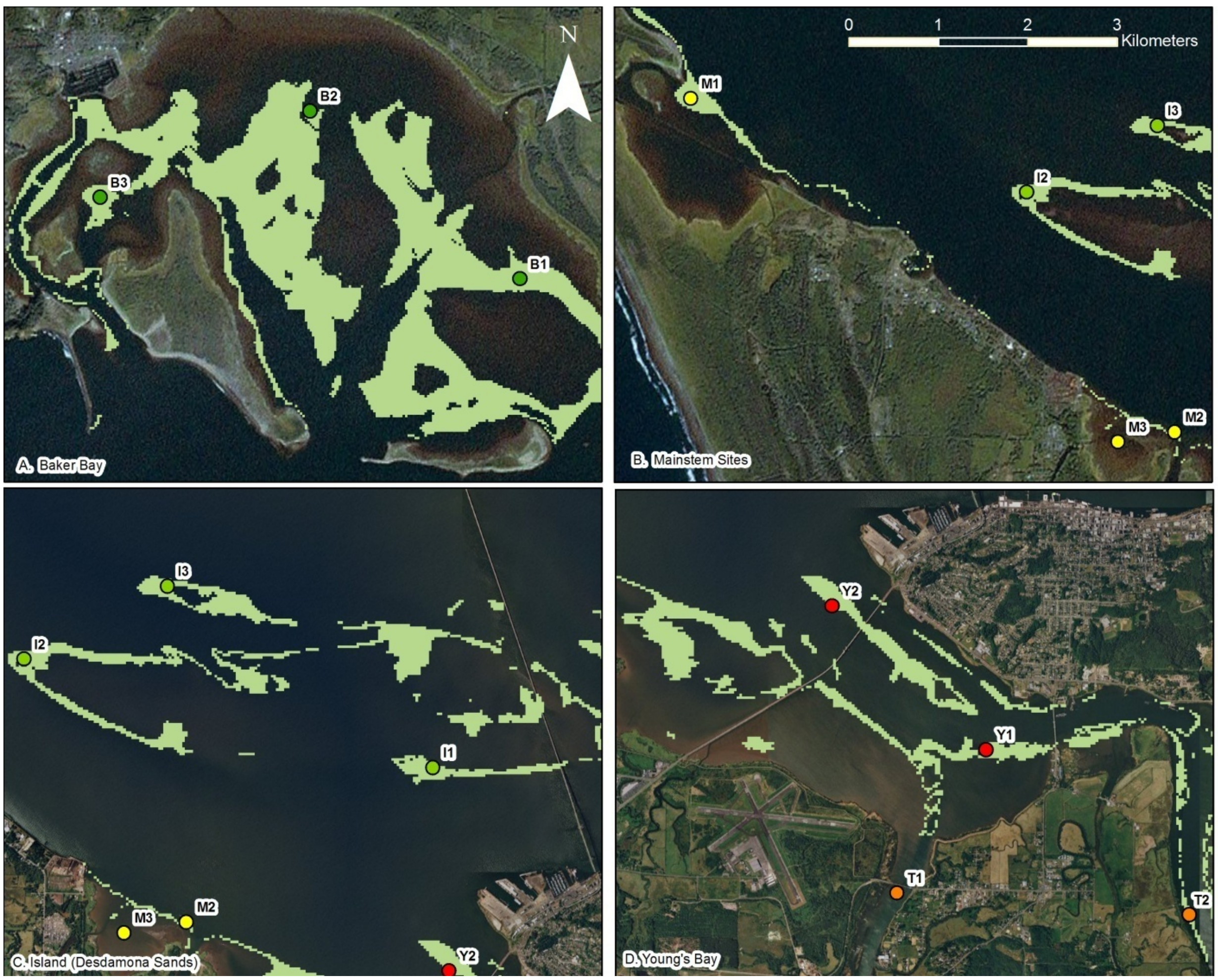
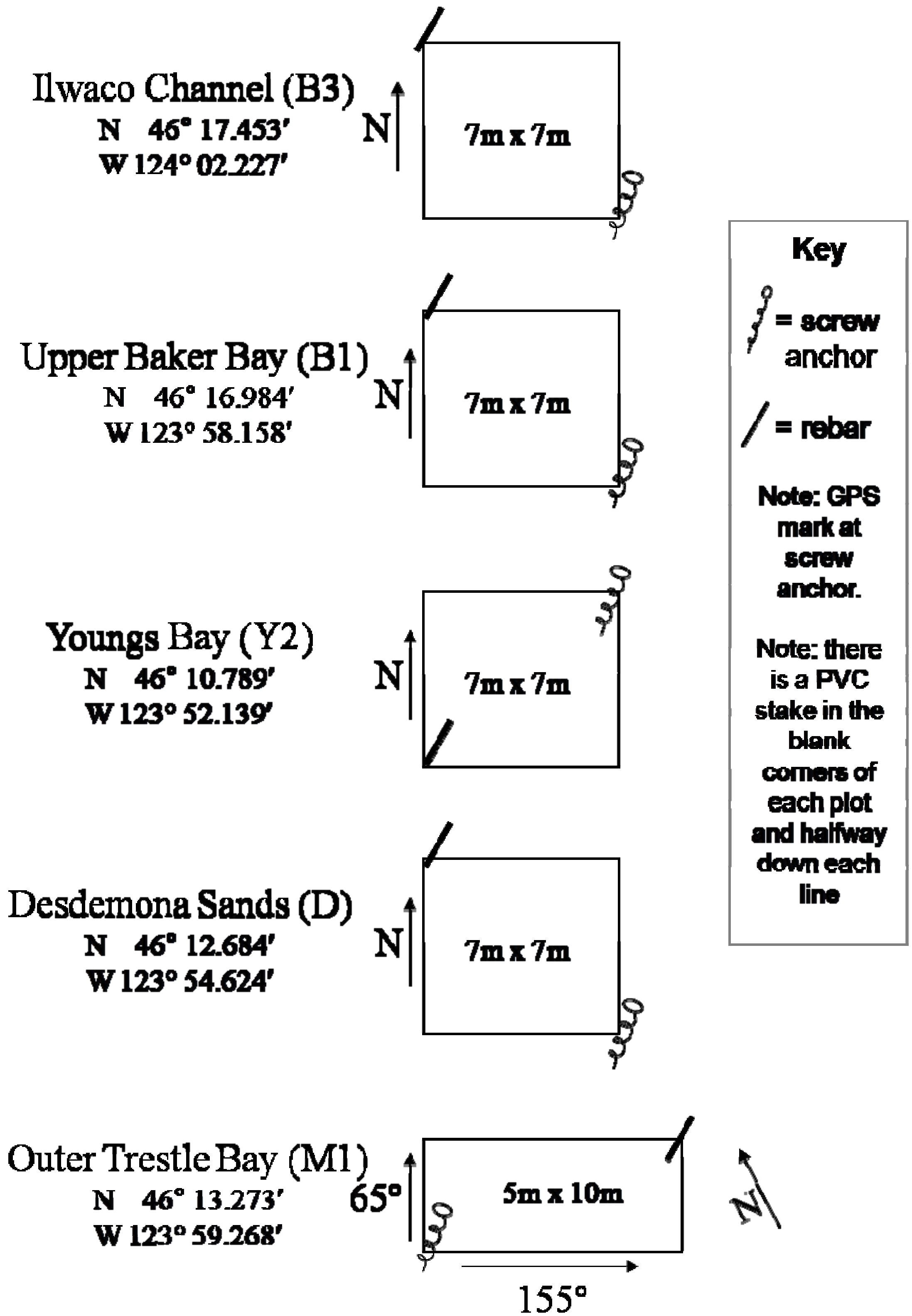


Figure B. Sites visited on site assessment trip, include (A) Baker Bay, (B) Mainstem sites, (C) Island Sites, and (D) Young's Bay and its tributaries sites.

Table B-1. Field crew comments from potential restoration sites. Sites selected for planting are highlighted in green.

Sites	Location	Field Crew Comments	Result
B1	Baker Bay	• Very small patches of eelgrass in vicinity • More eelgrass across channel • Could be a good site to plant	Site selected for planting
B2	Baker Bay	• One *Zostera marina* shoot at site • Substrate has fines on top, but firm beneath • Site difficult to access	Not selected for planting. Site is difficult to access, and other areas available.
B3	Baker Bay	• No eelgrass at site • Substrate is mixed fines, appears appropriate • No apparent reason that eelgrass is absent	Site selected for planting
M1	Mainstem	• Site is exposed at +1 MLLW • Channel on side of flat appears possible • No eelgrass	Site selected for planting, but moved to channel
M2	Mainstem	• Habitat type would be narrow and fringy • Tide too high to observe bottom (can't say if eelgrass is present) • Concern over navigation channel traffic	Not selected for planting
M3	Mainstem	• Flats exposed • Channel is brown with tannins • No eelgrass observed	Not selected for planting
I1	Desdemona	• Currents not strong, but likely exposure • No eelgrass present	With concern over wave exposure from channel traffic, a new site was selected (D1), which was in a more protected area.
I2	Desdemona	• Channel exposed to wave energy • Very sparse eelgrass present	
I3	Desdemona	• Very exposed on both sides • Patchy eelgrass south of site in protected area	
T1	Tributary	• Though model showed salinity intrusion, site appears to have freshwater • Observed Milfoil, *Patomogeton zosteraforma* and Ruppia spp.	Not selected for planting. Freshwater habitat.
T2	Tributary	• Site has freshwater SAV	Not selected for planting
Y1	Young's Bay	• Eelgrass bed present at approximately 1m MLLW • Freshwater species observed from 0 to -0.3m	Not selected for planting, eelgrass bed present.
Y2	Young's Bay	• No eelgrass observed at site, but bed across channel.	Site selected for planting


Ilwaco Channel (B3)
N 46° 17.453′
W 124° 02.227′
N
7m x 7m
Upper Baker Bay (B1)
N 46° 16.984′
W 123° 58.158′
N
7m x 7m
Youngs Bay (Y2)
N 46° 10.789′
W 123° 52.139′
N
7m x 7m
Desdemona Sands (D)
N 46° 12.684′
W 123° 54.624′
N
7m x 7m
Outer Trestle Bay (M1)
N 46° 13.273′
W 123° 59.268′
65°
5m x 10m
155°
N
Key
= screw anchor
= rebar
Note: GPS mark at screw anchor.
Note: there is a PVC stake in the blank corners of each plot and halfway down each line

Appendix C: Monitoring Field Notes for Eelgrass

West Baker Bay (B3) This site off the Ilwaco channel was surveyed during a falling tide close to the slack low in order to access the site. The marking buoy was attached and visible at the surface to provide easy identification of the site. The site appeared to be undisturbed and still fairly sandy, but very little eelgrass was still present. The divers only documented eight shoots in the plot (survival rate = 0.65%). These shoots were generally pretty small, at approximately 10cm long. None of the initial staples were found, which were used to anchor eelgrass, but most of the markers at the site were still present.

East Baker Bay (B1) This location farther up into Baker Bay was harder to find because the marking buoy was missing, but the divers were able to locate the markers that included the screw anchor, rebar, and many of the PVC stakes. There was still eelgrass present at this site and while divers could see some of the initial checkerboard pattern there did appear to be some new growth. Eelgrass was also present outside the plot in low numbers. Both the eelgrass inside and outside the experimental plot appeared to be a mixture of sizes, with some long healthy shoots and some smaller individuals (could have been *Zostera japonica*). The currents at the site prevented differentiating between the morphological types in the survey counts or proper identification of the species. Eelgrass densities were 10.9 shoots m^{-2} ($\pm$ 8.75 SD) yielding an estimated 535 shoots in total. This equates to approximately 43.6% survival over the first year. Divers also noted at least three flowering shoots.

Trestle Bay (M1) Access to the Trestle Bay plot was initially difficult due to the low water and sand flats surrounding the site, but the divers were able to walk in, find the marking buoy, and delineate the site. Markers at all four corners were located. The survey of the area yielded no eelgrass shoots or staples in or around the experimental plot. The divers observed that the substrate was flocculent and easily disturbed.

Desdemona Sands(D1) The marking buoy was also missing from this location but the divers were able to locate the screw anchor and rebar stakes during a search. All the PVC stakes were missing. Evaluate of the site only yielded three small eelgrass shoots (survival = 0.24%). Divers did notice a lot of staples, many in the identifiable checkerboard planting pattern, throughout the experimental plot. None of these staples had any eelgrass attached and many were exposed 0.5cm or so on top, suggesting the site has eroded since planting. No staple was noticed with the three shoots found. Divers also noted sand ripples in the substrate associated with strong currents.

Young's Bay (Y2) The Young's Bay site had the most eelgrass of any site visited during this trip, both inside and outside the experimental plot. The location of the site was verified by the marking buoy and many of the markers on the bottom. The planted checkerboard pattern of the eelgrass within the plot was only noticeable at times, suggesting a lot of new growth had occurred in the past year. Eelgrass density in the experimental plot was 133.1 shoots m^{-2} ($\pm$ 42.8). This extrapolates to approximately 6524 total shoots and 533% survival in the first year. Eelgrass appeared healthy, although it got patchier in the northern part of the study area.

Appendix D: Monitoring Results from Eelgrass Restoration Projects

Location	Transplant Method	Study Period	Initial Planting	Shoot Survival	Reference
Keil Cove, San Francisco Bay	Rhizosphere Core Method	1 Year	160 cores total	30%	Zimmerman *et al.* 1995
Paradise Cove, San Francisco Bay	Rhizosphere Core Method	1 Year	160 cores total	10%	Zimmerman *et al.* 1995
Bellingham Bay, #1	Diver	1 Year	640 shoots	170.40%	Stutes *et al.* 2009
Bellingham Bay, # 2	Diver	1 Year	640 shoots	114%	Stutes *et al.* 2009
Bellingham Bay, # 3	TERFs	1 Year	1536 shoots	59.70%	Stutes *et al.* 2009
Bellingham Bay, # 4	TERFs	1 Year	1536 shoots	18.70%	Stutes *et al.* 2009
Tod Inlet Victoria, BC # 1	TERFs	3 Months	1,800 shoots	24.70%	Albrecht 2002
Tod Inlet Victoria, BC # 2	TERFs	3 Months	281 shoots	9.30%	Albrecht 2002
Tod Inlet Victoria, BC # 3	TERFs	3 Months	2,176 shoots	30.70%	Albrecht 2002
Weymouth, Boston	TERFs	1 Year	1,000 shoots	40.6% (after 1 month)	Estrella 2007
Long Island South, Boston	TERFs	1 Year	1,000 shoots	66.6% (after 1 month)	Estrella 2007
Long Island South, Boston	Hand Planting	1 Year	1,000 shoots	69.6% (after 1 month)	Estrella 2007
Peddocks East, Boston	Hand Planting	1 Year	1,000 shoots	88.6% (after 1 month)	Estrella 2007
Hidden Harbor Marina, BC	Shoots	1 Year +	NA	28%	Thom 1990
Blaine Marina, WA	Plugs	8 Months	NA	8%	Thom 1990
Padilla Bay, WA	planted Shoots in pots and in plots		1 Year +	~100% for pots; 20% for plots	Thom 1990
Dakota Creek, WA	Shoots	1 Year	NA	80% survival at low elevations; <30% at higher elevations	Thom 1990
Smith Cove, WA	Plugs	2 Years +	NA	0%	Thom 1990
Magnolia, WA	unknown	1 Year	NA	0%	Thom 1990
Siuslaw River, OR	Shoots	1 Year	NA	90%	Thom 1990
Bodega Harbor, CA	shoot bundles	2 Years	NA	40% survival on tidal flat; 5% survival on channel banks	Thom 1990
Richmond Harbor, San Francisco Bay, CA	shoot bundles	13 months	NA	~0%	Thom 1990

Appendix E: Dungeness Crab Usage Study

Dungeness Crab Use of Shallow Water Habitat in the Columbia River Estuary

Curtis Roegner, NOAA Fisheries

Background

Benefits of an enhanced or restored eelgrass bed include feeding and refuge space for a variety of marine organisms. Here we assess the functional improvement of habitat by comparing use by Dungeness crabs (*Cancer magister*) of shallow subtidal vegetated and unvegetated areas. The Columbia River estuary (CRE) serves as an important nursery for this commercially important crustacean (Emmett and Durgin 1985; Armstrong et al. 2003). However, estuarine habitat types provide unequal benefit for vulnerable crab life stages. Settling larvae and young-of-the-year, or 0+ age, crabs strongly prefer areas of structural complexity, such as intertidal eelgrass beds and shell hash, over unstructured substrate (Fernandez et al. 1993; McMillan et al. 1995). Predation by a variety of fish and invertebrates, including conspecifics, is extremely high in habitats that lack adequate cover (Fernandez et al. 1993). 0+ aged crabs occur both sub- and intertidally in the CRE and other estuaries (Emmett et al. 1983; Stevens and Armstrong 1982), but intertidal habitat in many estuaries appears to offer an important refuge for 0+ crabs compared to subtidal environments where predation pressure is intense (Dumbauld et al. 1993). As crabs grow larger (>30 mm or so), they tend to leave intertidal areas of structural complexity and reside in shallow subtidal areas (Armstrong et al. 1987), from where they forage in intertidal zones during nighttime high water periods (Holtsman et al. 2006). Many crabs eventually migrate from the estuary to the ocean after their second year (>2+ age), and male crabs from estuaries can form an important component of the regional crab fishery after 4+ age (Armstrong et al. 2003).

The CRE is an environment of great spatio-temporal variability in physical factors that influence crab distribution and growth. Salinity ranges are extreme; tidal variation can cause 30 psu changes in a 6 h period, and during the spring freshet salinities can be reduced for extended periods (Roegner et al. submitted). This variation affects crab distribution and behavior, as crabs become inactive at salinities < 12 ppt (McGraw et al. 1999). Another important variable is dissolved oxygen, which at low levels impairs mobility and feeding (Bernatis et al. 2007). In contrast, temperature affects metabolic processes and growth rates of crabs but ranges are generally not limiting to crabs in the CRE.

The link between ontogeny and habitat preference indicates critical habitat for juvenile crabs may be limiting in the in the CRE, since bivalve shell deposits are rare and eelgrass beds are not extensive. The abundance of these habitats in the intertidal appears especially lacking, which may limit the utility of the littoral zone as a predation refuge for the smallest crabs. As a consequence, McCabe et al. (1988) found few juvenile crabs in unstructured intertidal zones of the CRE. Subtidal eelgrass beds may offer an important alternative habitat for young crabs. Thus, one potential benefit of an eelgrass enhancement project is an increase in the survival of 0+ aged crabs in subtidal eelgrass over the surrounding unvegetated substrate.

Methods

Bated crab traps were used to sample for *Cancer magister* abundance and size. We used collapsible Fukui fish traps (60 by 45 by 20 cm with 12 mm mesh) baited with herring or sardines; these traps are effective at retaining crabs > 15 mm (J3 stage), and are a standard sampling gear for crab research in the Pacific Northwest (e.g. Yamada et al. 2005; Holsman et al. 2006).
Traps were deployed at high water and fished for 23-25 h. Samples were collected at 2 week to 1 month intervals from June through October 2008 and from February though the present (this report includes data acquired up to July 2009).

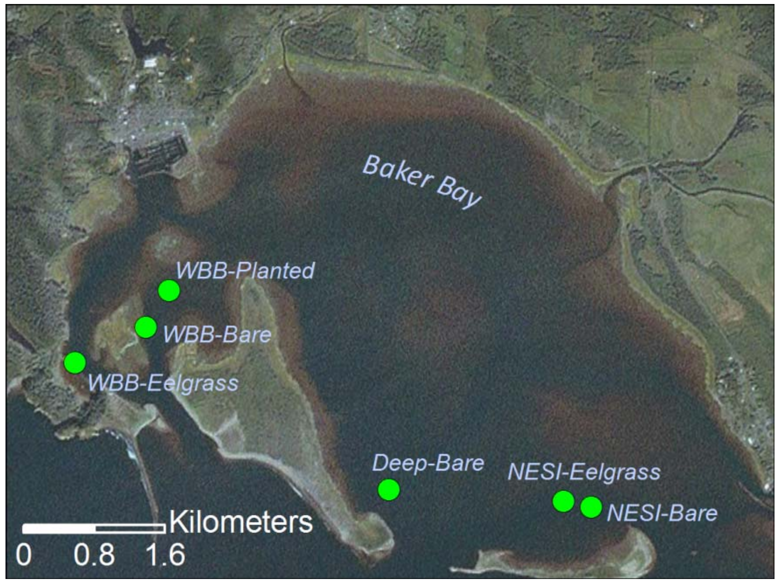


Figure E - 1. Study deployment sites for crab traps

Crabs were counted, measured (carapace width at the 10^{th} anterior spine), sexed, appraised for appendage loss, and returned to the site of capture.
The intended experimental design compared utilization by crabs (measured by catch per unit effort, CPUE) and size of crabs at unvegetated, natural eelgrass, and transplanted eelgrass habitats. However, the eelgrass transplant treatments proved too small for adequate replication. We therefore primarily compared natural eelgrass and unvegetated treatments, with traps in and surrounding one transplant site. We studied two sites in Baker Bay, near the mouth of the Columbia River (Figure E - 1). Baker Bay routinely supports the highest crab abundances in the CRE (Emmett et al. 1984; McCabe et al. 1988). One site was located in West Baker Bay (WBB), adjacent to the Ilwaco channel, and included unvegetated, eelgrass, and transplant treatments. The second site was located north of East Sand Island (NESI), where we compared unvegetated and eelgrass habitats. In spring 2009, we added a deep water (20 m) station north of West Sand Island. All other sites were in shallow subtidal zones situated approximately 2 to 4 meters below MLLW. Sites were also located within 100 m of intertidal sand banks where larval crabs settle from the plankton and juvenile crabs find shelter (Stevens and Armstrong 1984; Armstrong et al. 1987). Three replicate traps were deployed within each habitat type. We also measured vertical profiles of temperature (^{o}C), salinity (psu), and dissolved oxygen concentration (mg/L) upon trap retrieval. Temperature loggers deployed at both sites are still operational at the time of this writing.

We computed time series of mean CPUE and mean size per deployment for each treatment at both sites. ANOVA was used to test for differences in mean CPUE between habitat types. Regressions of mean size by day of year were made to compare relative growth rates. Crab year class (cohort age) can be estimated by carapace width (Armstrong et al. 1987). We used the size- frequency of crabs to determine cohort age for each of the six treatment plots, first for the entire sample and then as a time series for crabs pooled into two-month bins. We evaluated the sex distribution, percent limb loss, and incidence of multiple limb loss of crabs categorized into 50 mm size intervals. Finally, to investigate trends of habitat use with physical variables, we calculated regression statistics for mean crab CPUE and size by day of year, and temperature, salinity, and dissolved oxygen concentration measured at the benthos.

Results

Mean crab abundance varied from 0 to 15 crabs per trap at NESI and 0 to 26 crabs per trap at WBB (Figure E - 2a,b). There was generally high variation between replicates, which precluded detecting differences between treatments. Crab abundance was low or zero at all sites during February through May, increased from June through September, and subsequently declined at NESI while remaining high at WBB. Overall mean abundance was nearly identical between treatment plots (ANOVA, $p>0.1$) (Figure E - 3). There was also no significant difference between treatments for crab <50 mm. Mean crab size increased linearly with time over the measurement interval (Figure E - 2c,d). There were few consistent differences in mean size per time within a site, except the deep unvegetated site which was

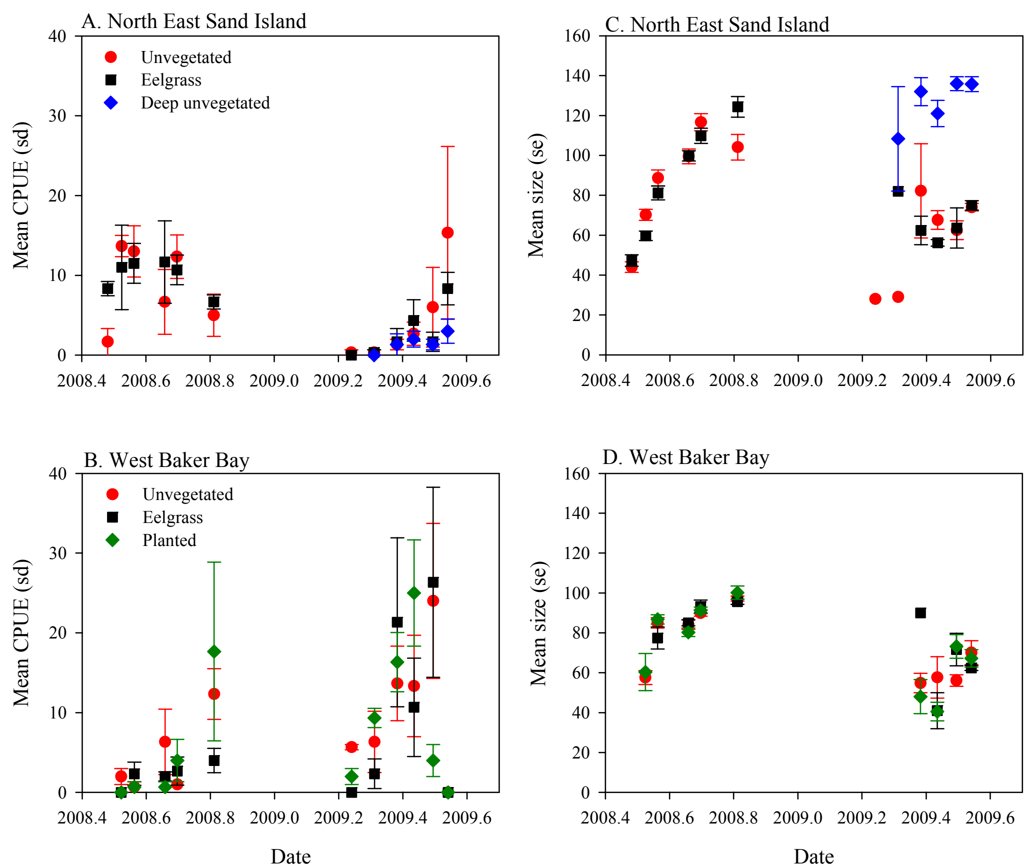


Figure E - 2. Temporal variation of CPUE and size. Left column: Time series of mean crab CPUE at NESI (A) and WBB (B). Right column: Time series of mean crab size at NESI (C) and WBB (D).

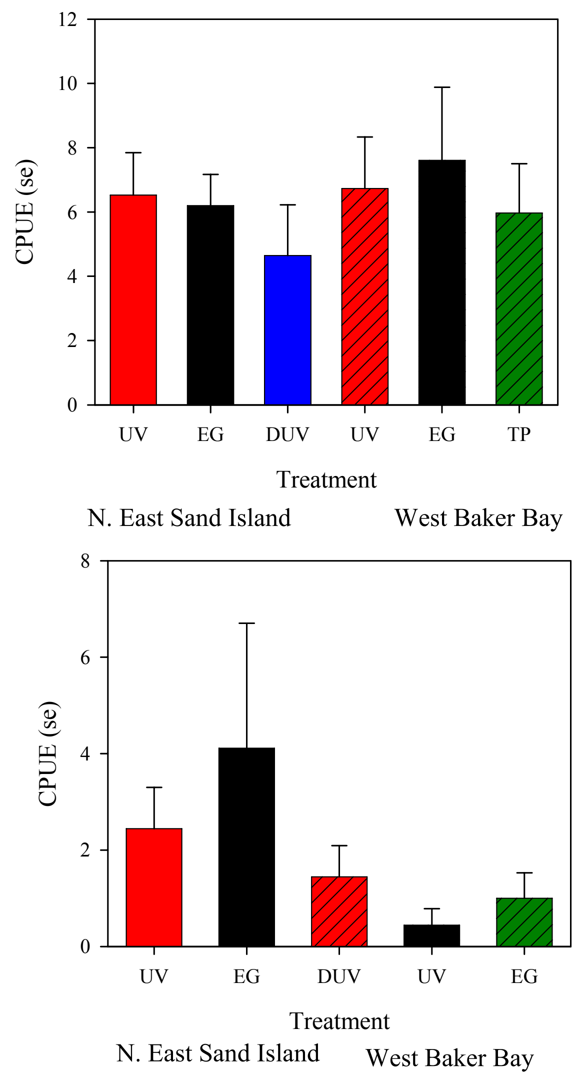


Figure E - 3. Comparison of mean CPUE by habitat type. Top: Mean crab CPUE by treatment and site. Bottom: Mean crab CPUE < 50 mm by treatment and site.

occupied by much larger individuals than the shallow sites. Based on linear regressions, the mean size of crabs at a given time was larger at NEST than at WBB. A mean size of 86 mm (the averaged size of all crabs measured during the study) occurred around day 220 at NEST but not until 250 at WBB. Estimated growth rates ranged from 0.20 to 0.41 mm/d.

The size frequency of the crab population was not normally distributed (Chi square, $p<0.001$). There was low abundance of crabs > 115 mm (Figure E - 4). Based on the size ranges encountered (Armstrong et al. 1987), less than 5% of the crabs were young of the year. The population was composed mostly (83%) of 1+ and 2+ year aged crab, with the remainder evenly split between 3+, 4+ and 5+ cohorts. Legal size for recreational fishing is 147 mm, and few crabs above that limit were found.

Pooled size frequency histogram plots show differences between treatments (Figure E - 4). The unvegetated site at NESI tended to have a greater distribution of 2+ crabs than the eelgrass site. Both sites had low numbers of older crabs. The deep unvegetated site was composed mostly of larger >2+ year old crabs. At WBB, the unvegetated site had lower numbers of 1+ crabs than the other sites; all three sites had few crabs > 2+ age.

Time series of size frequency histograms show growth or changing habitat used based on size. (Figure E 5-6) At NESI, 1+ and 2+ crabs were abundant during June and July of both 2008 and 2009, but the size distribution switched to mostly 2+by August and September. Abundance of all cohorts declined in October- November. A similar pattern was observed at WBB, except >2+ crabs remained abundant through October and November.

We evaluated the sex distribution, percent limb loss, and incidence of multiple limb loss of crabs categorized into 50 mm size intervals (Figure E - 7a). The sex ratio was near unity for all size classes except those > 125 mm, which was dominated by males. Overall 53.4% of measured crabs were male. The percent limb loss increased with increasing size for both males and females, reaching 35.7% of large males and 28.7% of large females (Figure E - 7b). Overall, ~10% of the population had lost at least one limb. Males were much more likely to have multiple limb loss than females, and males in the 50 to 100 mm size range suffered higher incidence than larger males (Figure E - 7c).

Finally, to investigate trends of habitat use with physical variables, we computed regressions of mean crab CPUE and mean crab size by day of year, and temperature, salinity, and dissolved oxygen concentration measured at the benthos (Figure E - 8). Regression of mean CPUE with time, temperature, and salinity all resulted in significant p values and positive regression slopes; however, the explained variance was low. Day of year was the best predictor of CPUE, since catches were zero or low during spring and highest in late summer or autumn. Most samples were clustered at temperatures between 16 and 18 ^{o}C, and mean CPUE of crabs caught in that range varied between 1 and 26 ind. Bottom salinity ranged from 3 to 33 psu, and crabs were captured throughout this range, but highest abundances were found between 9 and 16 psu. Most of the low catches occurred at salinity below 9 psu. Oceanic values of salinity were only found at the deep station. Abundance was not significantly related to oxygen concentration. Values were always > 70% saturated at the shallow stations, but below 40% saturation at the deep site on two occasions. These low values are stressful for crabs and other fauna.

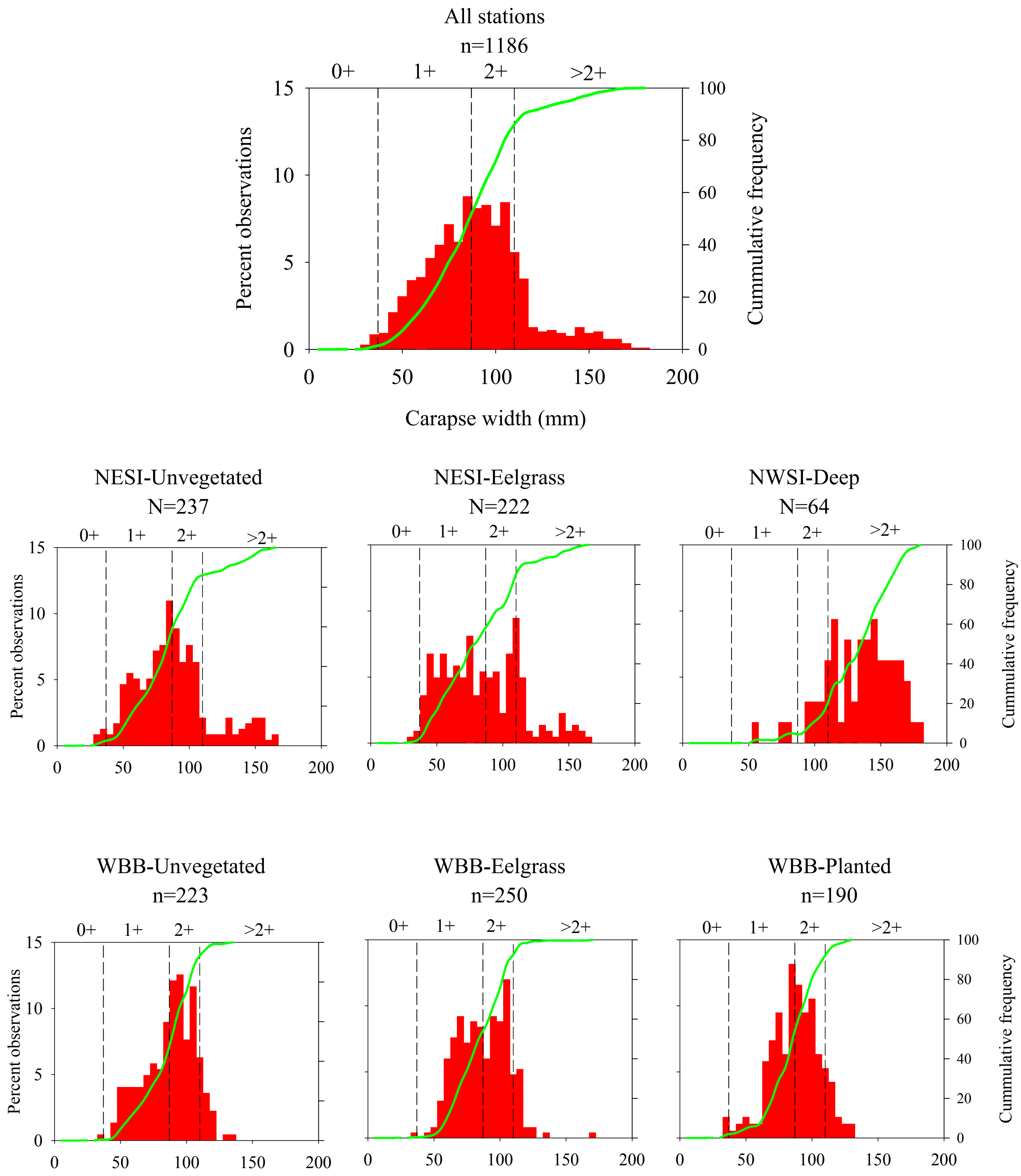


Figure E - 4. Percent size frequency histogram (bars) and cumulative frequency plot (green line) in relation to estimated age class of crabs. Top: All crabs. Middle row: Treatment plots at NESI. Bottom row: Treatment plots at WBB. Number of observations is given.

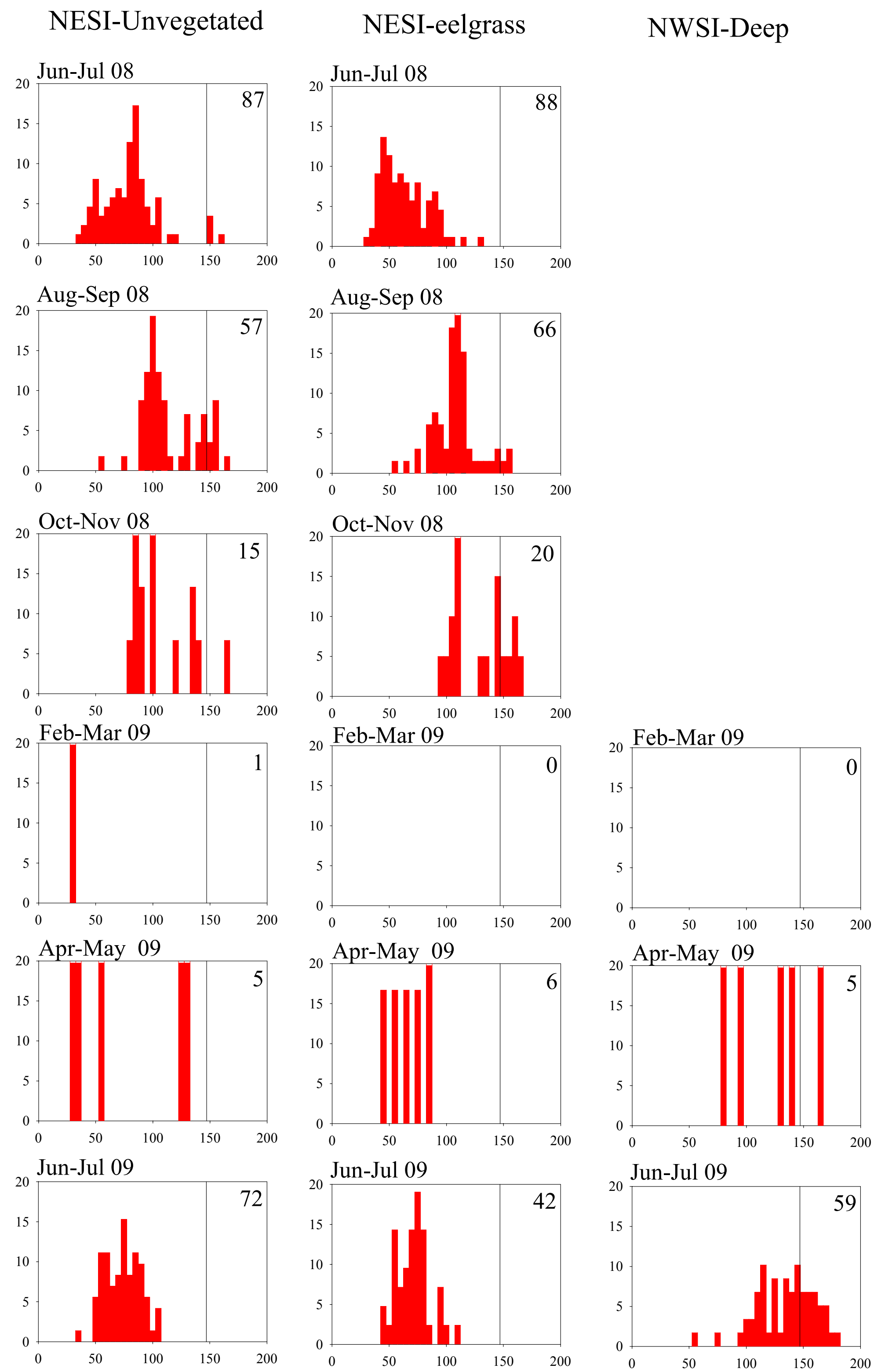


Figure E - 5. Percent size frequency histogram (bars) at NESI. Data for each plots are binned into 2-month time periods as shown. Vertical line is legal size limit. Number of observations is given.

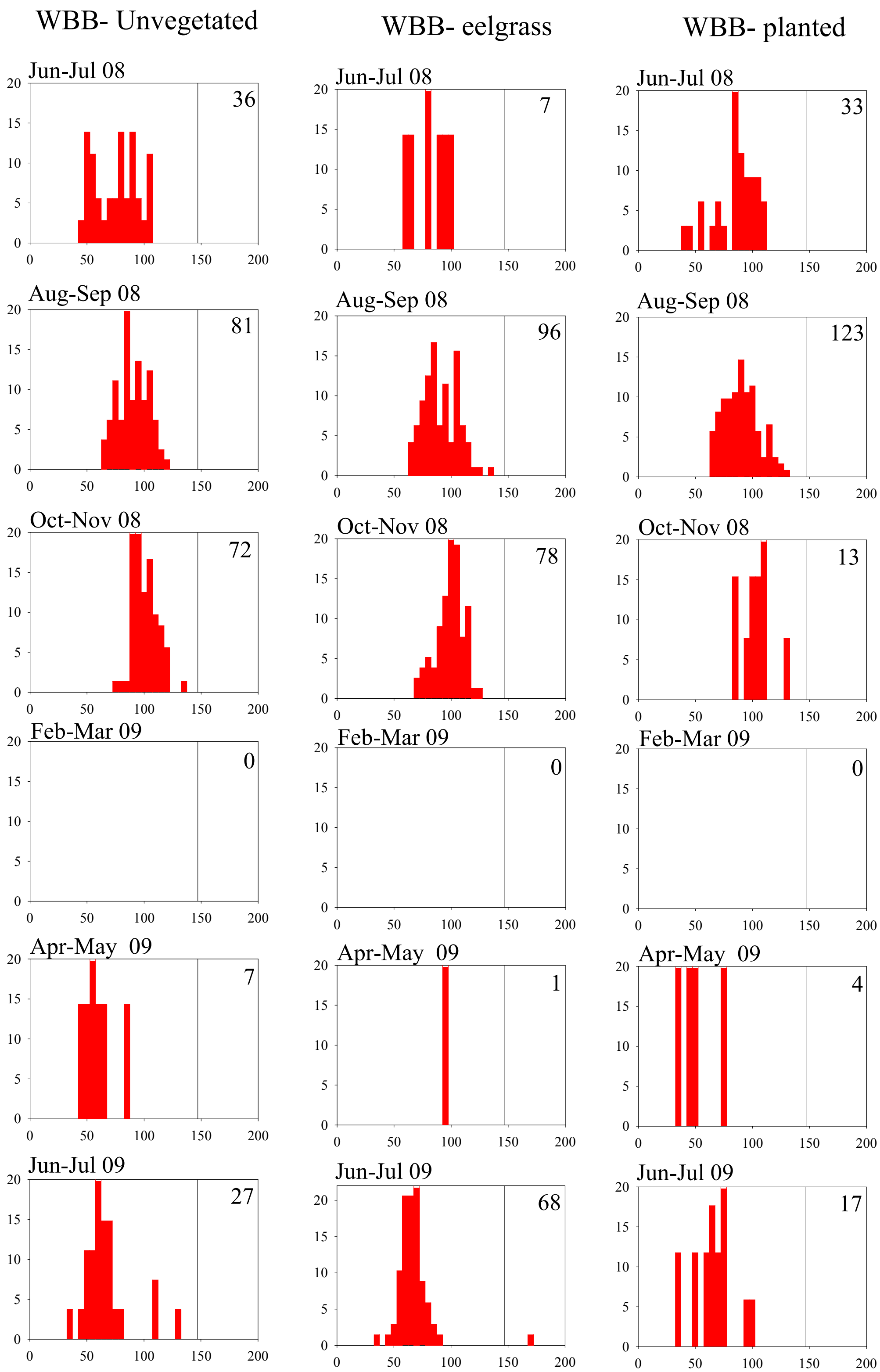


Figure E - 6. Percent size frequency histogram (bars) at WBB. Data for each plots are binned into 2-month time periods as shown. Vertical line is legal size limit. Number of observations is given.

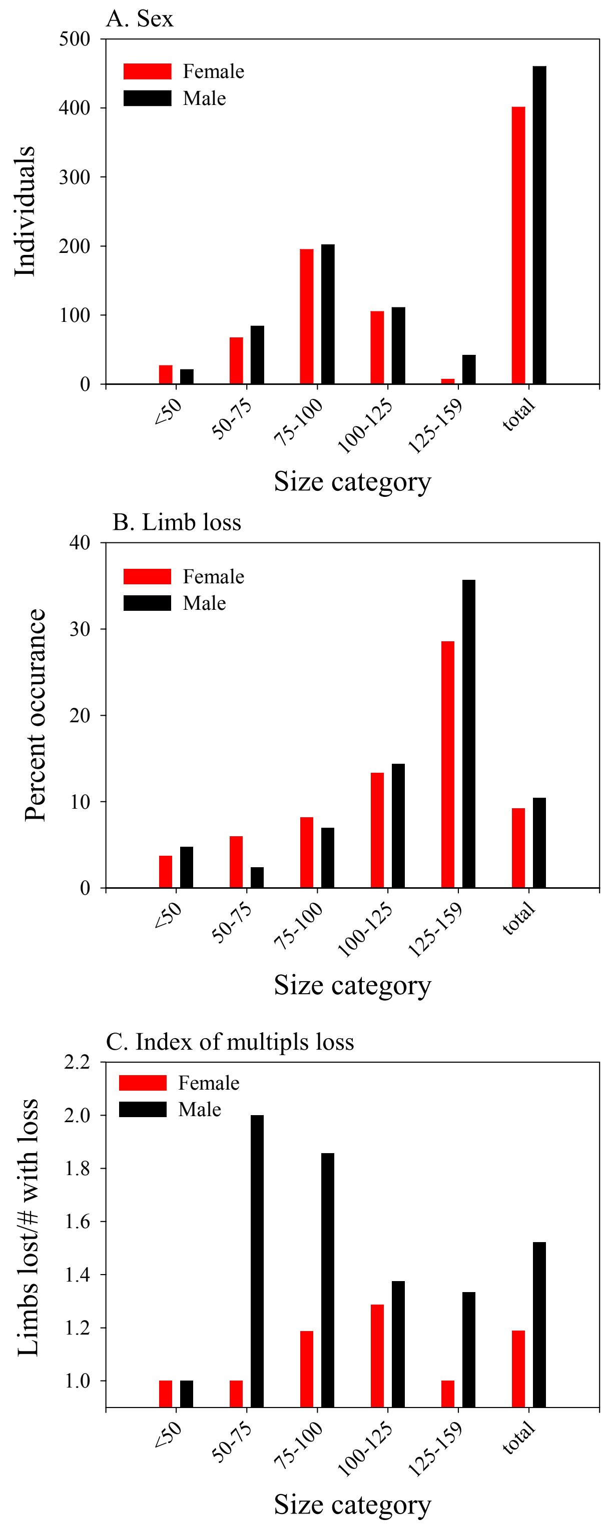


Figure E - 7. Sex and limb loss by size category. A. Sex. B. Percent limb loss. C. Index of multiple limb loss (Number of limbs lost/individuals with limbs lost; 1.0 = 1 limb lost per crab).

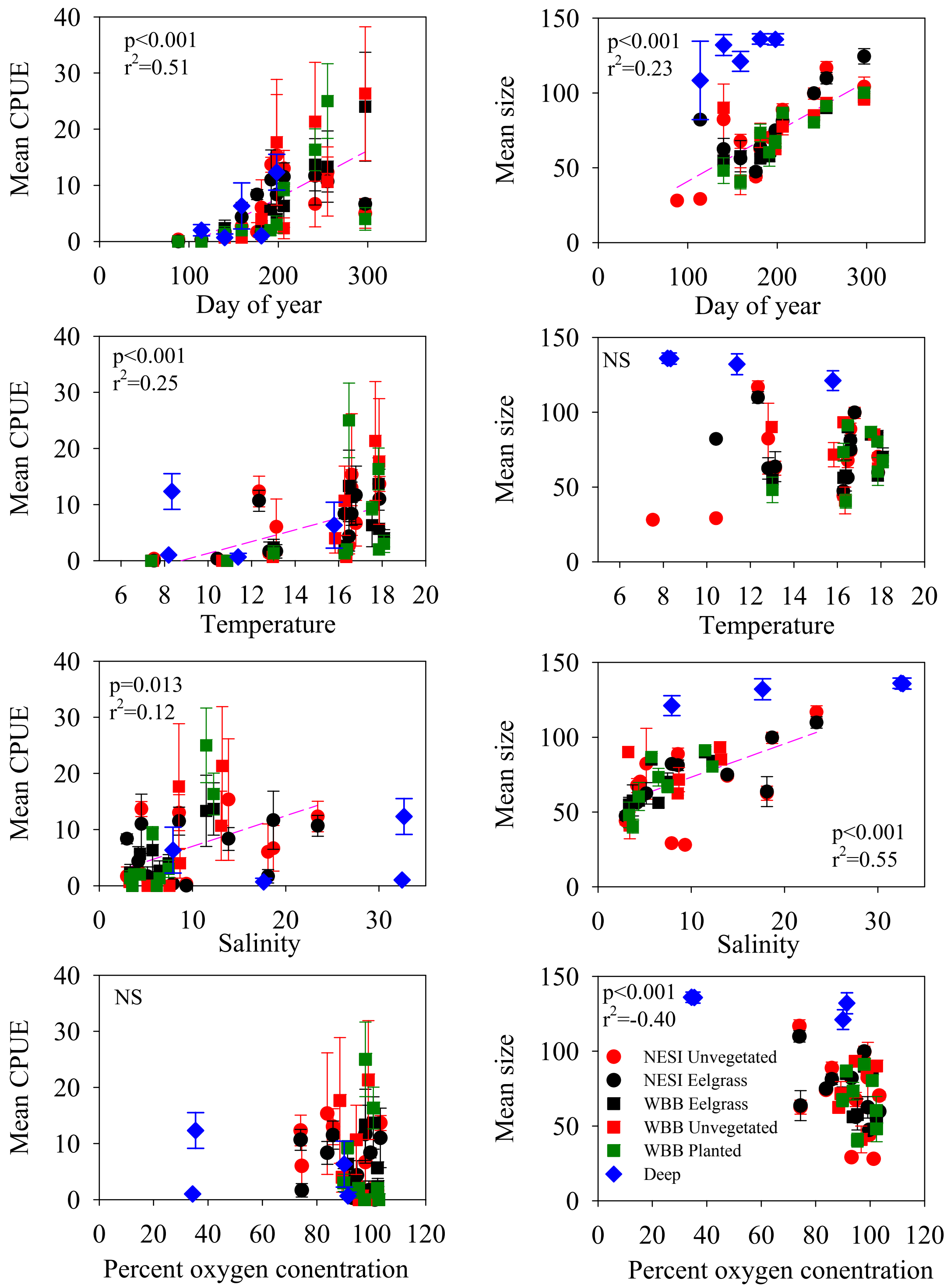


Figure E - 8. Crab mean CPUE (left column) and mean size (right column) by day of year, temperature (C), salinity (psu), and percent oxygen concentration (% saturation). Probability value and r^2 given for significant regressions (computed for combined treatments excluding the deep station).

Regression of mean size with time, salinity, and percent oxygen concentration all resulted in significant p values (Figure E - 8). Again, explained variance was low. As discussed above, mean size increased linearly with time with the largest crabs found in autumn. Larger crabs were also tended to be caught in higher salinity, but again most crabs were sampled in < 16 psu water. Size was negatively related to oxygen saturation, but values were within acceptable ranges except at the deep site. Crab size was not significantly related to temperature.

Discussion

Shallow subtidal areas in Baker Bay were primarily occupied by 1 and 2 year old crabs. Only 85 crab < 50 mm were present at our shallow water sampling sites, and ANOVA did not detect a significant difference in the number of small crabs between treatment sites. A more variable abundance of >2+ crabs were found, and larger crabs predominated in the 20 meter site. Other studies sampling crabs by bottom trawl (Emmett & Durkin 1985; McCabe et al. 1988) or beach seine (personal observation) have found high densities of 0+ age crab in subtidal sites in the CRE, so it is evident that subtidal settlement and juvenile growth does occur. However, the low numbers found during our data does not support the hypothesis of increased abundance of 0+ crab in subtidal eelgrass beds compared to unvegetated sites.

Ontogenic changes in habitat use are well established for Dungeness crabs. Based on recruitment data from Grays Harbor (Stevens et al 1983; Armstrong 1987), we would expect to see a influx of >30 mm crabs to the subtidal in late summer as crabs grow to a size refuge that allows them to move out of structured intertidal habitat. This movement may be accompanied by a diet switch from small bivalves and worms to one based more on crangon shrimp and juvenile fish (Stevens et al. 1982). Several possible reasons could account for low 0+ abundance found in our study. First, McCabe et al. (1984) found low intertidal habitat use in Baker Bay intertidal transects (albeit sampling effort was minimal). Larval settlement is a highly variable process (Roegner et al. 2007), and there may have been low recruitment to Baker Bay during 2007 and 2008. Interestingly, size frequency histograms from trawl survey data compiled by Emmett & Durkin (1985) resemble our data for 1973 (i.e. without many crabs < 50 mm), but not in 1980, when a clear 0+ cohort was present. Brown & Terwilliger (1992) found the first crab instars had less osmoregulatory capacity than megalopae or adults, and the low salinity levels in Baker Bay may have reduced juvenile survival. Alternatively, during our study small crabs may have avoided the traps, although we did not evaluate this possibility. For larger crabs, overall patterns of patterns of abundance exhibiting peaks in autumn and troughs in spring were similar to that found by McCabe et al. (1988).

Sex ratios in our study were near unity except for the largest size class (>125 mm), which were predominantly male. In contrast, Durkin et al. (1984) using commercial traps in deeper main stem channels found 89% of sampled crab (range 62-162 mm) were male. These were generally larger crabs (mean size 136 mm) than our study, and this skewed pattern may reflect the migration of adult female crabs (>130 mm or so) from the estuary to the near shore zone. These large crabs also experienced a higher degree of limb loss and in our study (66% vs about 10%). It would appear larger crabs are more susceptible to limb loss. Males in our study also had a higher incidence of multiple limb loss than females. It is not known if this is a consequence of antagonistic behavior or predation events.

Physical variables explained relatively little of the variation in mean CPUE or size of Cancer magister in the CRE. However, it is important to note that water parameters vary widely on both tidal and seasonal time scales in the CRE, and values recorded at the time of sampling do not necessarily characterize well the cumulative or synergistic conditions experienced by crabs. Continuous time series would offer more complete appraisal of the physical habitat. Regardless, two of the water parameters we sampled had values of concern for crab biology. Cancer magister is a weak osmoregulator and becomes inactive at low salinities. Salinity levels in the shallow areas of Baker Bay were often < 12 psu at high tide, which is the value reported to induce physiological and behavioral avoidance behaviors in Dungeness crabs (Sugerman et al. 1983; McGaw et al. 1999). Sugerman et al. (1983) found crabs reduce pumping water over the gills to reduce ionic loss at 23 psu, and cease pumping at 16 psu. Salinity gradients are strong in Baker Bay. Low salinity persists in shallow areas in winter/spring, and fluctuates greatly over a tidal cycle in summer/autumn. Crab activity in Baker Bay is probably keyed to mesohaline and greater salinities, which may explain the high abundances in traps in summer and fall. Deeper areas are more consistently high salinity.

The other parameter of concern was the low dissolved oxygen concentrations encountered at the deep site. Low DO in the estuary is due to the influx of high salinity upwelled water from the ocean (Roegner, in review). Bernatis et al. 2007 found Dungeness crabs are relatively tolerant of DO levels > 47% saturation (which more tolerant than most crustaceans). Crabs reduce food intake in hypoxia, and while they may forage in low DO areas, they move to higher O2 concentrations for digestion (which consumes oxygen). Stone & O'Clair (2001) found adult crabs in Barkley Sound remained in water > 50% saturation. The incidents of low DO water in the CRE is expected to be highest during the upwelling season (March-October). It is presently unknown what effect low DO will have on crab distributions and growth.

In conclusion, we failed locate the young-of-the-year Dungeness crab we hypothesized to be utilizing subtidal eelgrass beds. Identifying the habitat of these new recruits in Baker Bay will require further study. However, the shallow water, "lower side channel" habitat we investigated is recognized to be important rearing areas for subadult Dungeness crab (Rooper et al. 2003; Armstrong et al. 2003). We found both NESI and WBB to have relatively high abundances of 1+ and 2+ crabs with a lower number of older individuals. The steep decline in abundance of crab >110 mm can be attributed to molting to the first adult instar and migration from the estuary to the nearshore zone (Emmett & Durkin 1985; Armstrong et al. 1987). These shallow areas in our study appear to be important nursery areas, and may comprise staging grounds for crabs to ascend to intertidal feeding areas during nocturnal high tides (Stevens & Armstrong 1983; Holsman et al. 2007).

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Appendix F: Outreach and Public Involvement

During this project, we participated in several activities for education, outreach to the general public and to the scientific community.

- Three undergraduate interns participated in project

- PNNL media liaison worked with BPA for press release.   Article on initial planting was carried in the local Astorian newspaper, http://www.dailyastorian.info/main.asp?SectionID=2&SubSectionID=398&ArticleID=52572&TM=48917.98

- Participation in Poster Session of Lower Columbia River Estuary Conference (March 2008)

  Updated poster entitled: Innovative techniques in restoration: Eelgrass enhancement in the Lower Columbia is attached.

- Estuarine Research Conference, November 2009.
  We will be giving an oral presentation in Estuarine Research Conference's session, "Emerging Science and Restoration in the Pacific Northwest", based on this project.

  Abstract:
  Through the 2007 Innovative Program, funded by the BPA, we are evaluating the ability to expand the current distribution of eelgrass in the Columbia River Estuary for the purposes of enhancing feeding, refuge and rearing habitat for a number of fisheries species including juvenile Pacific salmon and Dungeness crab. We strongly suspect that limited eelgrass seed dispersal has resulted in the present distribution of eelgrass meadows, and that there are other suitable places for eelgrass to survive and form functional meadows.

  We are using a unique, integrated approach to help located and test the suitability of sites for eelgrass. This includes (1) methods to spatially assess habitat quality in order to select potential sites for eelgrass transplant; (2) experimental plantings in five of these selected areas, and (3) evaluation of eelgrass success and Dungeness crab presence in these plots. This integrated project should provide the first predictive maps of sites suitable for eelgrass in the lower estuary.

INNOVATIVE TECHNIQUES IN RESTORATION

Eelgrass enhancement in the Lower Columbia River Estuary

Amy Borde, Chael Judd, Ron Thom, Dana Woodruff, Zhaoqing Yang (PNNL); Curtis Roegner (NOAA Fisheries); Joseph Zhang (UGI)

Pacific Northwest NATIONAL LABORATORY

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Overview

Through the 2007 Innovative Program, funded by the BPA, we are evaluating the ability to expand the current distribution of eelgrass in the Columbia River Estuary for the purposes of enhancing feeding, refuge and rearing habitat for a number of fisheries species including juvenile Pacific salmon and Dungeness crab. We strongly suspect that limited eelgrass seed dispersal has resulted in the present distribution of eelgrass meadows, and that there are other suitable places for eelgrass to survive and form functional meadows.

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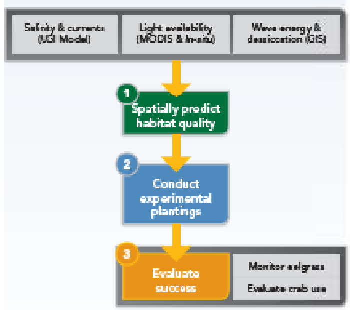
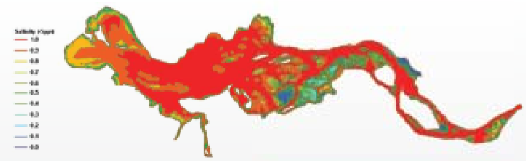


Predict habitat quality: *Identify potential sites by physical characteristics*

Salinity & Currents

Are salinity and currents suitable for growth?

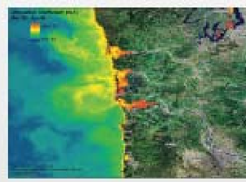
Though eelgrass can survive in freshwater for short periods, optimal conditions are above 5 psu. Using modeled outputs, we can examining frequency that salinity falls below optimal ranges, or when currents become too strong. This helps us identify potential restoration areas.

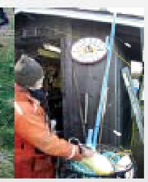


Light Availability

Would a plant receive sufficient light to survive?

Combining satellite imagery (MODIS), and *in-situ* measurements of light (PAR), we are creating a spatial map of areas which receive sufficient light for eelgrass survival.





Disturbance

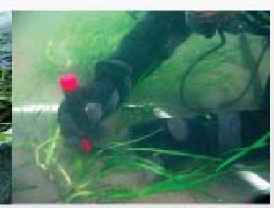
Are there other sources of disturbance that would impact the plant?

Shoreline armoring, wave energy, and other anthropogenic sources may stress plants. Using bathymetry and other GIS datasets, we can determine other local stresses to the species.

Experimental Plantings

Select five areas and plant eelgrass

In June 2008, we will plant eelgrass in five areas selected by the spatial analysis as potential restoration sites.



Evaluate Success

Monitor eelgrass health and crab use of habitat

We will monitor both eelgrass health and function. Juvenile crab use will be monitored pre- and post-restoration in restored areas, unrestored areas, and native beds. In addition, in 2009, researchers will re-visit the restored eelgrass beds to monitor eelgrass density and biomass in the new beds.

Image source: Oregon Department Fish and Wildlife

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