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Eelgrass (*Zostera marina* L.) Restoration in Puget Sound: Development of a Site Suitability Assessment Process

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Abstract

The restoration of eelgrass (*Zostera marina* L.) is a high priority in Puget Sound, Washington, United States. In 2011, the state set a restoration target to increase eelgrass area by 4,200 ha by 2020, a 20% increase over the 21,500 ha then present. In a region as large, dynamic and complex as Puget Sound, locating areas to restore eelgrass effectively and efficiently is challenging. To identify potential restoration sites we used simulation modeling, a geodatabase for spatial screening, and test planting. The simulation model of eelgrass biomass used time series of water properties (depth, temperature, and salinity) output from a regional hydrodynamic model and empirical water clarity data to indicate growth potential. The GIS-based analysis incorporated results from the simulation model, historical and current eelgrass area, substrate, stressors, and shoreline manager input into a geodatabase to screen sites for field reconnaissance. Finally, we planted eelgrass at test sites and monitored survival. We screened 2,630 sites and identified 6,292 ha of highly to very highly suitable conditions for eelgrass—ample area for meeting the 20% target. Test plantings indicated fine-scale data needs to improve predictive capability. We summarized the results of our analysis for the majority of the ~3,220 km of shoreline in Puget Sound on maps to support restoration site selection and planning. Our approach provides a process for identifying and testing potential restoration sites and highlights information needs and management actions to reduce stressors and increase eelgrass area to meet restoration objectives.

Keywords

Zostera marina; eelgrass model; Puget Sound; nearshore restoration; eelgrass transplanting

Author contributions: RT, JG, KB, AB designed the research, analyzed data; JG, AB, JV conducted assessments and plantings; KB refined and ran eelgrass model; LA, JG conducted planner surveys, DW analyzed light data; TK contributed hydrodynamic modeling results; JK contributed initial model; KB, RT, JG, AB, JV, LA, DW wrote the manuscript.

Introduction

Recent global declines in seagrasses have been attributed to anthropogenic stressors (Orth et al. 2006; Waycott et al. 2009), triggering the World Conservation Union (IUCN) to list nearly 25% of the world's seagrass species as endangered or threatened (Short et al. 2011). In Puget Sound, Washington, United States, declines in eelgrass meadows and localized extinctions have been attributed to anthropogenic shoreline modifications, periodic disturbances, and degradation in water quality (Dowty et al. 2010; Thom et al. 2011). In 2011, the Puget Sound Partnership (PSP) established a challenging recovery goal of increasing eelgrass area by 20% by 2020, an approximate 4,200 ha increase from the 2000-2008 baseline of 21,500 acres (Christiaen et al. 2017).

Puget Sound (Figure 1) is a fjord up to 200m deep with generally steep topography and 3,220 km of marine shoreline. It has a tidal range of up to 5m, seasonal river runoff from eight major rivers and hundreds of smaller streams, and substantial urban and rural development (Downing 1983). Eelgrass in Puget Sound forms expansive meadows in large intertidal/shallow subtidal flats and narrow fringe meadows along steeper shorelines.

Because of the size and complexity of Puget Sound and the short time frame for meeting the recovery goal, field studies are insufficient for identifying restoration sites. Hence, we developed a restoration potential geodatabase using hydrodynamic and physiological models; data on substrate, stressors, and eelgrass presence; and observations by resource managers to characterize site suitability. By using simulation models, our database differs from habitat suitability models that have been employed for this purpose in smaller, less complex systems (Short et al. 2002; Bos et al. 2005; Canal-Verges et al. 2016; Hotaling-Hagan et al. 2017).

This paper describes the process we developed (see Figure 2). Full details of our study are provided in a report Thom et al. (2014a).

Methods

Numerical Modeling of Biomass Production

We developed an eelgrass biomass model that accounts for the combined effects of light, temperature, and salinity on net production of carbon to estimate potential for growth at specific locations. Unlike static habitat suitability models (e.g., Short et al. 2002), this dynamic model allows for interactions of controlling factors such as light availability mediating the effects of high temperatures. It integrates environmental conditions over time via simulation rather than summary statistics.

We adapted a model for the tropical seagrass *Halodule wrightii* (Burd & Dunton 2001) for eelgrass in Puget Sound based on initial work by Kaldy & Eldridge (2006; Brown et al. 2007). We focused on aboveground biomass (C) because of limited data for belowground metabolism. The model (Equation 1) includes gross photosynthetic production (P), density dependence with carrying capacity κ , respiration (R), translocation of carbon to roots and rhizomes (τ), and mortality (M ; complete or partial loss of shoots or leaves). We derived

parameters for the model using data collected from eelgrass in the region (Thom 1990, Thom et al. 2003, 2008, 2014b, and unpublished). We modeled respiration as an exponential function of temperature (T) and gross photosynthetic production (GPP) as a function of light (I_z), temperature, and salinity (S). We evaluated candidate models for these functions using Akaike Information Criteria. The best-fit model for the relationship of GPP to temperature was quadratic, with maximum GPP at 15.5°C; for light, the Smith-Talling function (Eldridge et al. 2004). The effects of decreasing salinity from 30 psu were best modeled as a linear decrease in GPP. We obtained the remaining parameters, for which we lacked locally-collected data, from Kaldy & Eldridge (2006). Model development, functions, results, uncertainty and validation are discussed in more detail by Buenau & Thom (in prep).

$$C_{t+1} = C_t + \Delta t \left[(1 - \tau)P(I_z, T, S)C_t \left(1 - \frac{C_t}{K}\right) - R(T)C_t - MC_t \right] \quad (1)$$

We supplied the biomass model with time series of temperature, salinity, and water elevation for 5,076 nearshore nodes of the Puget Sound/Georgia Basin hydrodynamic model, a 3D unstructured-grid Finite-Volume Coastal Ocean Model (FVCOM), for the year 2007 (Yang & Khangoankar 2010). Light at the water surface was obtained from the Weather Research and Forecasting model (<http://www.wrf-model.org/index.php>).

We calculated photosynthetically active radiation (PAR) at eelgrass canopy level using light attenuation coefficients derived from Secchi depth data collected by the Puget Sound Water Quality Monitoring Program (http://www.ecy.wa.gov/programs/eap/mar_wat/). We delineated 14 areas of Puget Sound that had multiple years of sampling and calculated monthly mean attenuation coefficients for each area. We ensured attenuation coefficients were specified for areas around large river deltas and areas with low flushing.

We ran the model at each node for every meter –1 m to –9 m NAVD88, for 1 year, with an initial biomass of 2 mol C m⁻² (1/3 the modeled carrying capacity) to predict the potential for eelgrass to grow at densities comparable to eelgrass transplants. This value approximates the minimum viable transplant mass density (Thom et al. 2012). We used the final predicted biomass as an indicator to rank relative site suitability. Given the variability in empirical data, we used the value of 1.95 instead of 2 to allow for the potential of error in affecting the transition between biomass decreases and increases in response to conditions.

Site Characterization and Prioritization

We combined eelgrass modeling results with data on substrata, stressors, the current and historical extent of eelgrass, and input from shoreline managers (Figure 2) to create an Eelgrass Restoration Site Prioritization Geodatabase using ArcGIS 10.1 (ESRI, Redlands, California). The fundamental spatial unit is the “site” as defined by the Washington State Department of Natural Resources’ (DNR’s) Submerged Vegetation Monitoring Program (SVMP). The SVMP includes 2,781 fringe (each 1,000 m of shoreline) and flats (varying sizes) sites in Puget Sound (Christiaen et al., 2016). The SVMP had monitored 364 sites for eelgrass presence, absence, area, and depth range by 2013, the year initiated site selection.

We spatially joined the eelgrass biomass model results to a mosaicked bathymetry data set (Finlayson 2005), applying the model results for each depth to the appropriate bathymetry polygons. Elevations for the upper depth limit of eelgrass were based on 2000 – 2013 SVMP data and were converted from MLLW to NAVD88 using the National Oceanic and Atmospheric Administration's (NOAA's) VDatum tool, version 3.3 (Parker et al. 2003; NOAA 2010). Bathymetry polygons where model results $> 1.95 \text{ molC m}^{-2}$ were selected to represent the depths where eelgrass growth was likely. The polygons were intersected with the SVMP sites (151 were omitted due to lack of bathymetry, therefore $n=2,630$). The sum of the resulting polygon areas (within the depth limit and > 1.95) for a site is referred to as the 'bathymetric area.'

To estimate eelgrass growth potential across the site, we calculated a mean model estimated biomass (MEB) for each site, weighted MEB correct for varying depth polygon area:

$$MEB = \frac{\sum_1^n (value * a_n)}{\sum_1^n a_n} \quad (2)$$

where *value* is the estimated biomass (mol C m^{-2}) and a_n is the area of the n^{th} depth polygon with a value > 1.95 .

We integrated three sources of data on current eelgrass presence: (1) ShoreZone Inventory data for all sites; 2) DNR SVMP data for 364 sites; and 3) reconnaissance survey (See Field Visits and Test Planting section below). Testing and data from this study for 24 sites. All data were reclassified as presence/absence. To estimate historical presence or absence of eelgrass at each site, we used maps developed from the U.S. Coast Survey, which mapped the Puget Sound nearshore three times since the 1840s (<http://riverhistory.ess.washington.edu/tsheets.php>) (Thom & Hallum 1990; digitized by Jeremy Davies, NOAA 2007).

We sent 1,000 shoreline managers and stakeholders a survey regarding losses of eelgrass and potential causes (Thom et al. 2014a). We asked each manager to provide a description of the shoreline region they managed and to estimate the area of change they observed and used this to note sites observed to be declining, independent of the presence/absence data. We received 147 responses, hence the survey was not comprehensive of the entire region.

We included two common stressors by calculating the proportion of each site with armored shoreline and of area in each site covered by overwater structures, using data from the Puget Sound Nearshore Ecosystem Restoration Project (Simenstad et al. 2011).

Field Visits and Test Plantings

We selected 24 sites without known eelgrass in five areas (Figure 1) for reconnaissance based on MEB scores, substrata, historical evidence of eelgrass, expectation of limited stressors, site size (larger areas were given preference), and proximity to potential donor sites and other potential sites. At each site, using drop cameras or scuba, we noted eelgrass presence or absence, depth range, sediment grain size category (e.g., coarse sand, fine sand,

silt), wave energy, and potential stressors. If eelgrass was present, we would continue to another site.

Employing methods proven successful in the Pacific Northwest (Thom et al. 2012), we transplanted eelgrass in nine test plots at five areas, in northern, central and southern Puget Sound (Figure 1). Test plots ranged 22 – 45 m² in area, and contained an average shoot density of 20 m⁻². This was not specifically done for model validation, but rather to investigate suitability at specific sites under consideration for restoration. These areas represented conditions that appeared either highly suitable with no previous eelgrass records (Joemma Beach State Park, Zangle Cove, Anderson Island), or contained no eelgrass now but previously did (Liberty Bay mouth, Westcott Bay). With the former areas located in southern Puget Sound, we were evaluating whether eelgrass could be supported but perhaps had not been colonized (i.e., dispersal-limited). We were also interested in determining if conditions in the latter areas may have improved enough to support eelgrass. Four to six months after transplanting, divers qualitatively evaluated abundance, plant health, disturbances, water clarity, presence of other organisms, and sediment changes. In the spring following planting, divers assessed shoot abundance and recorded ancillary observations (e.g., uprooted plant anchors, burrows).

We deployed Odyssey PAR 2 π recording sensors (Dataflow Systems, Christchurch, NZ) near the transplant sites at Anderson Island (southern Puget Sound) and Westcott Bay (San Juan Island, northern Puget Sound) for the first six months to determine if PAR could be a limiting factor. At each site, paired sensors were positioned 1m apart vertically. The sensors were cleaned manually 2-3 times during the deployment period. Only the data for the week following each cleaning were used to estimate light attenuation.

Maps of Eelgrass Restoration Potential

To assist entities interested in locating eelgrass restoration sites, we developed maps of eelgrass restoration potential for the entire shoreline of Puget Sound. The predictions of eelgrass restoration potential consisted of the MEB scores divided into four categories: none (MEB<1.95), moderate (MEB = 1.95 – 2.0), high (MEB = 2.0 - 2.1) and very high (MEB > 2.1). Stretches of shoreline with suitable substrata are indicated using a line. Where eelgrass was known to be present is also indicated.

Results

Numerical Modeling and Spatial Analysis of Habitat Suitability

The numerical model predicted, as expected, the greatest biomass production in cool, well-circulated areas away from large river deltas. Predicted biomass was limited by low salinity on large river deltas, primarily in eastern Puget Sound, and higher temperatures in poorly flushed regions such as south Hood Canal. At lower elevations, light availability drove biomass production, with areas prone to sediment runoff and/or low circulation having notably lower predicted biomass and a more constrained depth range.

We estimated 32,227 ha with moderate to very high MEB and suitable substrate (Table 1). The San Juan Islands and Strait and central Puget Sound contained the greatest areas for

restoration. South Puget Sound ranked third, but contained no sites in the very high growth potential category.

Over all of Puget Sound, the area with suitable substrata where eelgrass was present is greatest where growth potential (EBM) values are high or very high (10,119ha + 8,758ha = 18,877ha), and is substantially lower (2,200ha) where growth potential is moderate (Table 1). This concordance, we believe, provides a reasonable basis to indicate of restoration site conditions throughout this system and subsequent site selection.

Shoreline managers observed declines of 4,281 ha in areas with suitable substrata and moderate to very high MEB scores (Table 2). Saratoga and Whidbey Island and San Juan Island and Strait contained the greatest area of decline, though the Saratoga and Whidbey Island region had mostly moderate MEB scores.

Sixteen sites contained overwater structures occupying 1-10% of the shoreline length, but were otherwise predicted to be high to very high restoration potential for eelgrass. On average, 33% of shoreline length within armored sites was otherwise rated as having high to very high restoration potential for eelgrass.

Field Tests of Sites

Of the nine test plots planted, five had declines >98% (Table 3) and are thus not good candidates for large-scale planting. The remaining four sites had marginal (17.2%) or better (>60%) survival. Two sites at Joemma State Park contained more shoots (a 31% and 9% increase) in 2014 than planted in 2013 (Vavrinec et al. 2014). Although Zangle Cove and Westcott middle sites had declines within the first year of transplanting (38 and 83%, respectively), results suggested that these sites warranted further investigation for large-scale restoration. Our PAR monitoring and visual observations indicated that the Anderson Bay and Westcott head of bay sites were turbid, with attenuation coefficients of 0.64 m^{-1} and 0.99 m^{-1} , respectively.

Maps of Restoration Potential

The maps of restoration potential for the entire shoreline of Puget Sound were developed to provide local and regional restoration practitioners and resource managers with a summary about their region of interest (see examples in Figure 3; all maps are available from Washington State Department of Natural Resources). We recommend that these maps be used as a preliminary guide, and that further investigation should be done to explain why eelgrass does not presently exist in areas that appear suitable based on our analysis employing existing data sources. For example, large areas in Liberty Bay (Figure 3c) and Dyes Inlet (Figure 3d) appear suitable but there is no reported eelgrass from these places. We suspect that poor water properties, unknown to us, may be affecting eelgrass establishment. For the region to the west of Ediz Hook (Figure 3a), we suspect that localized disturbances and perhaps relatively coarse substrata may be limiting eelgrass establishment. With the advent of the removal of the two Elwha River dams starting in 2012, massive sediment deposition was initiated in the river delta immediately west of the figure, and fine sediment has been accumulating along the shoreline eastward to Ediz Hook (Gelfenbaum et al. 2015). We expect conditions to improve as sediment stabilizes over time.

Discussion

Based on a global analysis of seagrass restoration projects, van Katwijk et al. (2016) concluded that seagrass restoration is challenging with the majority of projects failing to meet expectations. They concluded that removing threats is important prior to planting. Our study is focused on providing guidance for agencies tasked with restoring eelgrass in Puget Sound as part of a program to recover the ecosystem. An aspect of that task is to understand where eelgrass might be restored. Our approach to identifying suitable eelgrass habitat represents an advance in integrating multiple types and sources of data to support effective restoration of a foundational species across a large and complex area. Regions with highly variable conditions and multiple management challenges must translate the effects of many controlling factors into actionable information. By coupling large-scale hydrodynamic modeling with a locally-derived eelgrass physiological model, then combining results with other pertinent data into maps and site-level indices, we incorporated spatial and temporal heterogeneity in a range of drivers and stressors into estimates of potential restoration success. We suggest that our approach could be applied in other regions, but would require geospatial data sets on key conditions known to control eelgrass survival and growth. Although these types of data sets are often lacking, the data gaps can be identified and filled with informed monitoring and research efforts.

We produced Sound-wide maps reflecting restoration potential and the presence of eelgrass and suitable substrates, which restoration practitioners have used to select and prioritize projects. Our geodatabase provides access to additional information and multiple ways of summarizing stressors, present and potential eelgrass distributions, and associated remediation or mitigation actions. For example, we applied the database to estimate which regions of Puget Sound had the greatest suitable restoration area and calculate total area that could be restored relative to the restoration targets.

Beyond site selection, the geodatabase supports identification of priorities and locations for stressor remediation; e.g. where water quality or shoreline alterations limits the likelihood of restoration success, or sites where eelgrass is predicted to persist but is instead observed as declining because of disturbances or other stressors not included in the model. This approach may offer promise for addressing issues where multiple factors may be responsible for large-scale collapses of eelgrass as have occurred recently in Morro Bay, California (Merkel & Associates 2017), and several bays in Puget Sound (Christiaen et al. 2017).

The development and application of models parameterized with local data highlights information needs such as fine-scale light attenuation data; additional physiological data to predict survival during low light conditions and over winter; estimates of seasonal differences in mortality; and evaluation of any genetic or phenotypic adaptations that would result in different model parameters at different locations. Field visits, small-scale transplanting, and data collection at sites test model predictions and help to prioritize improvements to the model and database.

Field tests also identify factors that are not practical to include in region-wide modeling but should be evaluated *in situ* before transplanting. For example, test plantings in Westcott Bay,

an area that previously contained extensive stands of eelgrass, showed that the inner bay portion was poorly suited for eelgrass likely because of poor sediment conditions, but the near by mid-bay site showed some potential but needed further evaluation.

Our approach could be expanded with climate and land-use scenarios to evaluate the long-term outlook for eelgrass at restoration sites and across regions and inform planning to accommodate or mitigate for anticipated changes. With additional physiological models, the geodatabase could be adapted to include macroalgae or other foundational species, and to inform estimates of carbon storage and flux.

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Implications:

Simulation models in combination with a geodatabase and test plantings provided a comprehensive yet efficient approach for identifying sites suitable for restoring eelgrass in a large and complex estuary.

Our analysis showed that eelgrass restoration of 4,200 ha is achievable pending site-specific assessments, possible reduction in stressors, and following prudent restoration procedures.

The modeling and test planting identified fine-scale light attenuation data and improved physiological data, particularly in regard to low-light conditions and phenotypic or genotypic adaptations, as critical information needs to improve this method of restoration planning.

The model and database provide a methodology for assessing effects of climate and land use changes on species distributions and identify mitigation for these changes through stressor reduction and improved site selection.

Figure 1.
Regions of Puget Sound with locations of five test transplant sites. Four sites contained more than one plot, for a total of nine planted plots.

Figure 2.

Flow diagram of the linkages between the eelgrass biomass model, mean model estimated biomass (MEB), environmental conditions and data sets used to develop the restoration database and restoration potential maps.

Figure 3.

Example eelgrass restoration potential (see Figure 2) maps for five areas in Puget Sound (see Methods for description of relative rankings). The bottom right figure shows the general location of the areas in (A)–(E): (a) immediately east of the Elwha River mouth; (b) Port Gamble Bay; (c) Liberty Bay; (d) Dyes Inlet; and, (e) a part of South Puget Sound.

Table 1.

Estimated areas (ha) within the eelgrass depth range for Puget Sound and each region categorized according to modeled restoration potential, size of site, and eelgrass presence or absence. The area was determined based on locations where the model has growth potential (MEB = 1.95) at depths below the documented upper elevations of eelgrass. Areas are provided for three MEB categories reflecting degree of positive growth potential. The estimated areas are further categorized based on the estimated area of suitable substrata for each site. For each region, the areas are summed for total area and based on whether eelgrass has been documented as present or absent. The “present” category includes areas where eelgrass was noted to be declining (see Table 2). The area per region estimated to be suitable for restoration (i.e., where the eelgrass biomass model and substrata indicates suitability but eelgrass is absent) is indicated in **bold**.

Growth Potential (MEB)		Moderate (1.95-2.0)			High (2.0 - 2.1)			Very High (>2.1)			Total Area
Area with suitable substrate (ha)		0.1-9.9	10-50	>50	0.1-9.9	10-50	>50	0.1-9.9	10-50	>50	
Puget Sound ^I		783	1161	3281	4089	5263	4192	1575	5653	6230	32227
Present ^I		495	670	1035	2902	4101	3116	938	2586	5234	21078
Absent		179	287	111	1092	1012	637	563	2612	376	6868
San Juan Islands and Strait		164	82	0	597	959	962	442	2888	1875	7968
Present		154	82	0	480	781	737	281	665	948	4129
Absent		10	0	0	111	177	0	140	2073	376	2888
North Puget Sound		35	322	475	140	688	1310	1	0	4016	6987
Present		16	266	475	113	656	1310	1	0	4016	6853
Absent		11	15	0	13	0	0	0	0	0	39
Saratoga and Whidbey Is.		334	560	2695	555	536	147	1	0	0	4828
Present		192	265	560	528	511	147	1	0	0	2204
Absent		66	133	0	7	0	0	0	0	0	207
Central Puget Sound		35	41	0	1588	2397	1086	1131	2766	339	9382
Present		24	41	0	1102	1756	786	655	1921	270	6554
Absent		11	0	0	484	570	214	423	538	0	2241
Hood Canal		137	17	0	738	479	265	0	0	0	1636
Present		108	17	0	680	396	136	0	0	0	1338
Absent		4	0	0	5	60	0	0	0	0	69
South Puget Sound		77	139	111	470	204	423	0	0	0	1424
Present		0	0	0	0	0	0	0	0	0	0
Absent		77	139	111	470	204	423	0	0	0	1424

^ITotal areas for the regions and for ‘Present’ eelgrass include sites where eelgrass was observed in the SVMP surveys, Shorezone Inventory, or site visits. It includes sites where eelgrass was noted as declining during the stakeholder survey (see Table 2).

Table 2.

Estimated areas (ha) within the eelgrass depth range for Puget Sound and each region where observations of eelgrass declines were noted in the stakeholder survey; these areas may be candidates for stressor amelioration that would support recovery of remaining eelgrass. Areas are provided for three MEB categories reflecting degree of positive growth potential. The estimated areas are further categorized based on the estimated area of suitable substrata with each location.

Growth Potential (MEB)	Moderate (1.95-2.0)			High (2.0 - 2.1)			Very High (>2.1)			Total Area
Size of area within sites (ha)	0.1-9.9	10-50	>50	0.1-9.9	10-50	>50	0.1-9.9	10-50	>50	
Puget Sound	109	204	2134	95	150	440	73	456	620	4281
San Juan Islands and Strait	0	0	0	6	0	225	20	149	551	952
North Puget Sound	8	41	0	14	31	0	0	0	0	95
Saratoga and Whidbey Is.	76	163	2134	20	25	0	0	0	0	2417
Central Puget Sound	0	0	0	2	70	86	53	306	69	587
Hood Canal	25	0	0	53	23	129	0	0	0	230
South Puget Sound	0	0	0	0	0	0	0	0	0	0

Table 3.

Summary of survival at all the test planting plots including a recommendation about future restoration at the location. Mean initial planting density ~20 shoots m⁻². See text for details on when surveys were conducted.

Site	Shoots planted	Area planted (m ²)	Shoots survived	Change (%)	Mean end density (shoots m ⁻²)	Recommendation
Joemma State Park deep	712	36	930	+30.6	25.83	Larger planting
Joemma State Park shallow	712	36	775	+8.8	21.53	Larger planting
Zangle Cove	872	45	539	-38.4	11.98	Targeted planting
Westcott middle bay	472	25	81	-82.8	3.24	Another trial planting
Anderson Is. deep	720	36	14	-98.1	0.39	Reduce algae
Anderson Is. shallow	720	36	11	-98.5	0.31	Reduce algae
Liberty Bay (NW site)	600	30	8	-98.7	0.27	Increase light
Liberty Bay (SE site)	720	36	3	-99.6	0.08	Increase light
Westcott head of bay	448	25	0	-100.0	0.00	Improve sediment and light conditions