A Regional Assessment of the Condition and Quality of Southern California’s Eelgrass (*Zostera marina*) Habitat from the Perspective of Ecosystem Services

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SOUTHERN CALIFORNIA COASTAL WATER RESEARCH PROJECT
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ABSTRACT

SAV in general, and eelgrass (*Zostera marina*) in specific, are a key component of the estuarine habitat mosaic of Southern California and are the subject of both state and federal environmental management policies. Despite this, there has historically been no coordinated monitoring and assessment effort for eelgrass in Southern California – in part due lack of condition assessment tools for eelgrass. The goal of this study was to determine the extent of eelgrass condition across the region. Eelgrass aggregations – patches, discrete beds, and expansive meadows – of estuaries and coastal embayments were sampled across the region in the fall of 2024 using a stratified, random probabilistic survey design. The region's eelgrass resources were divided into three strata, based upon waterbody size and connectivity – large embayments, small embayments, and estuaries. A combination of field-based observations (bed perimeter, percent cover, shoot density, and presence of flowering shoots) and lab-based measurements (shoot height, leaves per shoot, leaf area, above ground biomass, and below ground biomass) were collected. These structural metrics were scored relative to condition benchmarks derived from regional population distributions of each metric. These scores were then combined using a novel condition assessment index – the Zostera Ecosystem Function Reporter (ZEFR) – to quantify the condition of each individual eelgrass aggregation. The assessment index was designed to evaluate the condition of the eelgrass from the perspective of its ability to provide seven key ecosystem functions and services: carbon sequestration, sediment stabilization, primary production, secondary production, nekton habitat, waterfowl habitat, and improvement of water quality. Of the approximate 55,000 m^2 of eelgrass in the sample frame of the region's estuaries and embayments, 12% was in Good condition, 65% was in Moderate condition, 20% was in Poor condition, and 3% was in Bad condition. *Zostera marina* from large embayments were in the best condition with 80% in Good or Moderate condition and 0% in Bad condition. Conversely, small embayment eelgrass was in the worst condition, with 60% in the Good or Moderate condition and 20% in the Bad category.

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INTRODUCTION

Submerged aquatic vegetation (SAV) is an ecologically, economically, and societally important component of estuarine and coastal systems across Southern California, as well as the world (Cullen-Unsworth et al. 2014, Dewsbury et al. 2016, Nordlund et al. 2016, Ruiz-Frau et al. 2017). SAV plays an important role in the ecology of coastal systems, as it provides unique structure and enhancement of biogeochemical processes. The physical structure of SAV can provide ecosystem function as temporary refuge from environmental threats, substratum as a permanent point of attachment, and a direct or indirect mechanism for food acquisition (Orth et al. 1984, Boström et al. 2006). Within many southern California estuarine environments, SAV forms expansive beds in shallow, soft-bottom sediments, comprising an important functional component of the mosaic of shallow subtidal and intertidal habitats, interspersed among emergent wetlands, biotic reefs, mudflats, and other intertidal habitats (Polis et al. 1997, Heck et al. 2008).

Southern California's coastal embayments are host to a variety of SAV species, including *Ruppia maritima* (widgeon grass), *Zostera pacifica* (wide-leaved eelgrass), and *Zostera marina* (narrow-leaved eelgrass (Green and Short 2003; Olsen et al. 2014), but *Z. marina* is the most common species present in estuaries and embayments (though see Johnson et al. 2003). Given its dominance in the region's coastal systems and high ecological value, most efforts at monitoring, restoration, and mitigation of SAV habitat in Southern California's coastal waters have focused on *Z. marina*. Historically though, most of these efforts have occurred in isolation – projects focused on a specific body of water or restoration location. To try and bring a greater uniformity to the management of eelgrass, Bernstein et al. (2011) assembled a panel of regulated, regulatory, environmental, and research organizations with a vested interest in eelgrass to develop a roadmap towards developing regional-scale monitoring and assessment program. Among their recommendations was to develop a condition assessment framework to understand the health of eelgrass.

Eelgrass and other types of SAV, like many other habitat engineering flora and fauna (e.g., Jones et al. 1994, Wright & Jones 2006), have a dual nature, both as semi-permanent biological resources, whose condition can be indicative of ecosystem health and integrity, as well as a unique habitat that facilitates or enhances novel food webs and biogeochemical cycling that are absent from adjacent habitats in shallow coastal waters. This dual nature can make them challenging to evaluate in the traditional bioassessment approach. Most traditional bioassessment tools focus on the organisms that reside in a system (e.g., benthic fauna, microalgae, nekton) as resources (Whitfield & Elliott 2002, Diaz et al. 2004, Borja et al. 2008). The health of individuals or the composition of multi-taxa assemblages are used to infer the condition of their resident habitat. Though not as commonly as benthic invertebrates, seagrasses have been used in this type of bioassessment context, where the size/biomass of the plants and the robustness of a given bed can be used to indicate waterbody condition (e.g., Montefalcone 2009, Neto et al. 2013, Anderson 2020).

Conversely, assessment of an organism as habitat tends to focus more on measures of its presence or extent (Grizzle et al. 2008, Vandermeulen 2014, De Clippele et al. 2017). This approach operates under a paradigm that "the more of the organism/habitat, the better", without explicit consideration of the ability of that habitat to provide the desired ecosystem functions and services. As an illustration, the majority of SAV-focused assessments in Southern California have been inventories of seagrass extent and location (Merkel & Associates Inc. 2014a, 2023, Sherman & DeBruyckere 2018). This is critical information, but it does not provide a fully realized evaluation of the condition of that habitat nor how it is performing as within the broader ecosystem.

Assessment of Ecosystem Function

A monitoring and assessment program that provides insight into the functioning and services provided by their target ecosystem is the desire of many environmental managers and regulators. In specific reference to eelgrass, California's Eelgrass Mitigation Policy (NOAA National Marine Fisheries Service, 2014) has the stated goal of "*…no net loss of eelgrass functioning*" due to development and management of California's coasts. However, regular, direct monitoring ecosystem functions is not practical at a large spatial scale and at regular frequencies, especially in monitoring programs driven by permit compliance. Monitoring for changes in structure, composition, or extent are much easier and much more common (e.g., Schiff et al. 2016, Stolzenbach et al. 2021, Merkel & Associates Inc. 2024). We propose to address this dichotomy by building new bioassessment frameworks and approaches centered on ecosystem function, while still maintaining a practicality that encourages their widespread usage. The resulting assessment tools should be based on strong conceptual models that link structural components of a biological community to their ecosystem function (e.g., McCune et al. 2020, O'Connor et al. 2025).

These goals of a function-focused bioassessment framework could be achieved by retrofitting the thresholds or endpoint of a pre-existing index – e.g., recalibrating a stream benthic macroinvertebrate O/E index to evaluate stream biodiversity. Or using parts of existing condition assessment tools designed for other purposes in new ways (e.g., inferring secondary production from biomass metrics in an MMI (Gillett 2010)). This can be a reasonable approach, but repurposing existing tools may cause confusion in their application and communication to non-technical audiences. Alternatively, there is the option of purpose-building new assessment tools designed to provide information on ecosystem functioning. While both retrofitting or new construction approaches show promise, we believe the latter option provides a more direct and robust approach to looking at habitat condition from the perspective of ecosystem function independent of the health of any single biological element of the ecosystem.

The goals of this study were two-fold. The first was to fully develop a novel condition assessment tool for eelgrass (*Z. marina*) centered on capturing the eelgrass of a given site's ability to provide key ecosystem functions and services. The second goal was to provide the first regional estimates of condition and health for eelgrass growing in the estuaries and coastal embayments of the Southern California Bight.

METHODS

Survey Design

A probabilistic tessellated sampling design was employed to provide robust statistical inferences from the sampled population of eelgrass to the true population of the region, (Stevens & Olsen 2003, 2004, Olsen & Peck 2008). A base layer map of eelgrass presence in embayments and estuaries from Point Conception, CA in the north to the US-Mexico border in the south served as the sample frame from which individual sample sites could be selected. This base layer was created by linking together publicly available eelgrass map data – typically from single embayments – from 2015- 2022 (Merkel and Associates 2023; Merkel and Associates 2016) (www.ecoatlas.org). These data were then supplemented with waterbody-by-waterbody site visits focusing on smaller, heretofore under-sampled embayments in the northern parts of the Southern California Bight (e.g., Hollister Ranch Lagoon, Gaviota Estuary, Refugio Estuary) looking for eelgrass in the summer of 2022. These small embayments were surveyed for the presence of eelgrass by paddling and snorkeling (when practical) their waters, recording the presence and type of any SAV that was observed. These observations were then digitized into polygons for inclusion into the base map. Lastly, the base map was amended and refined following consultations with local seagrass experts across the region. All of these eelgrass extent and presence data were combined into a single GIS data layer from which sample sites could subsequently be selected. (https://sccwrp.maps.arcgis.com/apps/webappviewer/index.html?id=fbd66a9bc6174ad7a5cf90b3d5b9405c).

To ensure the inclusion of waterbodies of different sizes and land uses in the random selection process, the sample frame was divided into three strata prior to the selection of sample sites (i.e., a stratified unequal design (e.g., Olsen & Peck 2008, Gillett et al. 2022)). The three strata were based upon categories of environmental setting, following Doughty et al. (2019) and local experience with the different systems:

- Large embayments – Enclosed or semi-enclosed waterbodies greater than 8 km^2 in area that have a permanent connection to the open ocean.
- Small embayments – Enclosed or semi-enclosed waterbodies less than 8 km^2 in area that have permanent connections to the open ocean.
- Estuaries – Small enclosed waterbodies with a distinct connection to upland freshwater sources and permanently maintained or seasonal/ephemeral connection to the open ocean.

The sample frame of the previously observed eelgrass area in each stratum was divided into $500m^2$ cells that would represent a potential sample site. Ten sample sites were randomly selected without replacement from each stratum (30 in total) using the sample_strat function in the R package spSurvey (v5.5.1) (Dumel et al 2023). Given the ephemeral nature of eelgrass aggregations that expand and contract in extent from year to year, 30 additional sites were identified for each stratum to serve as replacement sites (i.e., overdraw sites) in case any of the initial 10 sample sites did not have any vegetation in 2024.

Field Collection of Structural Metrics

Field protocols for sampling are fully detailed in McCune et al. (2020). However in brief, all in-water measurements and collection of material were conducted by teams of SCUBA divers and any intertidal portions of a location were omitted from sampling. If seagrass was present at a site, the perimeter of the aggregation was measured. Plants were considered to be of the same aggregation if there was less than 5m of bare sediment between plants. Eelgrass was classified into different growth categories:

- Patch – Eelgrass aggregation 3m or less on the longest axis
- Bed – Eelgrass aggregation between 5 and 60m along its longest axis and at least 5m along its cross axis (typically shallowest point to deepest point)
- Fringing Bed – Eelgrass aggregation between 5 and 60m along its longest axis and less than 5m along its cross axis
- Meadow – Eelgrass aggregation larger than a bed

For the bed growth category, a transect (maximum 50 m long) was laid along its longest axis (mid transect) and second transect was laid from the shallowest subtidal point to the deepest point (cross transect) that was roughly perpendicular to the mid transect. See Figure 1 for sampling scheme in each of the different growth categories. Starting at the beginning edge of the mid transect, 0.25m^2 quadrats were placed every 10m (i.e., a maximum of 5 mid transect quadrats) on the sediment surface. Similarly, quadrats were placed at the shallow and deep ends of the cross transect. At each quadrat, % cover of seagrass was visually estimated, as was % of drifting macroalgae. Shoot density was estimated by counting all of the distinct eelgrass shoots within the quadrat. Flowering shoot density was estimated as the number of shoots within the quadrat with distinct spathes (leaf structures that enclose the flowers) on their upper ends. For sites classified as patches, 1 or 2 0.25m^2 quadrats were haphazardly placed within the patch, depending on the size of the patch. For sites classified as meadows, a 50m X 20m area was identified and transects and quadrats were placed as normal. For sites classified as fringing beds, only a mid transect was used.

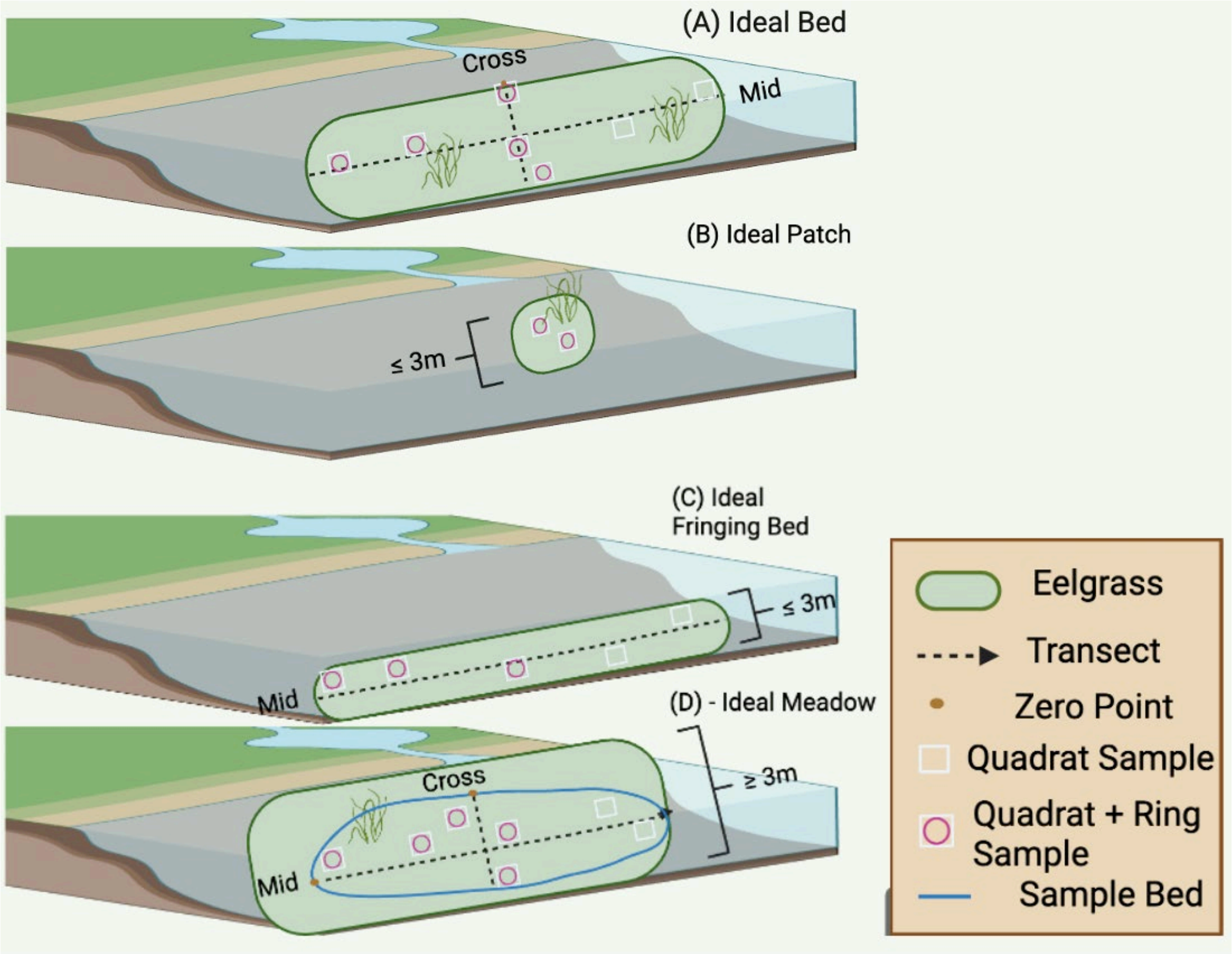

Figure 1. Schematic depicting the transect and quadrat sampling scheme for different growth forms of eelgrass. A The idealized Bed, B – The Idealized Patch, C – The Idealized Fringing Bed, and D – The Idealized Meadow. Any intertidal portions of given location were omitted from sampling. Images created in Biorender (www.biorender.com).

At sites classified as beds, eelgrass material was collected for subsequent lab analyses from the first 3 mid transect quadrats and 2 cross transect quadrats. A 10cm i.d. ring was placed in the middle of the quadrat. All above ground material (i.e., shoot base, leaves, and attached epiphytes) within the ring were cut at the sediment surface and placed in sample bags. All below ground material (i.e., roots and rhizomes) within the diameter of the ring were cut, removed from the sediment, gently rinsed, and placed in sample bags. For sites classified as patches, above and below ground material was collected within each quadrat. For sites classified as fringing beds, material was only collected from the first 3 mid transect quadrats. Sites classified as meadows, were sampled the same as bed sites.

Laboratory Measurement of Structural Metrics

Within the above ground material from a given site and quadrat, the total number of shoots and the number of leaves per shoot were recorded. All epiphytic material was gently removed from each leaf with a scalpel or glass microscope slide and pooled together for biomass measurement. The length of the of the longest leaf within each shoot was recorded as shoot height and the width of that longest leaf was recorded as shoot width. The total area of all the leaves in each shoot was measured with a leaf area meter (LI-COR™ LI-3100C Area Meter) or a calibrated benchtop scanner and ImageJ image analysis software (https://imagej.net/ij/) and recorded as leaf area. All epiphytic tissues, above ground eelgrass tissue, and below ground eelgrass tissue were blotted dry and measured for wet mass. Each type of tissue was then dried at 60°C for 48 hours and measured for dry mass. Dried samples were subsequently combusted at 500°C for 8 hours and measured for ash free dry mass.

Index Development

The guiding philosophy in developing an eelgrass condition assessment tool was the desire to evaluate the condition of a given eelgrass aggregation from the perspective of the different ecosystem functions and services eelgrass provides to the waterbodies where it is growing. Core to this approach was developing a series of conceptual models linking different combinations of structural metrics to eelgrass functions and services. These conceptual models (summarized in Table 1) were developed via a review of the SAV literature and through discussions with a panel of local managers and eelgrass experts (McCune et al. 2020). The key functions and services identified by the panel were Carbon Sequestration, Improving Water Quality, Nekton Habitat, Primary Production, Secondary Production, Sediment Stabilization, and Waterfowl Habitat. A suite of commonly measured eelgrass structural metrics, both at the plant-scale and bed-scale, was associated with each function as described in Table 1 To keep the conceptual models relatively simple, all parties agreed that the relationships between structural metrics and eelgrass condition would be built as positive-direct relationships, where the larger the metric, the better it contributes to the associated function or service.

Given the pervasive alteration of the estuaries and embayments of Southern California, it was determined that no truly unaltered eelgrass aggregations were available to be used as a reference benchmark for the creation of the condition assessment index. In discussion with coastal managers vested in the health and condition of eelgrass resources, it was decided to use a “best available” approach to reference benchmarking (Stoddard et al. 2006, Hawkins et al. 2010). A regional (i.e., Southern California Bight embayments) population distribution for each structural metric would be established and the metric value for a given bed would be scored relative that distribution: ≥ 75th percentile = 4, < 75th percentile & ≥50th percentile =3, <5 0th percentile & ≥ 25th percentile = 2, and < 25th percentile = 1. Individual structural metric scores were then averaged with a given ecosystem function (columns in Table 2), to create a component function score. These function scores were then averaged to produce an overall condition score for a given eelgrass aggregation. The process of combining individual metric measurements into function scores, and an overall score are illustrated in Figure 2. Overall condition and the component function numerical scores were also classified in one of four condition categories: ≥3.25 = Good condition, <3.25 and ≥2.25 = Moderate condition, <2.25 and ≥1.75 = Poor condition, and <1.75 = Bad condition.

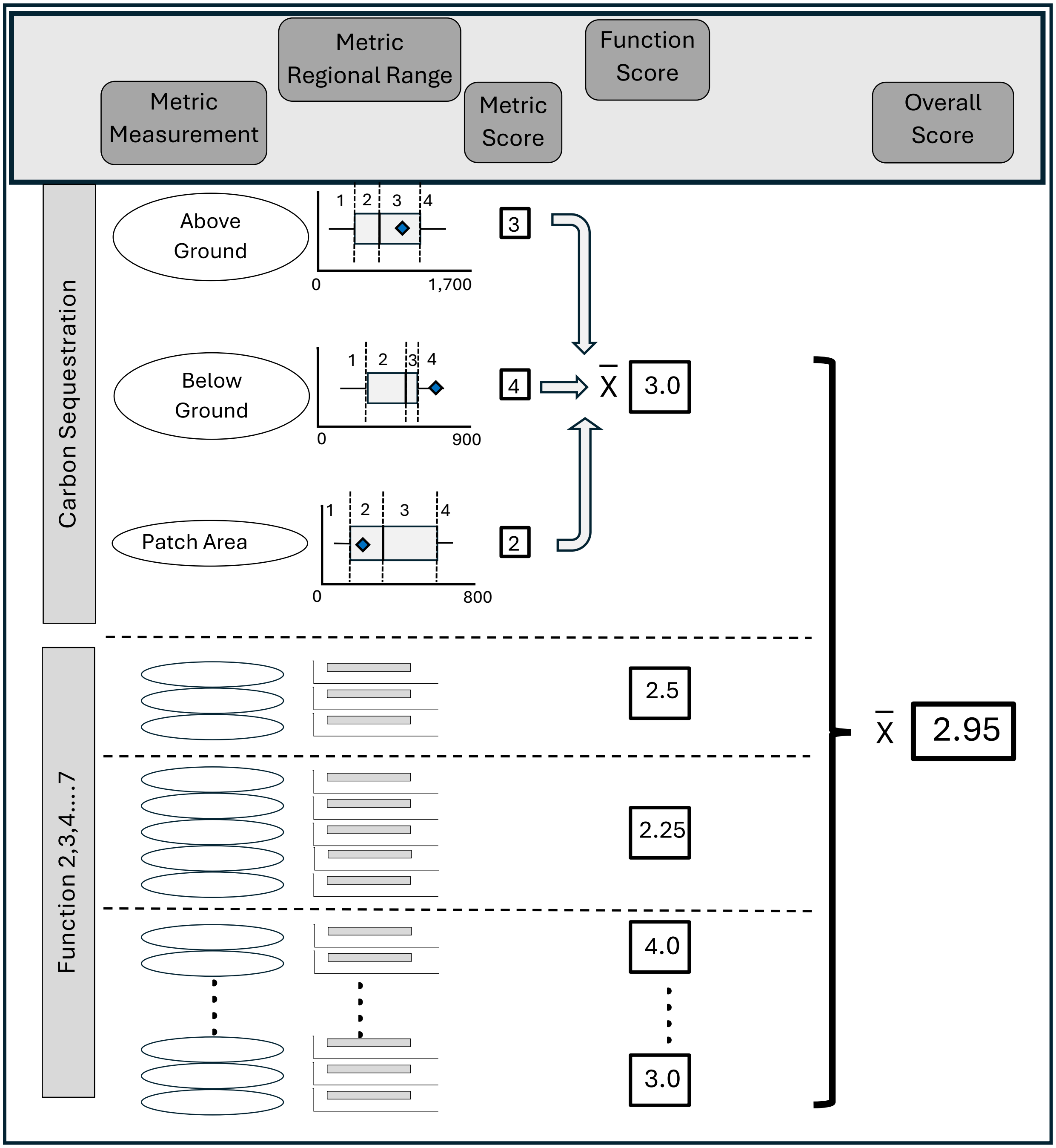

Figure 2. A diagram summarizing the index calculation process for an individual site. For each structure-function conceptual model (Table 1), structural metric measures are collected. Those values (blue diamonds) are compared to observed regional distributions (grey box-whisker plots) (Figure 3). Depending on their position relative to the regional range, each metric scored. The arithmetic mean of those scores is then calculated and represents the score for that function. The arithmetic mean of those function scores is then calculated and represents the overall condition score for the site.

Patterns in Condition

Area-weighted estimates of overall eelgrass condition and the component functions across the region and within the three strata were calculated using cat_analysis function in the R spsurvey package (v5.5.1). Area weights for each site were obtained from the sample draw information and 95% confidence intervals for each estimate were calculated using the Horvitz-Thompson estimator (Horvitz & Thompson 1952).

Index responsiveness was evaluated by comparing eelgrass score distribution against one stressor (% macroalgal cover) and one indicator of stress (eelgrass wasting disease) to eelgrass that were collected concurrently during the study. Unweighted overall condition and the individual component function scores were treated as response variables with percent macroalgal cover as the predictor variable in a least squares linear regression. Similarly, unweighted overall condition and the component function scores were treated as response variables in regression models with the number of observations of wasting disease in a bed as the predictor variable in a least squares linear regression. Both linear regressions were conducted using the lm function in R (v4.4.2).

RESULTS

Thirty-one sites, with one field duplicate, were sampled (Table 2). An extra (estuary) site beyond the intended 30 sites was accidentally sampled and was therefore included in subsequent analyses for a total of 31 sites. Of the original 30 randomly selected sites, 24 had eelgrass in Autumn of 2024 and 6 did not (4 estuary sites and 2 small embayment sites). Following standard survey protocols, the 6 bare sediment sites were sequentially replaced with overdraw sites from the appropriate stratum, until sites with extant vegetation were selected. All of the selected eelgrass structural metrics were successfully collected at nearly all sites (Figure 3), though bed perimeter data were not recorded for 3 sites. The 25th, 50th, and 75th percentiles of each metric were calculated from the full data set (Table 3) and then used for scoring each individual bed relative to the regional population. These values were then combined following the conceptual models described in Table 1, to provide overall and component ecological function scores for each individual site (Table 2, Table 4). It is worth noting that flowering shoot density was very low in the Autumn of 2024 relative to other years (K. Merkel, pers obs), with only 5 of the 31 sites having observable spathes. Consequently, all of the calculated quartiles were 0 and therefore all sites were scored as a 4 (i.e., Good) for the flowering shoot metric.

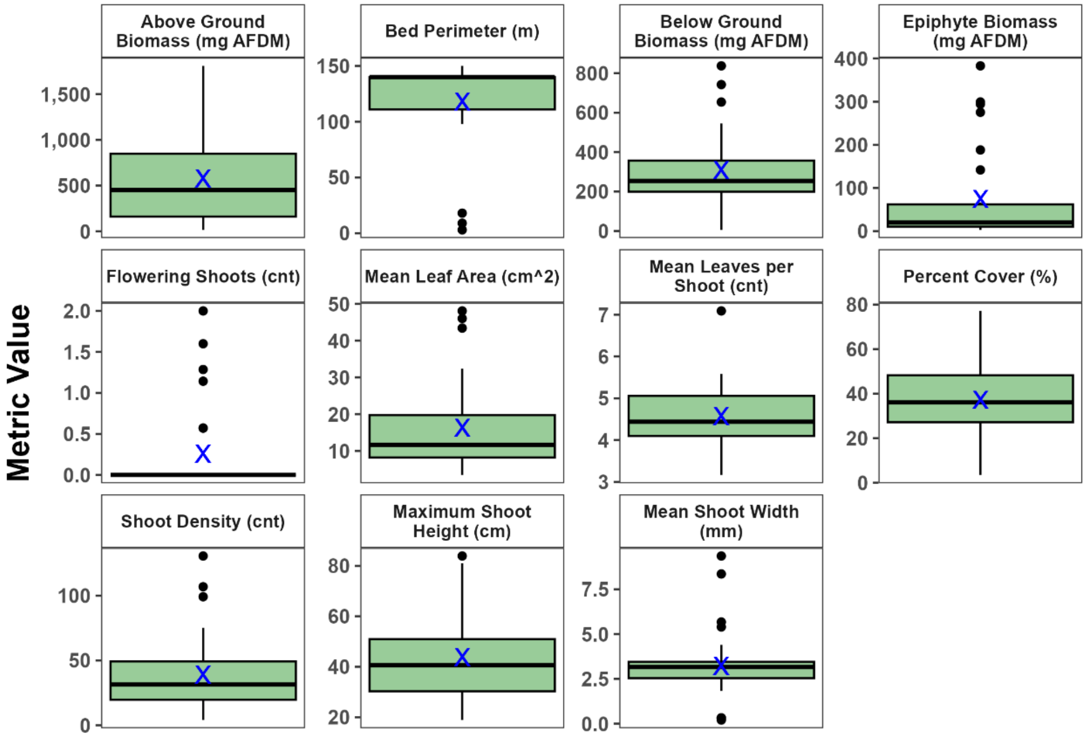

Figure 3. Schematic boxplots (box represent the 25th – 75th percentile, with the black line representing the median. Points represent values beyond 1.75X the inter-quartile range) of eelgrass structural metrics from the 32 sampled sites across the Southern California Bight. Plotted values are the site-scale mean of all quadrats measured within a given eelgrass aggregation. The blue X represents the mean value for a given metric.

Regional Estimates of Eelgrass Condition

Across the whole of the Southern California Bight, the sample frame represented ~55,090 m^2 of eelgrass in embayments. Twelve percent of the eelgrass was in Good condition, 65% was in Moderate condition, 20% was in Poor condition, and 3% was in Bad condition (Figure 4; Table 5). Among the three sampling strata, Large Embayments had eelgrass in the best condition, with 80% of the area in Good or Moderate condition, 20% in Poor condition, and 0% in Bad condition (Figure 5; Table 5). Small Embayments had the worst condition eelgrass, with 60% in Good or Moderate condition and 40% in Poor or Bad condition. Estuaries were in between the other two strata, with 73% in Good or Moderate condition and 27% in Poor or Bad condition.

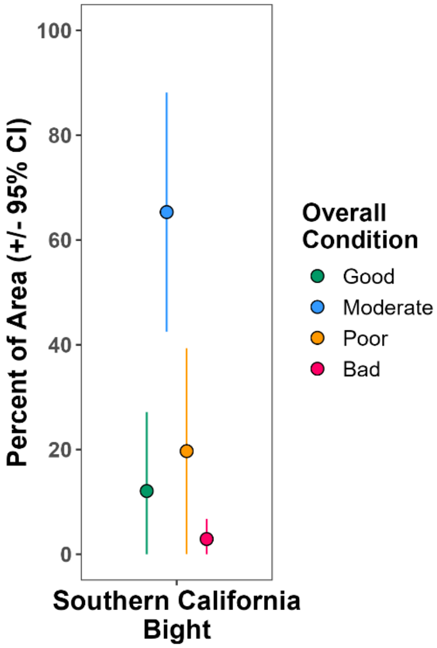

Figure 4. Area-weighted distribution of eelgrass condition categories across the whole Southern California Bight region. The error bars represent the 95% confidence intervals calculated using the Horvitz-Thompson estimator (Horvitz & Thompson 1952).

A feature of our approach to assessing the condition of eelgrass is that beyond the overall condition assessment, the index provides an assessment of eelgrass condition relative to the different ecosystem functions that are combined for the overall score (Table 6). From the region-wide perspective, the majority (46 – 68%) of eelgrass area was in Moderate condition for all seven of the ecosystem functions (Figure 6). The largest amounts of eelgrass area were in Good condition relative to Carbon Sequestration and Waterfowl Habitat. Conversely, eelgrass scored most poorly (i.e., largest amounts of Bad and Poor condition area) from the perspective of Improving Water Quality and Secondary Production. When broken down by the different strata, the Large Embayments showed the clearest patterns, with a majority of areas scoring in Good to Moderate condition with respect to most of the ecosystem functions (Figure 7; Supplemental Material A). Conditions were distributed relatively evenly across functions within the Small Embayment and Estuary strata. An exception to this pattern was Small Embayments performing poorest from the perspective of Carbon Sequestration, with 50% of the area in Bad condition. Another was that a large percentage of eelgrass within the Estuaries stratum scored in Moderate condition with regard to the Nekton Habitat and Primary Production functions.

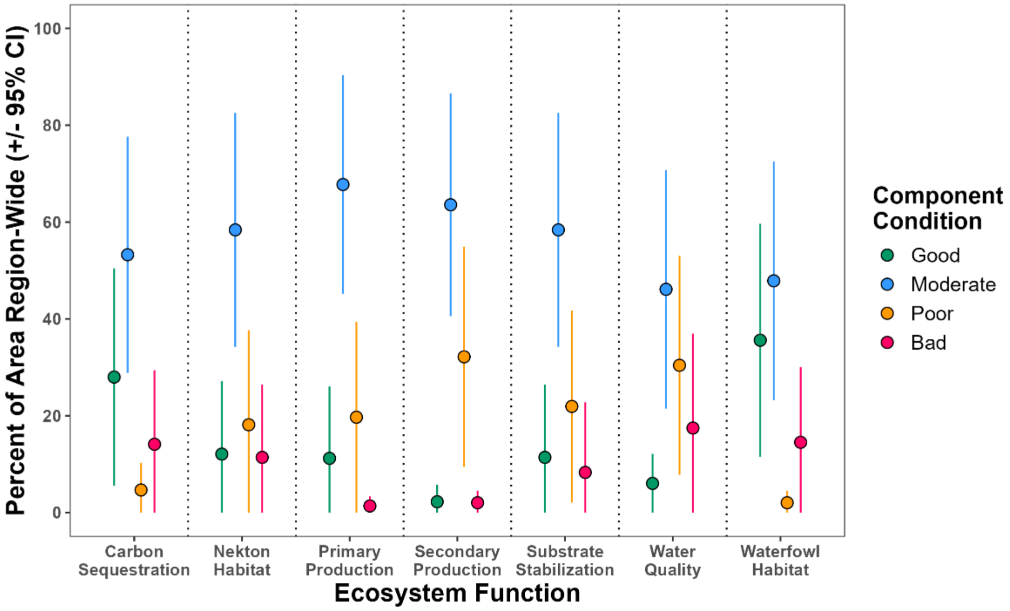

Figure 5. Area-weighted distribution of eelgrass condition categories relative to the component ecosystem functions across the whole Southern California Bight region. The error bars represent the 95% confidence intervals calculated using the Horvitz-Thompson estimator (Horvitz & Thompson 1952)

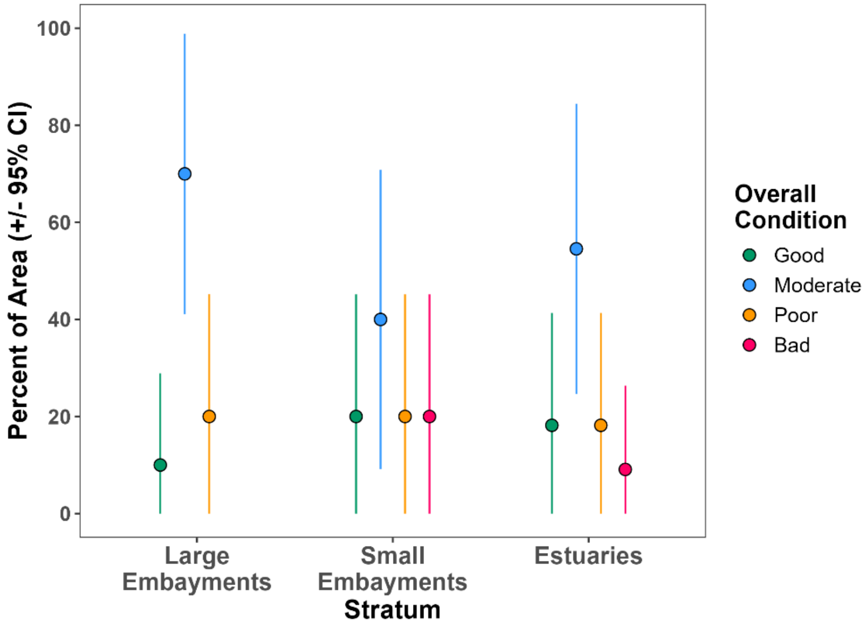

Figure 6. Area-weighted distribution of eelgrass condition scores across the three sample strata The error bars represent the 95% confidence intervals calculated using the Horvitz-Thompson estimator (Horvitz & Thompson 1952)

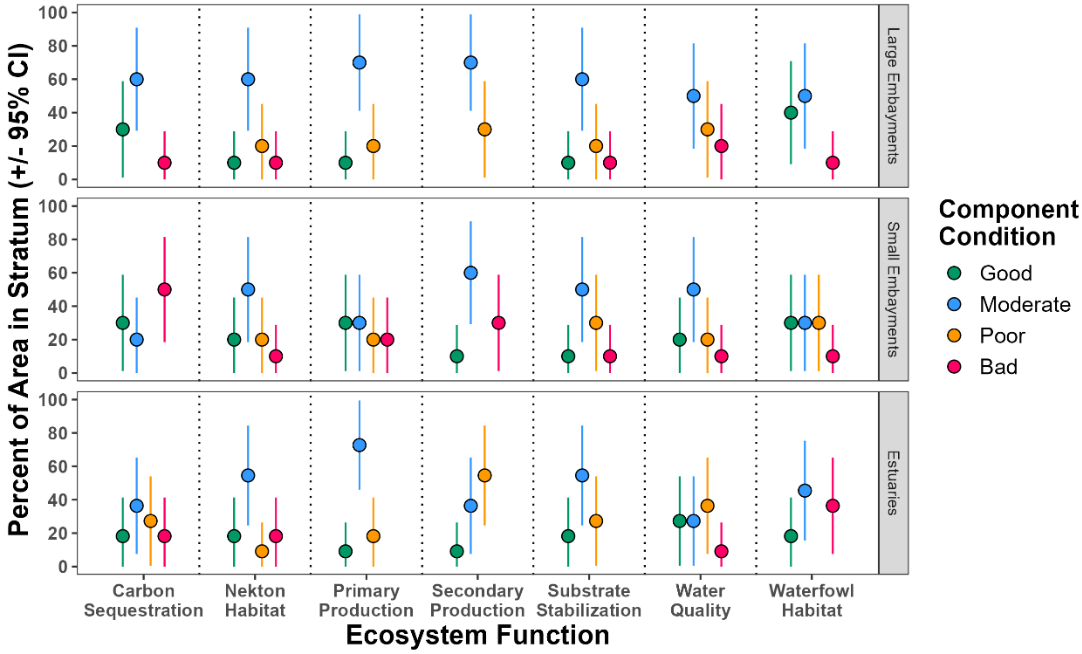

Figure 7. Area-weighted distribution of eelgrass condition scores for the three sample strata relative to the component ecosystem functions. The error bars represent the 95% confidence intervals calculated using the Horvitz-Thompson estimator (Horvitz & Thompson 1952).

Index Performance

As expected, eelgrass condition score at a site had an inverse relationship with the maximum % macroalgal cover observed at that site (Figure 8), as expected. Though the inverse relationship between eelgrass condition and a potential stressor to eelgrass health was statistically significant (n=28, d.f.=1, T=-2.11, p=0.044), the model fit was relatively poor (r^2=0.146). This is confirmed by visual inspection of Figure 8. There was no statistically meaningful relationship (n=24, d.f.=1, T=0.76, p=0.455) between eelgrass condition and the number of shoots with evidence of eelgrass wasting disease (Figure 9).

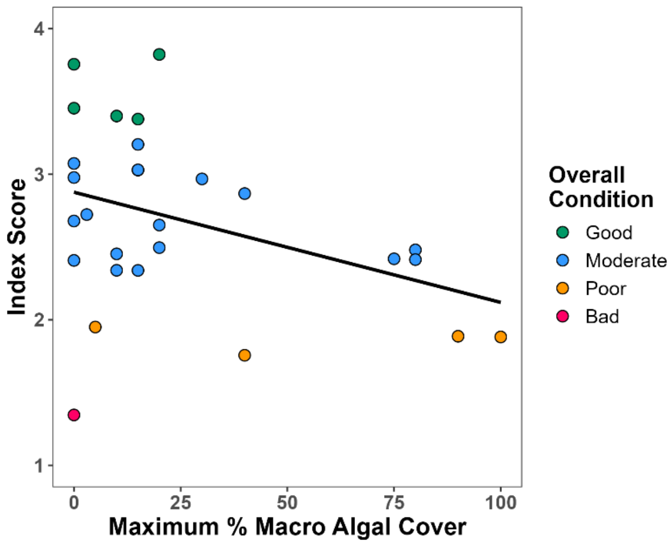

Figure 8. Scatter plot of overall index score for each site versus the maximum % macroalgal cover observed at that site. The color of the points indicates their condition category.

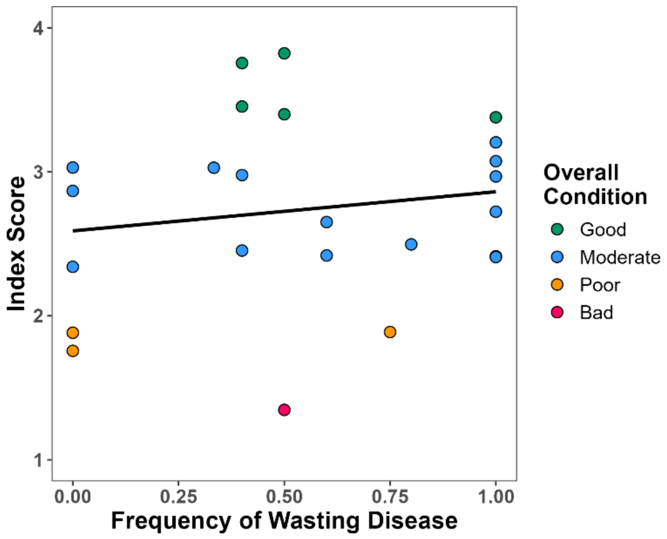

Figure 9. Scatter plot of overall index score for each site versus the frequency at which eelgrass wasting disease was observed on shoots collected for above ground biomass measurement. The color of the dots indicates their condition category.

DISCUSSION

The results of this study present the first quantitative assessment of eelgrass condition in the Southern California Bight. We have coined this new assessment tool as the Zostera Ecosystem Function Reporter (ZEFR, pronounced as *zephyr*) index. Based upon our interpretation of the data that were collected, we can estimate that 77% of the region's eelgrass in estuaries and embayments were in Good to Moderate condition in 2024. These data, and this survey in general, address one of the key management needs and recommendations for monitoring eelgrass in California from Bernstein et al. (2011). There are presently no similar estimates of eelgrass condition in Southern California against which this estimate can be compared. However, the most recent benthic infauna-based assessment of the same waterbodies indicated that 61% of the region's estuary and embayment sediments were in Reference or Low Disturbance condition (analogous to Good + Moderate eelgrass condition) (Gillett et al. 2022). Though condition of benthic infauna and eelgrass are conceptually influenced by different processes (sediment vs. water column stressors, respectively), a proportional agreement between the two assessments is interesting and suggests that there may be concordance between the two independent indicators. That similar pattern indicates that at the regional-scale this new eelgrass condition-based indicator is tracking ecosystem condition like other more established assessment frameworks.

To date, most monitoring of eelgrass in the Southern California region have been inventories of eelgrass extent (Merkel & Associates Inc. 2011, 2014b, Sherman & DeBruyckere 2018, Merkel & Associates Inc. 2023). This is an important element to managing eelgrass resources in the coastal zone (Bernstein et al. 2011, San Francisco Estuary Institute & Southern California Coastal Water Research Project 2025), but it does not provide managers insight into the health and functioning of their SAV resources as called out in state policies. Site-specific and regional-scale estimates of eelgrass condition relative ecosystem functioning directly speaks to the California Eelgrass Mitigation Policy's recommendation of "….no net loss of eelgrass habitat function in California" (NOAA National Marine Fisheries Service 2014) and more generally to management of Essential Fish Habitat and Designated Beneficial Uses provided by coastal embayments and eelgrass.

Beyond providing managers and other stakeholders insight into the health of the region's eelgrass, this work also represents the first practical application of an eelgrass assessment framework conceptualized by McCune et al (2020). The different combination of scaled eelgrass structural metrics were responsive to stress, tracking the relative amount of drift macroalgae found in at a site and which can smother the eelgrass – shading it and inhibiting primary production for the seagrass (e.g., Hauxwell et al. 2001, McGlathery 2001). The distribution of index scores relative to macroalgal cover presented in Figure 9 interestingly illustrates that within our dataset the worst condition eelgrass sites actually had relatively low amounts of macroalgae – at least at the time of sampling. This observation – a classic, wedge-shaped stressor response – highlights that there are a variety of potential stressors to eelgrass in the Southern California Bight that could not be accounted for in the present study. Eutrophication can lead to phytoplankton blooms and upland erosion and lead to turbid, sediment filled waters, both of which can inhibit eelgrass photosynthesis and growth (e.g., Duarte 2002, Burkholder et al. 2007). Furthermore, physical disturbance from boating activity, wave exposure, and other forms of human recreation in densely populated coastline of Southern California can deteriorate the condition of an eelgrass aggregation (Fonseca & Bell 1998, Hansen & Reidenbach 2012). Future eelgrass with this approach should synoptically collect measures of multiple types of environmental stress (e.g., physical disturbance, elevated water temperature, low salinities) to further evaluate the ZEFR index's performance and sensitivity.

In contrast to the expected, if somewhat muted, relationship with macroalgal cover, there was no apparent relationship between eelgrass condition and the prevalence of eelgrass wasting disease at sites within our dataset. Whereas macroalgal cover can be viewed as direct stressor to the eelgrass, infection by *Labyrinthula* (i.e., eelgrass wasting disease) can be viewed as an indicator of exposure to environmental stressors to the eelgrass (Burdick et al. 1993, Dawkins et al. 2018, Groner et al. 2021). As infection progresses, the disease itself become stressor to the plant (Ralph & Short 2002, Groner et al. 2016). In the present study, only the presence of wasting disease on a given shoot was recorded, the extent of the infection was not. If we had a more quantitative measure of degree of infection, there might have been a clearer relationship between the disease and the ZEFR estimates of eelgrass condition. A potential secondary reason for the lack of a clear relationship between condition and wasting disease infection rate, is that the index was built around a suite of ecosystem functions versus individual plant health. Unless grossly infection to the point where the structural integrity of the plant is compromised, only the Primary Production, and possibly Carbon Sequestration, functions would be directly impacted by the severity of wasting disease infection (Ralph & Short 2002)

In addition to being one of the few *Z. marina*-specific quantitative condition indices available in the literature (see Anderson (2020)), the ZEFR index is one of the first examples of a new generation of bioassessment indices purpose-built to assess condition from the perspective of the functions and services the biotic resource is expected to provide its resident ecosystem. These new indices (e.g., O'Connor et al. 2025) have been designed to provide the management community with a relatively direct and repeatable approach to monitoring and interpreting how their biotic resources are contributing to the functioning of their resident ecosystems. Moreover, in the present approach where multiple ecosystem functions are assessed together, one can focus on the patterns associated with functions one is most interested in, in addition to the overall condition assessment. For example, a fisheries manager would be interested in the health of their eelgrass, but they may be specifically interested in the health of an eelgrass bed relative to the provision of Nekton Habitat and supplementing Secondary Production. Our assessment tool can be "opened up" to allow a focus on specific ecosystem functions. Additionally, understanding which structural metrics inform different ecosystem functions can allow a manager to design a monitoring program to focus only on the priority functions in lieu of collecting all the structural metrics.

The results from this study are unique – a quantitative assessment of eelgrass condition and habitat quality at a regional scale is an important step forward in the management of vegetated sediments. However, this is just a first step and this condition assessment index should still be considered to be in development. By design, the index uses a "best available" approach to reference condition (e.g., Stoddard et al. 2006) and benchmarks the condition of the eelgrass relative to distribution of structural metric magnitudes across the region. As we only have data from the Autumn of 2024, the assessment benchmarks (i.e., the 25th, 50th, or 75th percentiles of each structural metric) do not incorporate any meaningful inter-annual variability (e.g., Middelboe et al. 2003, Thom et al. 2003, Ward & Amundson 2019). As more eelgrass structural data are collected across the region, the associated benchmarks of condition will most likely shift. The most glaring example in the present data set was that nearly none of the sites that were sampled in this survey had flowering shoots. This was most likely an anomaly related to 2024 (e.g., Phillips et al. 1983), but that cannot be formally evaluated at the moment until a regional, annual pattern of Southern California eelgrass flowering dynamics can be created. Consequently, that metric and its benchmarks are, for the present time, not useful in assessing eelgrass condition. As subsequent surveys of eelgrass in the Southern California Bight are conducted (https://www.sccwrp.org/about/research-areas/regional-monitoring/southern-california-bight-regional-monitoring-program/), the temporal breadth of the baseline data will increase and that temporal variability will accounted for when creating assessment condition benchmarks. Once a broad enough spatial and temporal data set for each of the structural metrics are available, the condition benchmarks for each metric can be made permanent.

The Southern California Bight is only part of eelgrass' growth range in the Northeast Pacific, from Alaska to Baja California (Green & Short 2003, Sherman & DeBruyckere 2018). Within California and along this whole growth range, there is interest from the management and regulatory communities in using a quantitative index of eelgrass condition, especially one oriented towards the ecosystem functions and services that eelgrass provides (Bernstein et al. 2011, NOAA National Marine Fisheries Service 2014, https://marinesanctuary.org/nearshore-save/). The index developed in this study provides a template that can be applied in these other habitats. The basic monitoring approach, ecosystem functions, structural metrics, and interpretation framework should translate to eelgrass in other parts of the growing range. However, we would caution against directly using the structural metric thresholds presented in Table 3. Across the whole of the Northeast Pacific coast, irradiance, water temperature, and population genetics (among other natural factors) will vary and consequently influence the upper and lower expectations for normal structural dimensions (i.e., shoot height, leaf area, and biomass) of a healthy eelgrass plant, irrespective of any additional limitations caused by exposure to stress (Hughes et al. 2009, Emmett Duffy et al. 2022). Furthermore, within California there is a gradient in the proportion of a given eelgrass bed that is subtidal versus intertidal. In the south, the majority of a given aggregation's plants are subtidal. Moving northward, a greater proportion becomes intertidal (Sherman & DeBruyckere 2018). This shift in microhabitat will most likely impact the morphology of the plants as well as the previously mentioned aspects of latitudinal variability. As the approach described in this study are propagated to other parts of the coast, local expectations in plant morphology (e.g., Table 3) will have to be created to properly score the condition of eelgrass in these new locations outside of Southern California.

Based upon our interactions with the coastal management community, the interest in condition assessment indices that speak to ecosystem functioning and services is growing. As noted earlier, we believe having strong conceptual models linking structural metrics to functions or services is key to building these assessment tools. Just as important is validating those conceptual models and their structure-function links (McCune et a. 2020). Within the ZEFR index, each conceptual model represents an expert-informed hypothesis of how different aspects of an eelgrass aggregation inform the impact it has on the surround ecosystem. Special studies focused on evaluating those conceptual models and potentially proposing new combinations of structural metrics for a given ecosystem function (see Blanch (2025) for Nekton Habitat or McCune (2021) for Carbon Sequestration) will be important for the continued evolution and improvement of this condition assessment framework.

CONCLUSIONS

More than 2/3rds of the eelgrass in the estuaries and coastal embayments of Southern California were in Good to Moderate condition in 2024. This was first regional-scale assessment of its kind, and it was based upon a new eelgrass bioassessment framework designed to evaluate eelgrass condition and quality from the perspective of ecosystem functioning (ZEFR index). This first estimate of the extent of eelgrass condition in the region was important and provides managers both an answer to their questions of the condition of the eelgrass in waterbodies they are responsible for, but also how the condition compares to the rest of the region's. Moreover, there is now an assessment tool and monitoring guidance that managers can use in their own programs at site- and regional-scales beyond this study and the present survey can serve as the starting point for temporal trend analysis in the future.

The ZEFR index still needs to mature by incorporating interannual and additional spatial variability into its interpretation scheme, but the regulatory and monitoring environment in Southern California suggests that this will happen over the coming years. Furthermore, the component conceptual models of the index should continue to be evaluated and adjusted, if need be, to improve the index’s link to functioning of the ecosystem.

LITERATURE CITED

Anderson NB (2020) The Development , Validation , and Application of the Eelgrass Health Index. University of New Hampshire

Bernstein B, Merkel K, Chesney B, Sutula M (2011) Recommendations for a Southern California Regional Eelgrass Monitoring Program - SCCWRP Technical Report 632. Costa Mesa, CA.

Blanch, C (2025) Correlates of Fish Abundance and Community Composition in Eelgrass Beds in Southern California. Masters Thesis. California State University, Long Beach

Borja A, Bricker SB, Dauer DM, Demetriades NT, Ferreira JG, Forbes AT, Hutchings P, Jia X, Kenchington R, Marques JC, Zhu C (2008) Overview of integrative tools and methods in assessing ecological integrity in estuarine and coastal systems worldwide. Mar Pollut Bull 56:1519–1537.

Boström C, Jackson EL, Simenstad CA (2006) Seagrass landscapes and their effects on associated fauna: A review. Estuar Coast Shelf Sci 68:383–403.

Burdick DM, Short FT, Wolf J (1993) An index to assess and monitor the progression of wasting disease in eelgrass Zostera marina. Mar Ecol Prog Ser 94:83–90.

Burkholder JAM, Tomasko DA, Touchette BW (2007) Seagrasses and eutrophication. J Exp Mar Bio Ecol 350:46–72.

De Clippele LH, Gafeira J, Robert K, Hennige S, Lavaleye MS, Duineveld GCA, Huvenne VAI, Roberts JM (2017) Using novel acoustic and visual mapping tools to predict the small-scale spatial distribution of live biogenic reef framework in cold-water coral habitats. Coral Reefs 36:255–268.

Cullen-Unsworth LC, Mtwana Nordlund L, Paddock J, Baker S, McKenzie LJ, Unsworth RKF, Mtwana Nordlund L, Paddock J, Baker S, McKenzie LJ, Unsworth RKF (2014) Seagrass meadows globally as a coupled social-ecological system: Implications for human wellbeing. Mar Pollut Bull 83:387–397.

Dawkins PD, Eisenlord ME, Yoshioka RM, Fiorenza E, Fruchter S, Giammona F, Winningham M, Harvell CD (2018) Environment, dosage, and pathogen isolate moderate virulence in eelgrass wasting disease. Dis Aquat Organ 130:51–63.

Dewsbury BM, Bhat M, Fourqurean JW (2016) A review of seagrass economic valuations: Gaps and progress in valuation approaches. Ecosyst Serv 18:68–77.

Dumelle, M, Kincaid, T, Olsen, AR, Weber, M (2023) spsurvey: Spatial Sampling Design and

Analysis in R. Journal of Statistical Software, 105: 1-29. doi:10.18637/jss.v105.i03

Diaz RJ, Solan M, Valente RM (2004) A review of approaches for classifying benthic habitats and evaluating habitat quality. J Environ Manage 73:165–181.

Doughty CL, Cavanaugh KC, Ambrose RF, Stein ED (2019) Evaluating regional resiliency of coastal wetlands to sea level rise through hypsometry-based modeling. Glob Chang Biol 25:78–92.

Duarte CM (2002) The future of seagrass meadows. Environ Conserv 29:192–206.

Emmett Duffy J, Stachowicz JJ, Reynolds PL, Hovel KA, Jahnke M, Sotka EE, Bostrom C, Boyer KE, Cusson M, Eklof J, Engelen AH, Eriksson BK, Joel Fodrie F, Griffin JN, Hereu CM, Hori M, Randall Hughes A, Ivanov M V., Jorgensen P, Kruschel C, Lee KS, Lefcheck JS, Moksnes PO, Nakaoka M, O’Connor MI, O’Connor NE, Orth RJ, Peterson BJ, Reiss H, Reiss K, Paul Richardson J, Rossi F, Ruesink JL, Schultz ST, Thormar J, Tomas F, Unsworth R, Voigt E, Whalen MA, Ziegler SL, Olsen JL (2022) A Pleistocene legacy structures variation in modern seagrass ecosystems. Proc Natl Acad Sci U S A 119:1–8.

Fonseca M, Bell SS (1998) Influence of physical settings on seagrass landscapes near Beaufort, North Carolina, USA. Mar Ecol Prog Ser 171:109–121.

Gillett DJ (2010) Effects of habitat quality on secondary production in shallow estuarine waters and the consequences for the benthic-pelagic food web. PhD. Dissertation. The College of William and Mary, Virginia Institute of Marine Science.

Gillett DJ, Enright W, Walker JB (2022) Southern California Bight 2018 Regional Monitoring Program: Volume III. Benthic Infauna. SCCWRP Technical Report 1289. Costa Mesa, CA.

Green EP, Short FT (2003) World Atlas of Seagrasses. UNEP World Conservation Monitoring Cetere (ed) University of California Press, Berkley, CA.

Grizzle RE, Brodeur MA, Abeels HA, Greene JK (2008) Bottom habitat mapping using towed underwater videography: Subtidal oyster reefs as an example application. J Coast Res 24:103–109.

Groner ML, Burge CA, Kim CJS, Rees E, Van Alstyne KL, Yang S, Wyllie-Echeverria S, Drew Harvell C (2016) Plant characteristics associated with widespread variation in eelgrass wasting disease. Dis Aquat Organ 118:159–168.

Groner ML, Eisenlord ME, Yoshioka RM, Fiorenza EA, Dawkins PD, Graham OJ, Winningham M, Vompe A, Rivlin ND, Yang B, Burge CA, Rappazzo B, Gomes CP, Drew Harvell C (2021) Warming sea surface temperatures fuel summer epidemics of eelgrass wasting disease. Mar Ecol Prog Ser

679:47–58.

Hansen JCR, Reidenbach MA (2012) Wave and tidally driven flows in eelgrass beds and their effect on sediment suspension. Mar Ecol Prog Ser 448:271–287.

Hauxwell J, Cebrián J, Furlong C, Valiela I (2001) Macroalgal canopies contribute to eelgrass (Zostera marina) decline in temperate estuarine ecosystems. Ecology 82:1007–1022.

Hawkins CP, Olson JR, Hill RA (2010) The reference condition: predicting benchmarks for ecological and water-quality assessments. J North Am Benthol Soc 29:312–343.

Heck KL, Carruthers TJB, Duarte CM, Hughes AR, Kendrick G, Orth RJ, Williams SW (2008) Trophic transfers from seagrass meadows subsidize diverse marine and terrestrial consumers. Ecosystems 11:1198–1210.

Horvitz DG, Thompson DJ (1952) A Generalization of Sampling Without Replacement From a Finite Universe.

Hughes AR, Stachowicz JJ, Williams SL (2009) Morphological and physiological variation among seagrass (Zostera marina) genotypes. Oecologia 159:725–733.

Johnson MR, Williams SL, Lieberman CH, Solbak A (2003) Changes in the abundance of the seagrasses Zostera marina L. (eelgrass) and Ruppia maritima L. (widgeongrass) in San Diego, California, following an El Nino event. Estuaries 26:106–115.

Jones CG, Lawton JH, Shachak M (1994) Organisms as ecosystem engineers. Oikos 69:373–386.

McCune K, Gillett DJ, Stein ED (2020) Methods and Guidance on Assessing the Ecological Functioning of Submerged Aquatic Vegetation in Southern California Estuaries and Embayments. Costa Mesa, CA.

McGlathery KJ (2001) Macroalgal blooms contribute to the decline of seagrass in nutrient-enriched coastal waters. J Phycol 37:453–456.

Merkel & Associates Inc. (2011) 2011 San Diego Bay Eelgrass Inventory San Diego Unified Port District.

Merkel & Associates Inc. (2014a) 2014 San Diego Bay Eelgrass Inventory.

Merkel & Associates Inc. (2024) 2023 San Diego Bay Eelgrass Inventory Update. San Diego, CA.

Merkel & Associates Inc. (2023) San Diego Regional Eelgrass Surveys. San Diego, CA.

Merkel & Associates Inc. (2014b) Southern California Bight Regional Eeglrass Surveys. NOAA/

National Marine Fisheries Service West Coast Region Protected Resources Division, San Diego, CA.

Middelboe AL, Sand-Jensen K, Krause-Jensen D (2003) Spatial and interannual variations with depth in eelgrass populations. J Exp Mar Bio Ecol 291:1–15.

Montefalcone M (2009) Ecosystem health assessment using the Mediterranean seagrass Posidonia oceanica : A review. 9:595–604.

Neto JM, Barroso D V., Barría P (2013) Seagrass Quality Index (SQI), a Water Framework Directive compliant tool for the assessment of transitional and coastal intertidal areas. Ecol Indic 30:130–137.

NOAA National Marine Fisheries Service (2014) California Eelgrass Mitigation Policy and Implementing Guidelines.

Nordlund LM, Koch EW, Barbier EB, Creed JC, Mtwana Nordlund L, Koch EW, Barbier EB, Creed JC (2016) Seagrass ecosystem services and their variability across genera and geographical regions. PLoS One 11:1–23.

O’Connor K, Fulkerson B, Walker J, Stein E, Whitcraft CR, Huckeba J (2025) Estuary Marine Protected Area Fall 2023 Data Analysis Report SCCWRP Technical Report #1430. Costa Mesa, CA.

Olsen AR, Peck D V. (2008) Survey design and extent estimates for the Wadeable Streams Assessment. J North Am Benthol Soc 27:822–836.

Orth RJ, Heck KL, van Montfrans J (1984) Faunal communities in seagrass beds: A review of the influence of plant structure and prey characteristics on predator-prey relationships. 339–350.

Phillips RC, Grant WS, McRoy CP (1983) Reproductive strategies of eelgrass (Zostera marina L.). Aquat Bot 16:1–20.

Polis GA, Anderson WB, Holt RD (1997) Toward an integration of landscape and food web ecology: The dynamics of spatially subsidized food webs. Annu Rev Ecol Syst 28:289–316.

Ralph PJ, Short FT (2002) Impact of the wasting disease pathogen, Labyrinthula zosterae, on the photobiology of eelgrass Zostera marina. Mar Ecol Prog Ser 226:265–271.

Ruiz-Frau A, Gelcich S, Hendriks IE, Duarte CM, Marbà N (2017) Current state of seagrass ecosystem services: Research and policy integration. Ocean Coast Manag 149:107–115.

San Francisco Estuary Institute, Southern California Coastal Water Research Project (2025)

Tracking Coastal Habitat Change Over Time : Considerations for a Statewide Mapping Program - SCCWRP Technical Report 1438. Costa Mesa, CA.

Schiff K, Greenstein D, Dodder N, Gillett DJ (2016) Southern California Bight regional monitoring. Reg Stud Mar Sci 4.

Sherman K, DeBruyckere LA (2018) Eelgrass Habitats on the U.S. West Coast. State of the Knowledge of Eelgrass Ecosystem Services and Eelgrass Extent. A publication prepared by the Pacific Marine and Estuarine Fish Habitat Partnership. 67.

Stevens DL, Olsen AR (2004) Spatially Balanced Sampling of Natural Resources. J Am Stat Assoc 99:262–278.

Stevens DL, Olsen AR (2003) Variance estimation for spatially balanced samples of environmental resources. Environmetrics 14:593–610.

Stoddard JL, Larsen DP, Hawkins CP, Johnson RK, Norris RH (2006) Setting expectations for the ecological conidition of streams: The concept of refernce condition. Ecol Appl 16:1267–1276.

Stolzenbach K, Johnson T, Stransky C, Rudolph J, Isham B, Merkel K, Stidum B, Gonzales C, Wood V, Prickett K, McPherson R, Centeno C, Luedy J (2021) 2018 Biological Surveys of the Los Angeles and Long Beach Harbors. San Diego, CA.

Thom RM, Borde AB, Rumrill S, Woodruff DL, Williams GD, Southard JA, Sargeant SL (2003) Factors Influencing Spatial and Annual Variability in Eelgrass (Zostera marina L.) Meadows in Willapa Bay, Washington, and Coos Bay, Oregon, Estuaries. Estuaries 26:1117–1129.

Vandermeulen H (2014) Bay-scale assessment of eelgrass beds using sidescan and video. Helgol Mar Res 68:559–569.

Ward DH, Amundson CL (2019) Monitoring annual trends in abundance of eelgrass (Zostera marina) at Izembek National Wildlife Refuge, Alaska, 2018: U.S. Geological Survey Open-File Report 2019-1042. Reston, VA.

Whitfield AK, Elliott M (2002) Fishes as indicators of environmental and ecological changes within estuaries: A review of progress and some suggestions for the future. J Fish Biol 61:229–250.

Wright JP, Jones CG (2006) The concept of organisms as ecosystem engineers ten years on: Progress, limitations, and challenges. Bioscience 56:203–209.

TABLES

Table 1. A matrix summarizing the expert consensus on how different structural metrics (vertical axis) of an eelgrass aggregation inform key ecosystem functions (horizontal axis). Where the intersections are shaded grey, the panel decided that the that the structural metric would be linked to the function (S-F Link). After McCune et al (2020).

	Ecosystem Services and Functions						
Structural Metrics	Carbon Sequestration	Improvement of Water Quality	Nekton Habitat	Primary Production	Secondary Production	Substrate Stabilization	Waterfowl Habitat
Above ground biomass	S-F Link	S-F Link		S-F Link	S-F Link		
Above ground C and N content				S-F Link	S-F Link		
Below ground biomass	S-F Link			S-F Link	S-F Link	S-F Link	
Below ground C and N content				S-F Link			
Patch area	S-F Link					S-F Link	S-F Link
Perimeter		S-F Link	S-F Link				
Percent cover		S-F Link	S-F Link				
Shoot density		S-F Link	S-F Link	S-F Link	S-F Link	S-F Link	
Leave per shoot				S-F Link	S-F Link		
Flowering shoot density				S-F Link			
Shoot height		S-F Link			S-F Link	S-F Link	S-F Link
Leaf area		S-F Link	S-F Link	S-F Link		S-F Link	
Epiphyte biomass			S-F Link	S-F Link	S-F Link		
Infauna diversity			S-F Link		S-F Link		
Infauna biomass					S-F Link		

Table 2. Overall condition scores and categories for each sample site within the three sampling strata. The growth type, number of quadrats sampled, water depth corrected to mean high water, and location of the site are also presented. NR indicates where data were not recorded

Stratum	Waterbody	Site ID	Field Replicate	Overall Condition Score	Overall Condition Category	Growth Type	Central Depth (m)	Central Latitude (dd)	Central Longitude (dd)	Number of Quadrats
Large Embayment	Mission Bay	RESCQ-021	1	3.5	Good	Bed	2.53	32.7629	-117.2489	7
	San Diego Bay	RESCQ-022	1	2.5	Moderate	Meadow	1.75	32.6599	-117.1506	7
	San Diego Bay	RESCQ-023	1	3.1	Moderate	Meadow	2.73	32.6798	-117.2228	7
	Mission Bay	RESCQ-024	1	3.0	Moderate	Meadow	2.92	32.7911	-117.2233	7
	San Diego Bay	RESCQ-025	1	1.9	Poor	Meadow	1.37	32.6379	-117.1169	7
	San Diego Bay	RESCQ-026	1	2.4	Moderate	Meadow	1.41	32.6421	-117.1201	7
	Mission Bay	RESCQ-027	1	2.9	Moderate	Meadow	3.09	32.7784	-117.2241	7
	Mission Bay	RESCQ-028	1	1.9	Poor	Meadow	3.96	32.7903	-117.2177	7
	San Diego Bay	RESCQ-029	1	2.4	Moderate	Meadow	1.39	32.6113	-117.1321	7
	San Diego Bay	RESCQ-030	1	2.5	Moderate	Meadow	4.43	32.6761	-117.1653	7
Small Embayment	Newport back bay	RESCQ-012	1	2.0	Poor	Bed	NR	33.6218	-117.8934	7
	Cabrillo Beach	RESCQ-013	1	3.8	Good	Bed	2.55	33.7090	-118.2782	7
	East San Pedro Bay	RESCQ-014	1	1.3	Bad	Patch	2.64	33.7582	-118.1515	2
	Newport back bay	RESCQ-016	1	1.6	Bad	Bed	NR	33.6211	-117.8974	7
	Cabrillo Beach	RESCQ-017	1	3.0	Moderate	Meadow	2.33	33.7097	-118.2801	7
	Dana Point Harbor Common Eelgrass Beds	RESCQ-020	1	2.3	Moderate	Patch	7.40	33.4568	-117.6973	2
	East San Pedro Bay	RESCQ-061	1	2.7	Moderate	Patch	3.07	33.7607	-118.1612	2
	Talbert Marsh	RESCQ-062	1	2.1	Poor	Bed	NR	33.6362	-117.9577	7
	Oceanside Harbor	RESCQ-064	1	3.0	Moderate	Meadow	3.78	33.2108	-117.4035	7
	East San Pedro Bay	RESCQ-065	1	3.4	Good	Meadow	2.80	33.7613	-118.1807	7
Estuary	Anaheim Bay - Signal Pond	RESCQ-001	1	2.7	Moderate	Bed	0.93	33.7425	-118.0804	7
	Bolsa Chica Estuary	RESCQ-002	1	1.6	Bad	Bed	NR	33.6864	-118.0364	7
	Anaheim Bay - Case Pond	RESCQ-003	1	1.8	Poor	Bed	1.25	33.7463	-118.0720	7
	Batiquitos Lagoon	RESCQ-004	1	3.2	Moderate	Meadow	1.51	33.0890	-117.2898	7
	Batiquitos Lagoon	RESCQ-004	2	3.8	Good	Meadow	1.51	33.0890	-117.2898	7
	Agua Hedionda Lagoon	RESCQ-007	1	3.0	Moderate	Fringing Bed	1.25	33.1418	-117.3317	5
	Agua Hedionda Lagoon	RESCQ-008	1	2.5	Moderate	Bed	1.89	33.1425	-117.3224	7
	Anaheim Bay	RESCQ-009	1	2.0	Poor	Fringing Bed	0.85	33.7309	-118.0838	7
	Anaheim Bay	RESCQ-010	1	2.7	Moderate	Meadow	1.05	33.7364	-118.0759	7
	Batiquitos Lagoon	RESCQ-031	1	3.4	Good	Meadow	2.81	33.0851	-117.3056	7
	Bolsa Chica Estuary	RESCQ-033	1	2.3	Moderate	Meadow	2.59	33.6945	-118.0343	7
	San Dieguito Lagoon	RESCQ-060	1	2.4	Moderate	Fringing Bed	1.57	32.9725	-117.2655	5

Table 2 - Overall condition scores and categories for each sample site within the three sampling strata. The growth type, number of quadrats sampled, water depth corrected to mean high water, and location of the site are also presented.

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	San Diego Bay	RESCQ-023	1	3.1	Moderate	Meadow	2.73	32.6798	-117.2228	7
	Mission Bay	RESCQ-024	1	3.0	Moderate	Meadow	2.92	32.7911	-117.2233	7
	San Diego Bay	RESCQ-025	1	1.9	Poor	Meadow	1.37	32.6379	-117.1169	7
	San Diego Bay	RESCQ-026	1	2.4	Moderate	Meadow	1.41	32.6421	-117.1201	7
	Mission Bay	RESCQ-027	1	2.9	Moderate	Meadow	3.09	32.7784	-117.2241	7
	Mission Bay	RESCQ-028	1	1.9	Poor	Meadow	3.96	32.7903	-117.2177	7
	San Diego Bay	RESCQ-029	1	2.4	Moderate	Meadow	1.39	32.6113	-117.1321	7
	San Diego Bay	RESCQ-030	1	2.5	Moderate	Meadow	4.43	32.6761	-117.1653	7
Small Embayment	Newport back bay	RESCQ-012	1	2.0	Poor	Bed	not recorded	33.6218	-117.8934	7
	Cabrillo Beach	RESCQ-013	1	3.8	Good	Bed	2.55	33.7090	-118.2782	7
	East San Pedro Bay	RESCQ-014	1	1.3	Bad	Patch	2.64	33.7582	-118.1515	2
	Newport back bay	RESCQ-016	1	1.6	Bad	Bed	not recorded	33.6211	-117.8974	7
	Cabrillo Beach	RESCQ-017	1	3.0	Moderate	Meadow	2.33	33.7097	-118.2801	7
	Dana Point Harbor Common Eelgrass Beds	RESCQ-020	1	2.3	Moderate	Patch	7.40	33.4568	-117.6973	2
	East San Pedro Bay	RESCQ-061	1	2.7	Moderate	Patch	3.07	33.7607	-118.1612	2
	Talbert Marsh	RESCQ-062	1	2.1	Poor	Bed	not recorded	33.6362	-117.9577	7
	Oceanside Harbor	RESCQ-064	1	3.0	Moderate	Meadow	3.78	33.2108	-117.4035	7
	East San Pedro Bay	RESCQ-065	1	3.4	Good	Meadow	2.80	33.7613	-118.1807	7
Estuary	Anaheim Bay - Signal Pond	RESCQ-001	1	2.7	Moderate	Bed	0.93	33.7425	-118.0804	7
	Bolsa Chica Estuary	RESCQ-002	1	1.6	Bad	Bed	not recorded	33.6864	-118.0364	7
	Anaheim Bay - Case Pond	RESCQ-003	1	1.8	Poor	Bed	1.25	33.7463	-118.0720	7
	Batiquitos Lagoon	RESCQ-004	1	3.2	Moderate	Meadow	1.51	33.0890	-117.2898	7
	Batiquitos Lagoon	RESCQ-004	2	3.8	Good	Meadow	1.51	33.0890	-117.2898	7
	Agua Hedionda Lagoon	RESCQ-007	1	3.0	Moderate	Fringing Bed	1.25	33.1418	-117.3317	5
	Agua Hedionda Lagoon	RESCQ-008	1	2.5	Moderate	Bed	1.89	33.1425	-117.3224	7
	Anaheim Bay	RESCQ-009	1	2.0	Poor	Fringing Bed	0.85	33.7309	-118.0838	7
	Anaheim Bay	RESCQ-010	1	2.7	Moderate	Meadow	1.05	33.7364	-118.0759	7
	Batiquitos Lagoon	RESCQ-031	1	3.4	Good	Meadow	2.81	33.0851	-117.3056	7
	Bolsa Chica Estuary	RESCQ-033	1	2.3	Moderate	Meadow	2.59	33.6945	-118.0343	7
	San Dieguito Lagoon	RESCQ-060	1	2.4	Moderate	Fringing Bed	1.57	32.9725	-117.2655	5

Table 3. Population estimates for each structural metric measured at the 32 sample sites. Percentiles were calculated from values averaged across all of the quadrats at a given site. For the index, values ≥ 75th percentile were scored a 4, < 75th percentile & ≥50th percentile scored a 3, <50th percentile & ≥25th percentile scored a 2, and values <25th percentile were scored a 1.

Metric	75th Percentile	50th Percentile	25th Percentile
Above Ground Biomass (mg AFDM)	850.94	509.35	200.71
Bed Perimeter (m)	140.00	140.00	111.00
Below Ground Biomass (mg AFDM)	360.24	254.06	203.55
Epiphyte Biomass (mg AFDM)	62.07	19.87	10.50
Flowering Shoot Density (count)	0.00	0.00	0.00
Mean Leaf Area (cm^2)	21.33	12.14	8.24
Mean Leaves per Shoot (count)	4.97	4.44	4.11
Percent Cover (%)	48.21	36.07	27.14
Shoot Density	49.25	31.36	19.68
Mean Maximum Shoot Height (cm)	52.81	42.47	28.77
Mean Shoot Width (mm)	3.54	3.17	2.78

Table 4. Condition scores and categories (score-category) for each of the component functions used to assess the overall condition of the eelgrass at each site within the three sampling strata.

Stratum	Waterbody	Site ID	Field Replicate	Carbon Sequestration	Improving Water Quality	Nekton Habitat	Primary Production	Secondary Production	Substrate Stabilization	Waterfowl Habitat
Large Embayment	Mission Bay	RESCQ-021	1	3.7 - Good	3.2 - Moderate	3.4 - Good	3.1 - Moderate	3.2 - Moderate	3.6 - Good	4 - Good
	San Diego Bay	RESCQ-022	1	2.7 - Moderate	2 - Poor	2.4 - Moderate	2.6 - Moderate	2.3 - Moderate	2.2 - Poor	3 - Moderate
	San Diego Bay	RESCQ-023	1	3.3 - Good	2.8 - Moderate	2.8 - Moderate	3.3 - Good	3 - Moderate	2.8 - Moderate	3.5 - Good
	Mission Bay	RESCQ-024	1	3.7 - Good	2.6 - Moderate	2.6 - Moderate	3 - Moderate	2.8 - Moderate	3 - Moderate	3.5 - Good
	San Diego Bay	RESCQ-025	1	2.3 - Moderate	1.2 - Bad	1.6 - Bad	2.1 - Poor	1.8 - Poor	1.6 - Bad	2.5 - Moderate
	San Diego Bay	RESCQ-026	1	3 - Moderate	2 - Poor	2.4 - Moderate	2.4 - Moderate	2.2 - Poor	2.4 - Moderate	2.5 - Moderate
	Mission Bay	RESCQ-027	1	2.7 - Moderate	3 - Moderate	3.2 - Moderate	2.6 - Moderate	2.3 - Moderate	2.8 - Moderate	3.5 - Good
	Mission Bay	RESCQ-028	1	1.3 - Bad	1.6 - Bad	1.8 - Poor	2.1 - Poor	2 - Poor	1.8 - Poor	2.5 - Moderate
	San Diego Bay	RESCQ-029	1	2.7 - Moderate	2.8 - Moderate	2.4 - Moderate	3 - Moderate	2.7 - Moderate	2.4 - Moderate	1 - Bad
	San Diego Bay	RESCQ-030	1	3 - Moderate	1.8 - Poor	2.2 - Poor	2.6 - Moderate	2.5 - Moderate	2.4 - Moderate	3 - Moderate
Small Embayment	Newport back bay	RESCQ-012	1	1 - Bad	2.2 - Poor	2.5 - Moderate	1.6 - Bad	1.6 - Bad	2.3 - Moderate	3 - Moderate
	Cabrillo Beach	RESCQ-013	1	4 - Good	3.4 - Good	3.4 - Good	3.9 - Good	3.8 - Good	3.8 - Good	4 - Good
	East San Pedro Bay	RESCQ-014	1	1.7 - Bad	1 - Bad	1 - Bad	1.9 - Poor	1.5 - Bad	1.4 - Bad	1 - Bad
	Newport back bay	RESCQ-016	1	1 - Bad	1.8 - Poor	2 - Poor	1.4 - Bad	1.4 - Bad	1.8 - Poor	2 - Poor
	Cabrillo Beach	RESCQ-017	1	3.3 - Good	2.8 - Moderate	2.4 - Moderate	3.1 - Moderate	3.2 - Moderate	3 - Moderate	3 - Moderate
	Dana Point Harbor Common Eelgrass Beds	RESCQ-020	1	1.7 - Bad	2.6 - Moderate	2.2 - Poor	2.7 - Moderate	2.5 - Moderate	2.2 - Poor	2.5 - Moderate
	East San Pedro Bay	RESCQ-061	1	2.7 - Moderate	3 - Moderate	2.4 - Moderate	3.4 - Good	3.2 - Moderate	2.4 - Moderate	2 - Poor
	Talbert Marsh	RESCQ-062	1	1.5 - Bad	2.4 - Moderate	2.5 - Moderate	2.2 - Poor	2.4 - Moderate	1.8 - Poor	2 - Poor
	Oceanside Harbor	RESCQ-064	1	3.3 - Good	2.6 - Moderate	2.8 - Moderate	3.1 - Moderate	2.8 - Moderate	3 - Moderate	3.5 - Good
	East San Pedro Bay	RESCQ-065	1	3 - Moderate	3.4 - Good	3.6 - Good	3.3 - Good	3.2 - Moderate	3.2 - Moderate	4 - Good
Estuary	Anaheim Bay - Signal Pond	RESCQ-001	1	3.3 - Good	2 - Poor	2.4 - Moderate	2.9 - Moderate	2.7 - Moderate	2.8 - Moderate	2.5 - Moderate
	Bolsa Chica Estuary	RESCQ-002	1	2 - Poor	1.4 - Bad	1.5 - Bad	1.8 - Poor	1.8 - Poor	1.8 - Poor	1 - Bad
	Anaheim Bay - Case Pond	RESCQ-003	1	1.7 - Bad	1.8 - Poor	1.6 - Bad	2.4 - Moderate	2 - Poor	1.8 - Poor	1 - Bad
	Batiquitos Lagoon	RESCQ-004	1	4 - Good	3.2 - Moderate	3.2 - Moderate	3 - Moderate	2.8 - Moderate	3.2 - Moderate	3 - Moderate
	Batiquitos Lagoon	RESCQ-004	2	4 - Good	4 - Good	4 - Good	3.4 - Good	3.3 - Good	4 - Good	4 - Good
	Agua Hedionda Lagoon	RESCQ-007	1	2.3 - Moderate	3.8 - Good	3.2 - Moderate	3.1 - Moderate	3 - Moderate	2.8 - Moderate	2.5 - Moderate
	Agua Hedionda Lagoon	RESCQ-008	1	2.7 - Moderate	2.4 - Moderate	2.4 - Moderate	2.4 - Moderate	2.2 - Poor	2.8 - Moderate	2.5 - Moderate
	Anaheim Bay	RESCQ-009	1	1.7 - Bad	2 - Poor	2.2 - Poor	2.3 - Moderate	2 - Poor	2 - Poor	1.5 - Bad
	Anaheim Bay	RESCQ-010	1	2.7 - Moderate	2.6 - Moderate	3.2 - Moderate	2.3 - Moderate	2 - Poor	3 - Moderate	3 - Moderate
	Batiquitos Lagoon	RESCQ-031	1	3 - Moderate	3.6 - Good	3.8 - Good	3 - Moderate	3 - Moderate	3.4 - Good	4 - Good
	Bolsa Chica Estuary	RESCQ-033	1	2 - Poor	2.2 - Poor	2.8 - Moderate	2.1 - Poor	1.8 - Poor	2.4 - Moderate	3 - Moderate
	San Dieguito Lagoon	RESCQ-060	1	2 - Poor	3 - Moderate	2.6 - Moderate	2.9 - Moderate	2.5 - Moderate	2.4 - Moderate	1.5 - Bad

Table 5. Area-weighted estimates of overall eelgrass condition in each of the 4 condition categories (+/- 95% confidence intervals calculated with the Horvitz-Thompson estimator) for the whole of the Southern California Bight and the three sampling strata used in the present study.

Subpopulation	Category	% of Area	Lower 95% CI	Upper 95% CI
Southern California Bight	Good	12.1	0.0	27.1
	Moderate	65.3	42.5	88.2
	Poor	19.7	0.0	39.4
	Bad	2.9	0.0	6.7
Large Embayments	Good	10.0	0.0	28.9
	Moderate	70.0	41.1	98.9
	Poor	20.0	0.0	45.2
	Bad	0.0	0.0	0.0
Small Embayments	Good	20.0	0.0	45.2
	Moderate	40.0	9.2	70.8
	Poor	20.0	0.0	45.2
	Bad	20.0	0.0	45.2
Estuaries	Good	18.2	0.0	41.3
	Moderate	54.5	24.7	84.4
	Poor	18.2	0.0	41.3
	Bad	9.1	0.0	26.4

Table 6. Area-weighted estimates of eelgrass condition relative to the component ecosystem functions in each of the 4 condition categories (+/- 95% confidence intervals calculated with the Horvitz-Thompson estimator) for the whole of the Southern California Bight. Estimates for the three sample strata are in Supplemental Material A

Component Function	Category	% of Area	Lower 95% CI	Upper 95% CI
Carbon Sequestration	Good	28.0	5.5	50.4
	Moderate	53.3	28.9	77.6
	Poor	4.7	0.0	10.3
	Bad	14.1	0.0	29.4
Improving Water Quality	Good	6.0	0.0	12.1
	Moderate	46.1	21.5	70.8
	Poor	30.4	7.8	53.0
	Bad	17.5	0.0	37.0
Nekton Habitat	Good	12.1	0.0	27.1
	Moderate	58.4	34.2	82.5
	Poor	18.1	0.0	37.7
	Bad	11.4	0.0	26.4
Primary Production	Good	11.2	0.0	26.0
	Moderate	67.8	45.1	90.4
	Poor	19.7	0.0	39.4
	Bad	1.4	0.0	3.3
Secondary Production	Good	2.2	0.0	5.7
	Moderate	63.6	40.6	86.6
	Poor	32.2	9.4	54.9
	Bad	2.0	0.0	4.5
Substrate Stabilization	Good	11.4	0.0	26.4
	Moderate	58.4	34.2	82.5
	Poor	21.9	2.1	41.8
	Bad	8.3	0.0	22.8
Waterfowl Habitat	Good	35.6	11.5	59.7
	Moderate	47.9	23.2	72.5
	Poor	2.0	0.0	4.5
	Bad	14.5	0.0	30.1

APPENDIX A – PERCENT AREA OF COMPONENT ECOSYSTEM FUNCTION SCORES BY STRATUM

Table A1. Area-weighted estimates of eelgrass condition in each of the 4 condition categories relative to the component ecosystem functions (+/- 95% confidence intervals calculated with the Horvitz-Thompson estimator) separated among the three sample strata

Stratum	Component Function	Condition	% of Area	Lower 95% CI	Upper 95% CI
Large Embayment	Carbon Sequestration	Good	30.0	1.1	58.9
		Moderate	60.0	29.1	90.9
		Poor	0.0	0.0	0.0
		Bad	10.0	0.0	28.9
	Improving Water Quality	Good	0.0	0.0	0.0
		Moderate	50.0	18.5	81.5
		Poor	30.0	1.1	58.9
		Bad	20.0	0.0	45.2
	Nekton Habitat	Good	10.0	0.0	28.9
		Moderate	60.0	29.1	90.9
		Poor	20.0	0.0	45.2
		Bad	10.0	0.0	28.9
	Primary Production	Good	10.0	0.0	28.9
		Moderate	70.0	41.1	98.9
		Poor	20.0	0.0	45.2
		Bad	0.0	0.0	0.0
	Secondary Production	Good	0.0	0.0	0.0
		Moderate	70.0	41.1	98.9
		Poor	30.0	1.1	58.9
		Bad	0.0	0.0	0.0
	Substrate Stabilization	Good	10.0	0.0	28.9
		Moderate	60.0	29.1	90.9
		Poor	20.0	0.0	45.2
		Bad	10.0	0.0	28.9
	Waterfowl Habitat	Good	40.0	9.1	70.9
		Moderate	50.0	18.5	81.5
		Poor	0.0	0.0	0.0
		Bad	10.0	0.0	28.9

Table A1. Continued.

Stratum	Component Function	Condition	% of Area	Lower 95% CI	Upper 95% CI
Small Embayment	Carbon Sequestration	Good	30.0	1.2	58.8
		Moderate	20.0	0.0	45.2
		Poor	0.0	0.0	0.0
		Bad	50.0	18.5	81.5
	Improving Water Quality	Good	20.0	0.0	45.2
		Moderate	50.0	18.5	81.5
		Poor	20.0	0.0	45.2
		Bad	10.0	0.0	28.9
	Nekton Habitat	Good	20.0	0.0	45.2
		Moderate	50.0	18.5	81.5
		Poor	20.0	0.0	45.2
		Bad	10.0	0.0	28.9
	Primary Production	Good	30.0	1.2	58.8
		Moderate	30.0	1.2	58.8
		Poor	20.0	0.0	45.2
		Bad	20.0	0.0	45.2
	Secondary Production	Good	10.0	0.0	28.9
		Moderate	60.0	29.2	90.8
		Poor	0.0	0.0	0.0
		Bad	30.0	1.2	58.8
	Substrate Stabilization	Good	10.0	0.0	28.9
		Moderate	50.0	18.5	81.5
		Poor	30.0	1.2	58.8
		Bad	10.0	0.0	28.9
	Waterfowl Habitat	Good	30.0	1.2	58.8
		Moderate	30.0	1.2	58.8
		Poor	30.0	1.2	58.8
		Bad	10.0	0.0	28.9

Table A1. Continued.

Stratum	Component Function	Condition	% of Area	Lower 95% CI	Upper 95% CI
Estuary	Carbon Sequestration	Good	18.2	0.0	41.3
		Moderate	36.4	7.5	65.2
		Poor	27.3	0.5	54.0
		Bad	18.2	0.0	41.3
	Improving Water Quality	Good	27.3	0.5	54.0
		Moderate	27.3	0.5	54.0
		Poor	36.4	7.5	65.2
		Bad	9.1	0.0	26.4
	Nekton Habitat	Good	18.2	0.0	41.3
		Moderate	54.5	24.7	84.4
		Poor	9.1	0.0	26.4
		Bad	18.2	0.0	41.3
	Primary Production	Good	9.1	0.0	26.4
		Moderate	72.7	46.0	99.5
		Poor	18.2	0.0	41.3
		Bad	0.0	0.0	0.0
	Secondary Production	Good	9.1	0.0	26.4
		Moderate	36.4	7.5	65.2
		Poor	54.5	24.7	84.4
		Bad	0.0	0.0	0.0
	Substrate Stabilization	Good	18.2	0.0	41.3
		Moderate	54.5	24.7	84.4
		Poor	27.3	0.5	54.0
		Bad	0.0	0.0	0.0
	Waterfowl Habitat	Good	18.2	0.0	41.3
		Moderate	45.5	15.6	75.3
		Poor	0.0	0.0	0.0
		Bad	36.4	7.5	65.2