Project: Regional Board 9 - Development of a Monitoring and Assessment Framework for Submerged Aquatic Vegetation (SAV)

Technical Report #2: Revisiting Bernstein et al. 2011 & Developing an SAV Assessment Bibliography

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Introduction

Zostera marina (eelgrass) is an important component of many temperate and boreal coastal habitats across the globe and is a key natural resource and habitat feature within many Southern California embayments. Despite this conceptual importance, Southern California (and many other coastal regions) has historically lacked a comprehensive, standardized approach to monitoring and assessing eelgrass as either a resource or a unique estuarine habitat. In recognition of this shortcoming, Bernstein et al. (2011) [Herein referred to as the Bernstein report] assembled a panel of regulated, regulatory, environmental, and research organizations to develop a roadmap for parties interested in eelgrass to develop a regional-scale monitoring program. This expert panel was given the charge to identify what the goals of a monitoring program for eelgrass should be, the status of monitoring efforts to date, and what further advances needed to be made in order to develop a regional monitoring program.

As detailed in the report, the expert panel identified series of key management questions an eelgrass monitoring program should address and produced a number of recommendations for realizing their goal of a comprehensive monitoring program. Though it touched on a broader suite of topics, the two key products of the report were 1.) Identified gaps in knowledge about eelgrass extent (and to a lesser degree condition) in the region; and 2.) a list of recommendations to inform what the infrastructure needs are for a monitoring program that is focused on extent estimates of eelgrass. In our opinion, these two pieces were quite useful and impacted the direction of eelgrass research/monitoring since the publication of the Bernstein report (more below).

Beyond how it has already been used, we believe that the Bernstein report can serve as a foundation from which we can broaden the way that eelgrass is considered by the management community and, in turn, how it is assessed. Whereas the focus of the Bernstein report was on developing an implementation strategy for monitoring eelgrass extent (i.e., eelgrass as a natural resource), we are more concerned with developing tools for assessing SAV that can be used in any future monitoring programs; tools that address SAV not only as a resource (i.e., assessing extent), but also as a habitat that facilitates and enhances a diverse coastal ecosystem (i.e., assessing condition and assessing function).

Our goals are to implement several key recommendations of the Bernstein report including 1) to enhance our understanding of how eelgrass communities respond to natural and anthropogenic gradients and pressures and 2) to develop standardized metrics and methods of data collection that can be used to assess eelgrass condition and ecological function.

A considerable amount of research on submerged aquatic vegetation in general, and eelgrass in specific, has occurred in the intervening years since the publication of the Bernstein report. To reflect this ongoing growth, we have attempted to collate all this information, as well as other important key works to form the underpinnings of our proposed assessment framework. For ease of reference we have aggregated this information into an annotated bibliography (see below). Interestingly, despite this additional work, little progress has been made in developing a true regional eelgrass monitoring program in Southern California. It is our hope that by developing an assessment framework building off the Bernstein report and with field-tested protocols, we will help in realizing our shared goals of multifaceted, regional-scale eelgrass monitoring program in Southern California.

In response to the recommendations of the Bernstein report, as well as a response to the ongoing interest in eelgrass ecosystems, we propose a multi-tiered assessment framework that could be implemented in local and regional eelgrass monitoring programs. The specific goals of the present report are to:

- Provide a brief summary of the recommendations of the Bernstein report
- Contextualize those recommendations with how they have been acted upon by local agencies and the types of research being done by the eelgrass scientific community in the region
- Present our proposed assessment framework within the context of the Bernstein report
- Provide an annotated bibliography of the relevant scientific research and regional eelgrass surveys that inform our proposed assessment framework
- Create a knowledge base from which structural indicators of eelgrass function can be developed

The Bernstein Report

Summary

The Bernstein report was the product of a panel of experts on eelgrass in Southern California. The panel consisted of mix of local, state, and federal government agencies, as well as scientists from non-government organizations, universities, and environmental consulting firms. The Bernstein report began with an inventory of available eelgrass bed extent information from the south coast mainland and the Channel Islands, as well as a summary of the different methods used to create these extent estimates. The remainder of the report was structured around five key eelgrass management questions: 1. What is the extent of eelgrass habitat and how is it changing over time?; 2. Where does eelgrass habitat have the potential to exist and where is eelgrass vegetation currently not persistent?; 3. What is the condition of eelgrass habitat?; 4. What is the effect of projects on regional eelgrass habitat; and 5. What are the significant stressors on eelgrass habitat and what are their effects?. The report could not answer these questions given the state of the science in the region, but the authors made recommendations towards the development of a comprehensive monitoring structure that eventually could. With this information available, local environmental managers will then be better able to make better informed decisions about eelgrass protection, restoration, and remediation in the coastal zone of Southern California. Using the five management questions a guide, Bernstein et al. presented an evaluation of the state of eelgrass science; its ability to answer each question, a summary of the methods used to collect information for each question, and a list of the priority knowledge gaps to advancing and eelgrass monitoring program in southern California.

Beyond aggregating the eelgrass extent data, the most important component of the Bernstein report is the series of recommendations it provides regarding the infrastructure necessary to build a regional monitoring network capable of answering their five key questions. Bernstein et al. realize that it is unlikely that one single organization will be conducting monitoring of eelgrass beds across the region and that any real regional monitoring efforts will need to be a collaboration between a network of different practitioners and parties responsible for the eelgrass found within their individual jurisdictions. As such, the report identifies the need for consistent sample frame (which may vary among the different management questions), consistent methodologies for data collection, and a consistent suite of indicators/data types to be collected as part of the process.

According to the Bernstein report, existing monitoring efforts were most well equipped to answer the question about eelgrass extent and it potential change over time. The remaining four questions had sizeable data gaps or were only answerable at a limited number of locations (e.g., habitat suitability/depth distribution). These areas represented the greatest research needs.

Since 2011

Since the Bernstein report was published, it has had a clear and traceable impact on how eelgrass has been studied in Southern California. In the intervening years, there has been considerable ongoing research on eelgrass in the region, with much of this work has focused on continuing surveys of spatial trends in eelgrass extent as recommended in the Bernstein report. Additional eelgrass extent surveys have been published for systems noted in the Bernstein document – e.g., San Diego Bay, 2014 and 2011 (Merkel & Associates Inc, 2014 and 2011); Newport Bay, 2016, 2014 and 2012 (Coastal Resources Management, 2017); Mission Bay, 2013 (Merkel & Associates Inc., 2013) – and other systems not thoroughly surveyed at the time of the report – e.g., Alamitos Bay, 2013 (Merkel & Associates Inc., 2014). Notably, the 2013 Southern California Bight Regional Eelgrass Survey (Merkel & Associates Inc., 2014) was specifically aimed at addressing recommendations about the data gaps in eelgrass extent highlighted in the Bernstein report, and presents system wide eelgrass acreage cover for Alamitos Bay, Anaheim/Huntington Harbor, Agua Hedionda Lagoon, Batiquitos Lagoon and San Dieguito Lagoon. While these surveys present robust spatial measures of eelgrass extent that are useful in answering questions about the amount of eelgrass in the region, they do not present any measures of eelgrass structure that could provide insight into habitat condition or other aspects of eelgrass ecology. Despite continuing efforts to survey eelgrass extent, these monitoring efforts remain focused on a singular, narrow aspect of eelgrass and are not addressing the other ecologically important aspects of the eelgrass which are needed for the appropriate management of these valuable components of the coastal ecosystem (e.g., questions 2-5 in the Bernstein report).

In contrast to the limited scope of most regular monitoring/surveying efforts published since the Bernstein report, there has been a reasonable amount of basic research into the characterization of eelgrass condition and functioning in the SAV scientific community. Many documents have recently provided concise definitions of SAV ecosystem services and broad foundational support for emphasizing these services as a basis for regional management – e.g., Nordlund et al. (2016) define regional and species-specific SAV ecosystem functions, while studies like those by Ruiz-Frau et al. (2017) and Dewsbury et al. (2016) provide strong example assessment structures which focus on seagrass ecological function. Nevertheless, there is still a lack of studies in southern California documenting measurable links to SAV function. The concept of seagrass ecosystem functions – both in diversity of functions and their magnitude – varying along a gradient of in situ measures of SAV structure is a prominent focus in recent papers from other systems where eelgrass occurs (e.g., Moore & Duffy, 2016; McGlathery et al., 2012; Hansen & Reidenbach, 2012; McCloskey & Unsworth, 2015). Additional studies have also developed mathematical-model links between seagrass structure and function (e.g., Adams et al., 2016; Carr et al., 2016). These findings suggest the efficacy and importance of measuring indicators of SAV ecosystem function (see Bibliography-Review Results section below), which we propose as a significant component of a southern California regional SAV monitoring and assessment framework.

Developing A Comprehensive Monitoring Structure

A framework focusing the multiple structural and functional facets of eelgrass (and other species of SAV) may provide a more direct means of achieving management goals for eelgrass habitats beyond merely mapping extent. We propose a three-tiered assessment approach that focuses on SAV Extent, SAV Condition/Health, and SAV Ecological Function to better capture the multiple aspects of SAV meadows (i.e., a living natural resource and a biologically-based habitat for other flora and fauna). The three elements or tiers of the framework can be seen to operate in a sequence of ecological completeness (*sensu* Haines-Young and Potschin 2009; Vlachopoulou et al. 2013) for the habitat:

1. If the landscape is ecologically suitable, is SAV present?;
2. If present, what is the condition of the SAV bed (health, structural integrity, etc.) and the waterbody where it is located?; and
3. Given the condition of the bed, how well is it functioning in the habitat mosaic of the coastal zone?

The tiers of this proposed extent-condition-function framework will operate at different spatial, ecological, and analytical scales given how each focus on a different aspect of SAV. Echoing the Bernstein report, it is our hope that all three pieces of the framework should be conceptually applicable at both the regional and statewide scales, with the appropriate amount of monitoring effort to produce data of enough spatial and temporal density to be evaluated within the framework. A more detailed description of the proposed framework and its conceptualization can be found in the attached report (Appendix A).

Of the three tiers of our proposed framework, the assessment of eelgrass ecological function is the most distinct from the material in the Bernstein report. This element also has the greatest relevance to local management interests and needs for assessing a multitude of beneficial uses. As such, our primary efforts have been focused on developing the third tier of our proposed framework. The components of this assessment – the ecological functions, how they can be measured or characterized, and their anticipated response to disturbance – can be built from the scientific literature. The results of our efforts to mine and synthesize the existing scientific knowledge base on eelgrass structure and function are presented in the bibliography described in the following section.

Bibliography

We conducted a search and review of conceptual and methodological documents related to seagrass to assess and construct the components of our proposed framework. Documents were gathered based on content related to seagrass in general, with an emphasis on documents related to ecological and environmental relationships and the Southern California region. Further review and assessment of the gathered documents was done to categorize each based on their support for a specific tier of our framework (e.g., habitat suitability, ecosystem condition, ecological function), as well the nature of the support (e.g., conceptual description, methodological description, or stressor-response description). Additionally, we were interested in collating as many studies of eelgrass extent in Southern California embayments that had been conducted since the publication of – and therefore potentially influenced by – the Bernstein report. The categories, notes, region and SAV species content within each document are noted in the attached excel document (Appendix B).

Literature Search Methods

Keyword searches were used on GoogleScholar and WebOfScience to search for journal articles, books and thesis documents. The following keywords were used in combination with the terms “seagrass”, “eelgrass”, “Zostera”, “Zostera marina” or “aquatic vegetation”: southern California, pacific coast, temperate, stress, nutrients, temperature, salinity, sediment, water, North America, Mediterranean, management, ecology, environment, phenology, habitat, ecosystem services, productivity, patch, meadow, model, suitability, fauna, GIS, distribution, monitoring, assessment.

Literature Search Methods – Regional Eelgrass Surveys

Most regional eelgrass surveys are government published agency reports that do not appear in citation engines, so further gathering of these documents was done in Google Search, using keywords “eelgrass”, “Zostera”, “Zostera marina”, “seagrass” or “aquatic vegetation” in conjunction with “survey”, “report”, “inventory”, “California”, “assessment”, “monitoring”, “management” or “distribution”. Additionally, some reports not found in our search were gathered from the Bernstein et al. (2011) bibliography.

Literature Review

We documented and annotated studies which met conceptual, methodological or environmental response information criteria important to building our framework. Sources were classified as conceptual if they focused on the demonstration or discussion of any of three tiers of the framework. Conceptual studies often provided important comprehensive assessment of the state of research knowledge regarding SAV ecosystem services – e.g., Adams et al. (2016) identified a broad suite of SAV morphological traits that affect accumulation of sediment, but no direct observational testing is performed by the authors. Sources classified as methodological were those that reported methods for direct assessment of SAV. When sources contained a characterization of SAV structural or functional response to stressors, they were placed in the stressor response category

Identifying Key Functions and Indicators

Our review identified several SAV functions and a large number of potential indicators of function. In conjunction with our SAV Technical Advisory Committee (TAC) (Table 1) we identified a prioritized list of eelgrass ecological functions (Table 2) and key indicators of those functions. Based on our review, the TAC was presented with an initial list of 32 measurable SAV features that have been used by other researchers as indicators of one or more of the eelgrass functions. The TAC worked with us to refine the list of potential indicators to create a suite of measurements that should be considered for inclusion in a regular, regional scale monitoring framework and can provide the information necessary to assess our targeted SAV functions. Twelve indicators were prioritized by the TAC (**Error! Reference source not found.**), including measures of SAV faunal communities (infauna and epifauna), SAV biomass, LAI, shoot height, shoot density and other whole meadow or patch scale measures (e.g., patch perimeter to area ratio).

Table 1. Project technical advisory committee member names and their agency affiliations.

Name	Affiliation
Bryant Chesney	NOAA NMFS
Joanna Engle	California Coastal Commission
Betty Fetscher	San Diego Regional Water Board
Brian Hentschel	San Diego State University
Kevin Hovel	San Diego State University
Chad Loflen	San Diego Regional Water Board
Martha Sutula	Southern California Coastal Water Research Project
Susie Theroux	Southern California Coastal Water Research Project
Rick Ware	Coastal Resource Management, Inc
Christine Whitcraft	California State University, Long Beach

Table 2. SAV functions identified via literature review and our perceived definition of each function. Reference studies shown support our definitions based on the results of the study or an overall assessment of SAV literature within the study.

Function	Definition	Studies
Substrate Stabilization	Stabilization of soft bottomed sediments within and adjacent to SAV beds by sediment/organic matter retention and wave attenuation	Fonseca & Cahalan (1992); Adams et al. (2016)
Carbon Sequestration	Uptake and long-term retention of carbon	Mateo et al. (2006); Duarte et al. (2010); Ricart et al. (2017)
Improving Water Quality	Enhancing local water quality by a variety of mechanisms, including uptake of nutrients, settlement of sediment particles, production of oxygen, and increases in pH due to photosynthesis	Risgaard-Petersen (1998); Moore (2004); Zarnoch et al. (2017)
Primary Production	Increased diversity and rates of primary production related to the above and below ground structural complexity of SAV beds	Moncreiff et al. (1992); Mazzella & Alberte (1986)
Secondary Production	Increased productivity of infauna and epifauna due to higher structural complexity and organic matter production in SAV beds	Fonseca et al. (1990); Heck et al. (1995); Wong (2018)
Nekton Habitat	Enhanced survival and greater food availability for fish and other nekton within and adjacent to SAV beds	Hosack et al. (2006); Lazzari (2013); Jones et al. (2013)
Waterfowl Habitat	High productivity of SAV estuarine habitat make attractive feeding grounds for many species of water fowl	Baldwin & Lovvorn (1994); Frazier et al. (2014); Kollars et al. (2017)

Table 3. Identified priority indicators of SAV ecological functions. Cell colors indicate the relative value of the indicator at informing the level of ecological function, practicality of use within a regional monitoring framework and other evaluation criteria established in Appendix A; red = low indicator value, yellow = medium indicator value, green = high indicator value.

Indicator	Carbon Sequestration	Nekton Habitat	Primary Production	Secondary Production	Substrate Stabilization	Waterfowl Habitat	Water Quality
above ground biomass	🟨		🟩	🟩			🟨
bed patchiness		🟩					🟥
below ground biomass	🟨	🟦	🟨	🟨	🟨		
epifauna biomass				🟩			
epifauna diversity		🟨		🟨			
Epiphyte biomass			🟩	🟩			
infauna biomass				🟩			
infauna diversity		🟨		🟨			
Leaf area index		🟩	🟩		🟨		🟩
patch perimeter:area ratio		🟨					
shoot density		🟩	🟩	🟩	🟩		🟩
shoot height		🟩	🟦	🟩	🟨	🟩	🟩

Review Results

Our final compiled bibliography was composed of 143 papers containing relevant information for the proposed assessment framework. The results of our review are further divided into the following sections based on their relevance to habitat suitability, ecological condition and ecological function, as these categories directly represent out proposed framework tiers. Only three of the sources reviewed covered all three tiers: conceptual papers geared towards proposing comprehensive monitoring frameworks (e.g., Abadie et al., 2018) or those focused on monitoring of long term restoration projects (e.g, McGlathery et al., 2012).

Habitat Suitability – Tier 1

Twenty-five papers reviewed covered the concepts and methodology of SAV habitat suitability. Older classic studies by Zimmerman, Duarte, Short, Fonseca and others used laboratory or post-transplant monitoring of SAV to characterize direct responses of seagrass to environmental factors – e.g., Zimmerman et al. (1991) detailed strict limitations of light availability required by eelgrass in San Francisco Bay, CA, USA; Fonseca and Bell (1998) reported effects of wave exposure, substrate composition/size distribution and other factors on eelgrass and *Halodule wrightii*. More recent articles have used spatial modeling of seagrass distribution to assess the importance of basic environmental factors in determining the presence/absence of seagrass. Valle et al. (2013) provided a good review of this literature, comparing and validating multiple modeling methods for eelgrass habitat suitability in a case study at the Ems estuary, Netherlands. It should be noted that habitat suitability has been used as a primary management focus for multiple regions – e.g., Bergstrom et al. (2013) used water clarity as a proxy for nutrient loading in eelgrass presence/absence models in the Baltic Sea; Bowen and Valiela (2001) used agricultural derived nitrogen loading to model eelgrass percent cover in Waquoit Bay, MA, USA; Thom et al. (2014) produced models of eelgrass biomass and habitat suitability built upon estimates of light availability, temperature, depth and substrate composition in Puget Sound, WA, USA.

Ecological Condition – Tier 2

Few of papers reviewed expressly stated that their intent was to measure the health of SAV, but 32 papers contained information on describing the concept of healthy eelgrass condition or providing direct measures of condition. Marba et al. (2013) and Connell et al. (2017) identify indicators directly aimed at assessing seagrass and ecosystem health. Marba et al. (2013) may be particularly useful for developing a framework for monitoring SAV ecological condition, as it provides 49 seagrass indicators used in European coastal monitoring programs for evaluating seagrass health as a measure of coastal ecological quality. Most other studies in the ecological condition category focus on describing deteriorating condition or resilience of seagrass in eutrophic conditions (e.g., Connell et al., 2017; Lin et al., 1996).

Ecological Function – Tier 3

A majority of our bibliography (98 studies) contains research regarding some aspect of SAV ecological function; 71 had methodological details, 27 provided conceptual discussion, and 20 illustrated changes in function with exposure to different stressors. A few conceptual papers covered the topic of seagrass ecosystem services broadly, including multiple functions (e.g., Nordlund et al., 2016; Ruiz-Frau et al., 2017; Cullen-Unsworth et al., 2014; Dewsbury et al., 2016). In the following sections we provide more specific sources that identify or measure each function individually.

Substrate Stabilization - The capacity for SAV to affect its substratum and adjacent sediment has important implications for protecting coastal regions from erosion. The topic has been reviewed by Adams et al. (2016), detailing how the physical structure of seagrass – measured as meadow height, meadow width, frontal meadow area per volume, shoot density, leaf area index and below ground biomass – serves as a mechanism for net sediment retention. A number of sources have demonstrated how wave energy was reduced by increasing complexity in seagrass bed structure (e.g., Fonseca & Cahalan, 1992; Bouma et al., 2009; McGlathery et al., 2012).

Carbon Sequestration - Long-term carbon storage in SAV is a prominent research topic within the realm of SAV management (Ruiz-Frau et al., 2017) and is widely recognized as a potentially important natural carbon sink due to its root-sediment carbon storage processes. In our review, we found the 16 papers linking SAV to carbon sequestration, 13 of which detailed methodology for measuring carbon sequestration capacity of SAV. Several studies we reviewed identified the significance of seagrass as a global carbon sink based on direct measures of carbon, radio carbon isotopes and other laboratory or calculation intensive methods (e.g., Fourqurean et al., 2012; Villa & Bernal, 2017; Duarte et al., 2010), which are probably not practical within the context of a regional monitoring program. Correlations between carbon sink potential and SAV structural measures (practical measures within a regional monitoring program) were found in a few studies we reviewed – e.g., Oreska et al. (2016), Ricart et al. (2017), Samper-Villarreal et al. (2018) and Schmidt et al. (2012) showed correlation between long-term organic carbon stocks, seagrass bed age, biomass (above and below ground) and patch size.

Water Quality Improvement - SAV can positively affect water quality via uptake of nutrients, reduction in suspended solids and the comparatively slow remineralization of vascular plant matter vs. algae. The magnitude of the water quality effect depends on the condition of the SAV bed, as well as other factors both intrinsic and extrinsic to the bed itself. Marba et al. (2006) provided evidence of increasing seagrass water column nutrient uptake and retention related to patch size and aboveground biomass; Moore (2004) directly measured the correlation between eelgrass aboveground biomass, eelgrass percent cover and several water quality parameters. Hemminga et al. (1991) provided a review of nutrient retention in seagrass, in which the mechanisms that allow for relatively high nutrient and organic matter retention or export are detailed.

Primary Production - The complex structure of SAV can allow for enhanced primary production, the rate of which can vary with an SAV bed's condition. We reviewed 26 papers that reported enhanced primary production in SAV beds or provided methods of monitoring primary production. Many of the reviewed documents reported high overall primary productivity within SAV systems and particularly high contribution of SAV epiphytic autotrophs to these high values – e.g., Pollard and Moriarty (1991) estimated up to 50% of gross primary productivity within Australian seagrass beds could be attributed to epiphytic algae. Significant indicators of SAV primary production have also been reported in a number of reviews – e.g., Moncreiff et al. (1992) reported a significant correlation between seagrass biomass, primary productivity and epiphytic algae biomass; Moriarty et al. (1990) reported correlations between primary productivity, seagrass biomass (above and below ground) and shoot density.

Secondary Production - Infaunal and epifaunal residents of SAV beds are provided protective and highly productive environments beneficial for their survival, which allows for higher overall secondary production within SAV beds. Thirty papers we reviewed demonstrated a pattern of increased secondary production in SAV beds compared to bare sediment (e.g., Hosack et al., 2006; Fonseca et al., 1990) and also identified SAV structural indicators of secondary production – e.g., Attrill et al. (2000) showed a significant correlation between macroinvertebrate abundance and eelgrass shoot density. Bowden et al. (2001) reported a correlation between eelgrass patch size/diameter and macroinvertebrate abundance and Wong (2018) reported belowground biomass and canopy height as significant factors influencing secondary production.

Nekton Habitat – We found 27 papers detailing how SAV beds provide fish and other highly motile fauna high density of food and refuge from predation. Multiple studies directly compared fish communities within SAV beds and bare substrate, with greater fish abundance within SAV bed habitats (e.g., Bertelli & Unsworth, 2014; Lazzari, 2013; Mattila et al., 1999). Other studies commonly reported links between SAV structural properties and fish abundance or fish community composition – e.g., Orth and Heck (1980) reported declining fish diversity and abundance with declines in eelgrass biomass; Sato et al. (2016) and Evans and Short (2005) showed a significant link between leaf area index and fish abundance and diversity; Common fish prey items were found to be significantly correlated with seagrass shoot density by Worthington et al. (1992). Many of these same structural metrics identified as important to fish communities were also found to have a significant link to the community structure of other highly motile organisms and transient residents of seagrass beds – e.g., Heck and Orth (1980) showed a positive correlation between eelgrass biomass and the seasonal abundance of decapod crustaceans; McCloskey and Unsworth (2015) provided evidence of a relationship between percent cover of eelgrass and abundance of motile macroinvertebrates.

Waterfowl Habitat - Waterfowl commonly utilize SAV beds, as they can serve as direct forage or can contain high densities of other waterfowl food sources, such as nekton (Frazier et al., 2014; Baldwin &

Lovvorn, 1994). We identified five sources that support SAV as an important habitat for waterfowl along the Pacific Coast. Much of the work done on identifying relationships between SAV and waterfowl has been for the purpose of evaluating the impacts of waterfowl grazing on SAV, or SAV species-specific usage patterns (e.g., Baldwin & Lovvorn, 1994; Kollars et al., 2017); however, Frazier et al. (2014) reported significant patterns in aboveground biomass, patch area and shoot height in relation to waterfowl usage.

Next Steps

Using the set of targeted eelgrass ecological functions and a suite of potential indicators to estimate function performance (as summarized by the literature), our next challenge will be crafting practical field and lab protocols for the measurement of each priority indicator. Our basic plan will be to synthesize the methods associated with each indicator as noted in our literature review and then modify them as needed for use in Southern California estuaries and embayments. The draft-versions of our protocols will be presented to the TAC for comment. After obtaining their feedback, we will then proceed to test each protocol as part of our data collection and analysis process.

Appendix A

Project: Regional Board 9 - Development of a Monitoring and Assessment Framework for Submerged Aquatic Vegetation (SAV)

Technical Report #1 – Monitoring and Assessment Framework

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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 (Nordlund et al., 2016; Dewsbury et al., 2016; Ruiz-Frau et al., 2017; Cullen-Unsworth et al., 2014). 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 function as temporary refuge from environmental threats, substratum as a permanent point of attachment and a direct or indirect mechanism for food acquisition (Boström et al. 2006; Hemminga and Duarte 2000; Orth et al. 1984). 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 (e.g., Heck et al. 2008; Polis et al. 1997). SAV beds, like many other "habitat engineering" flora and fauna (e.g., Wright and Jones 2006; Jones et al. 1994), 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 unique foodwebs and biogeochemical cycling that are absent from adjacent habitats in shallow coastal waters. Constructing a monitoring framework that addresses both the resource and the habitat nature, poses a unique challenge that will differ from traditional bioassessment efforts.

Southern California's coastal embayments are host to a variety of SAV species, including *Ruppia maritima*, *Zostera pacifica* (wide-leaved eelgrass) and *Zostera marina* (narrow-leaved eelgrass), but *Z. marina* is the dominant species present in these habitats (Green & Short, 2003; Olsen et al., 2014). Given its dominance in the region and high ecological value (Moore & Short, 2006), most efforts at monitoring, restoration, and mitigation of SAV habitat in Southern California coastal waters have focused on *Z. marina*, with more than 50 different eelgrass mitigation projects conducted in Southern California over the last 30 years (NMFS, 2014). These eelgrass beds, natural and constructed, represent greater secondary production than *R. maritima* (Heck et al. 1995) or bare subtidal sediment (Wong 2018) and higher rates of biogeochemical cycling compared to bare subtidal sediment (Jankowska et al., 2014; McGlathery et al. 2012).

Most present-day *Z. marina* monitoring programs in Southern California focus on the seagrass as a natural resource (as opposed to a habitat); monitoring the location and extent of the eelgrass beds across the region (e.g., Coastal Resources Management 2017; Merkel and Associates 2014; Merkel and Associates 2011). Under this type of assessment framework, the primary concern is where and how much of the resource there is across the region, as well as the how those values are changing through time. The goal is to establish a bench mark so that trends in areal extent can be tracked through time and used as a proxy for the condition of the habitat (Bernstein et al. 2011). Underpinning this approach is the implicit assumption that the presence and structure of the beds conveys that they are functioning as they should. A wide variety of studies have sought to investigate the linkage between eelgrass presence, structure, and function (e.g. Potouroglou et al. 2017; Boström et al. 2014; Hansen & Reidenbach 2012; McGlathery et al. 2012; Hovel 2003; Attrill et al. 2000), but were limited in spatial or temporal scale (i.e., not applied at a regional scale or in a regular monitoring context).

Despite the variety of ecological roles it serves in the coastal ocean and the high value it has to those who use the ecosystem, there is no robust framework for monitoring and assessing the resource and habitat function (or condition) aspects of SAV in Southern California. To that end, we propose a new assessment framework for assessing SAV structure and function in the region. Our initial work will focus on *Z. marina* as it is the dominant estuarine seagrass in Southern California, but it is our philosophy that the assessment framework should be broadly applicable to all species of SAV in the region. However, we would expect the spatial scale and complexity of the different monitoring elements to vary among species. Furthermore, we would expect the thresholds of desirable structure and function measures to vary from species to species.

Proposed Framework

We are proposing a three-tiered assessment approach that focuses on SAV Extent, SAV Condition/Health, and SAV Ecological Function to better capture the multiple aspects of SAV meadows (i.e., a living natural resource and a biologically-based habitat for other flora and fauna). The three elements or tiers of the framework can be seen to operate in a sequence of ecological completeness (*sensu* Haines-Young and Potschin 2009; Vlachopoulou et al. 2013) for the habitat:

1. If the landscape is ecologically suitable, is SAV present?;
2. If present, what is the condition of the SAV bed (health, structural integrity, etc.) and the waterbody where it is located?; and
3. Given the condition of the bed, how well is it functioning in the habitat mosaic of the coastal zone?

The tiers of this proposed extent-condition-function framework will operate at different spatial, ecological, and analytical scales of complexity given how each focuses on a different aspect of SAV (Table 1). That said, it is our hope that all three pieces of the framework should be conceptually applicable at both the regional and statewide scales, with the appropriate amount of monitoring effort to produce data of enough spatial and temporal density to be evaluated within the framework.

Table 1. A summary of the three tiers of the proposed SAV assessment framework, including the likely scale of interpretation and the potential components of each tier

Assessment Tier	Core Question	Spatial Scale of Interpretation	Potential Components
Tier 1 - SAV Extent	Is SAV present in those locations where it should be?	Statewide to Waterbody	Habitat Suitability Model Causal Assessment Tools
Tier 2 - SAV Condition	What is the condition of the vegetated parts of the coastal zone?	Statewide to Waterbody	Reference Habitat Definition Quantitative Condition Assessment Tool Causal Assessment Tools
Tier 3 - SAV Ecosystem Function	Are SAV beds functioning as a normal part of the coastal zone?	Regional to Individual Beds	Reference Habitat Definition Functional Assessment Tools

Tier 1 - SAV Extent

The first tier of the proposed assessment framework is designed to address the questions of "where should SAV beds be present in coastal waters of Southern California, based on physiological limitations in the absence of anthropogenic disturbance?", and "Is any SAV present in these suitable habitats?". This tier has three primary components corresponding to those questions: 1. Identifying the natural, abiotic characteristics that affect SAV distribution – its theoretical niche (e.g., Hutchinson 1959); 2. Mapping that niche space across Southern California; and 3. Determining the presence or absence of SAV in those locations.

Under the assumption that most SAV beds in Southern California are largely mono-cultures (e.g., Johnson et al. 2003), the process of identifying theoretical niche space and mapping it to the region will most likely be modularized into species-specific, habitat occupancy models; either statistical (e.g., Detenbeck and Rego 2015; Kemp et al. 2004) or mechanistic (Koch 2001; Wetzel and Neckles 1986). Site-specific landscape characteristics derived from remote sensing and or GIS databases can then be used to parameterize the models for sites across the region (Table 2). Model output, as a likelihood of SAV presence, can then be used to create an expectation of SAV bed presence or absence over a given area. This expectation would in turn be tested with observational data collected as part of a routine monitoring program (e.g., Christiaen et al. 2016; NMFS 2014; Morro Bay National Estuary Program 2013). Absence of SAV in locations where it would be expected could lead to focused monitoring efforts to confirm its absence. Furthermore, a causal assessment would be conducted to investigate presence or absence in the past and analyze anthropogenic and natural factors that could inhibit SAV bed growth and persistence. If SAV are present, the assessment would progress into the second tier.

Table 2 Potential types of data needed to construct a mechanistic habitat occupancy model to predict where SAV beds should occur in Southern California. The Limiting Rate indicates physiological rates or physical aspects of SAV plants that constrain their growth and survival. Forcing Factors are aspects of the environment that act upon the Limiting Rates of SAV plants. State Variables are some of the potential ways to measure the Forcing Factors and parameterize the model(s).

Limiting Rate	Forcing Factor	State Variables
Min/Max light for photosynthesis	Light Penetration	Water Depth Latitude Bottom Shear Stress
Recruitment	Connectivity to Other Beds	Distance to Nearest Bed
Sediment Setting	Permeability	Sediment Composition
	Available Nutrients	Sediment TN Sediment OM content
	Toxic Reduced Chemicals	Ammonia Concentration Sulfide Concentration
Growth Rate	Temperature	Water Temperature Tidal Range
	Osmotic Balance	Salinity
Physical Disturbance	Wave Exposure	Fetch Degree of Shelter Water Depth

Tier 2 – SAV Condition

The second tier of the proposed assessment framework is designed to address the questions of “How healthy is the SAV bed?” and “What is the ecological integrity of the waterbody in which the bed is found?”. There are a variety of assessment tools available to evaluate the condition of unvegetated parts of Southern California’s embayments and coastal ocean (e.g., Pelletier et al. 2018; Ranasinghe et al. 2009; Smith et al. 2001), but there is no formal approach for the SAV beds in these waterbodies (Bay et al. 2014). As such, this tier of the framework will focus on evaluating the integrity of the bed as a whole and evaluate if the local environmental conditions are supportive of plant growth and persistence. There has been reasonable amount of research in this area, most frequently using the presence/extent of SAV bed growth as an assessment of eutrophication impacts in a waterbody (e.g., Corbett et al. 2005; Kraus-Jensen et al. 2005; Dennison et al. 1993). The pre-existing work in the literature will provide a good knowledge base for this part of our framework, however, there are only limited examples (mostly from

Europe) where these patterns have been codified into a proper assessment tool (Garcia-Marin et al. 2013; Neto et al. 2013; Montefalcone 2009).

This tier of the framework will ultimately consist of an assessment scoring tool that uses various aspects of SAV bed health and vigor to infer the conditions of the locale in which the bed is located. This type of tool will be contingent on producing a sufficiently robust data set, and could take a variety of different forms – predictive vs. non-predictive, Multi-Metric Index vs. Stressor-Tolerance Index, bed-scale measures vs. individual plant-scale measures. Regardless of its form, an index will allow for quantitative estimates of SAV parameters that are demonstrated to be responsive to the different types of anthropogenic stressors the benthic zone of the coastal ocean is exposed to (i.e., eutrophication, habitat alteration, toxic chemicals, altered hydrology, sea level rise, climate change, ocean acidification). As part of this process, it will be important to identify the appropriate reference conditions (Stoddard et al. 2006) given the extensive alterations and degradation of Southern California's coastal zone (Stein et al. 2014; Ahn et al. 2005). It will also be important to determine if there is differential response to stressors among the different bed-scale and individual plant-scale aspects of SAV condition, as this will help to inform stressor diagnostics and causal assessment interpretation of any observed impacts to SAV condition. Completion of a tier 2 assessment will allow for a reasonable evaluation of waterbody health and provide insight into any potential disturbances that may be degrading the condition of the vegetated parts of the coastal ecosystem. If one's concerns extend beyond an evaluation of structural integrity and into the most integrative assessment of potential alteration to an ecosystem, then progressing onto the third tier of proposed framework would be required.

Tier 3 – SAV Ecosystem Function

The third tier of the proposed assessment framework is designed to address the question, "Are SAV beds providing the ecosystem functions they would be expected to?". This tier of the framework will focus on the extrinsic aspects of SAV beds; emphasizing how they are part of the mosaic of habitats in the coastal landscape and how they contribute to a healthy and fully functioning coastal ecosystem (e.g., Ruiz-Frau et al. 2017; Dewsbury et al. 2016; Nordlund et al. 2016; Cullen-Unsworth et al. 2014). Whereas tier 2 is focused around using structural aspects of SAV beds to infer the health and condition of their host waterbody, tier 3 is explicitly focused on evaluating if an SAV bed – natural or created – is providing the ecological functions it should. The presence and rate of a habitat's functions (e.g. productivity, hydrological buffering, biogeochemical cycling) speak to the most wholistic and direct assessment of anthropogenic impacts to a system (Strong et al. 2015; Cortina et al. 2006). Most studies covering ecosystem functions of SAV beds provide direct estimates of a function(s) through relatively intensive, local-scale measurements that provide insight into the magnitude of a function or how it may change under different abiotic or biotic scenarios (e.g., Lamb et al. 2017; Potouroglou et al. 2017; Thorhaug et al. 2017; Zarnoch et al. 2017). Much of this work however, is not conducive to implementation in a regional-scale, regular monitoring program. As such, much of the work associated with developing this tier will entail identifying key functions, easily measurable proxies for the functions, and understanding how they respond to different stressors in the coastal ocean.

This tier of the assessment framework will most likely consist of a series of assessment tools designed to evaluate the expression – and possibly magnitude/rate of flux – of different ecological functions in a given SAV bed. The initial tools will focus on suite of ecological functions determined to be of primary importance to local management agencies and experts in SAV ecology (Table 3). Given the difficulty of directly measuring all of the ecosystem functions described in Table 3, we will endeavor develop a series of SAV structural metrics (e.g., shoot density, above ground biomass, plant C:N ratio) that can be demonstrated to be predictive of function, responsive to stressor exposure, and relatively easy to incorporate into a regular regional monitoring program.

Table 3 Priority list of ecosystem functions that SAV beds are known to provide, as concluded by SAV ecological experts and resource managers from across Southern California. These functions will be the focal point of Tier 3 assessment tools.

Function	Definition
Substrate Stabilization	Stabilization of soft bottomed sediments within and adjacent to SAV beds by sediment/organic matter retention and wave attenuation
Carbon Sequestration	Uptake and long-term retention of carbon
Improving Water Quality	Enhancing local water quality by a variety of mechanisms, including uptake of nutrients, settlement of sediment particles, production of oxygen, and increases in pH due to photosynthesis
Primary Production	Increased diversity and rates of primary production related to the above and below ground structural complexity of SAV beds
Secondary Production	Increased productivity of infauna and epifauna due to higher structural complexity and organic mater production in SAV beds
Fish Habitat	Enhanced survival and greater food availability for fish and other nekton within and adjacent to SAV beds
Waterfowl Habitat	High productivity of SAV estuarine habitat make attractive feeding grounds for many species of water fowl

Incorporation of the three tiers into a single framework

As noted above, it is our vison that the framework presented here should be applicable across different species of SAV, but that the components of each tier are most likely species-specific in their construction and interpretation. While there are multiple paths forward, we advocate an approach of building out all three tiers for a single species – *Zostera marina*, given its importance and prevalence in the region – to help evaluate the scientific utility of the framework. Having a complete framework to deploy will also allow time for development of an understanding for how the framework can be used by interested parties and incorporated into regional monitoring programs like the Bight Regional Monitoring Program.

The three tiers of the framework are meant to be implemented sequentially, building upon the information from the previous tier while simultaneously increasing the ecological meaning of the results and drawing closer the beneficial uses they are meant to represent. In their application towards achieving natural resource management goals, each tier will probably have its own threshold for meeting management targets. These thresholds could be applied to a bed or waterbody independently (e.g., “X% of this estuary has desirable extent, Y% is in reference condition, and Z% is functioning at natural levels”) or they could be applied and interpreted in an aggregated fashion (e.g., “X% of this estuary meets the goal of desirable extent, condition, and function, but Z% is only meeting goals for extent”). Alternatively, an expectation of meeting extent and condition goals may be sufficient for SAV in all waterbodies, but evaluation of meeting the ecological function goals cold be applied to habitats undergoing restoration, mitigation, or some other priority designations, as these types of SAV beds are the more likely to have a breakdown of the “structure implying function” paradigm than naturally occurring beds and would need to have their functioning directly assessed.

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