Morro Bay National Estuary Program

Morro Bay Eelgrass Report 2022

Morro Bay National Estuary Program
601 Embarcadero, Suite 11
Morro Bay, CA 93442

November 2023

Contents

Introduction

Seagrass beds are among the most valuable coastal habitats worldwide. They perform a wide range of important ecosystem services, including carbon sequestration, water purification, and sediment accretion and stabilization (Nordlund et al. 2017). Eelgrass (*Zostera marina*), like other seagrasses, is a critical foundational habitat. Eelgrass creates habitat that leads to increased abundance and diversity of many invertebrate and fish species, and it serves as a nursery for ecologically and commercially-valuable species.

Eelgrass is a marine flowering plant with long, ribbon-like leaves that grow from an underground stem (rhizome). It is found worldwide in coastal waters. Eelgrass reproduces both sexually via flowers and seed production, and asexually via spreading rhizomes.

Unprecedented declines in seagrass distribution have been observed worldwide and are a growing cause for concern. The reasons for the decline are attributed to many natural and anthropogenic factors in coastal ecosystems. Natural impacts may come from changes in water depth, salinity, wave velocity, turbidity due to sediment or phytoplankton blooms, and herbivory pressure. Anthropogenic impacts may be either direct or indirect. Direct impacts include seagrass removal by dredging, propeller scarring, or shading caused by boat moorings or pier construction. Indirect impacts include the introduction of invasive species and non-point source loading of nutrients, herbicides, and sediment, which can negatively impact water clarity (Hauxwell et al. 2003). The indirect effects associated with sea level rise and climate change are not well understood but are widely expected to negatively impact seagrass distribution globally (Ralph et al. 2007).

The Estuary Program has witnessed fluctuations in total eelgrass acreage over the past two decades. From 2007 to 2016, more than 90% of Morro Bay's eelgrass disappeared, spurring many recent restoration, monitoring, and research efforts. Since 2016, eelgrass began to re-establish in areas where it had previously declined. Through restoration and natural recruitment, the past few years have been marked by significant growth, with eelgrass acreage now at pre-decline levels.

This report summarizes the eelgrass related efforts of the Morro Bay National Estuary Program (Estuary Program) and its partners in 2022, including mapping efforts, restoration, and detailed monitoring of new sites and existing eelgrass beds.

Morro Bay Project Area

Morro Bay is a shallow coastal lagoon located on California's Central Coast in San Luis Obispo County. Founded in 1870, the town of Morro Bay (population 10,861) is located in the northern extent of the estuary. The unincorporated community of Los Osos (population 14,503) is located on the southern shores of Morro Bay (Figure 1). Morro Bay was established as California's first State Estuary in 1994, paving the way for inclusion in the National Estuary Program in 1995. Today, Morro Bay is one of 28 recognized National Estuaries.

The Morro Bay watershed encompasses drainage from approximately 75 square miles. Freshwater inflows are delivered to the estuary via the Chorro Creek and Los Osos Creek sub-watersheds and through groundwater seepage in the Los Osos area. Non-urbanized lands in the Chorro Creek sub-watershed are used primarily as rangeland and public parks. Non-urbanized lands in the Los Osos sub-watershed are dominated by rangeland, row crop agriculture, and commercial greenhouse nurseries. There are a number of water quality impacts within the Morro Bay watershed and estuary. For more information, refer to the Estuary Program's Library at http://www.mbnep.org/library, under "Eelgrass" and "Technical Reports".

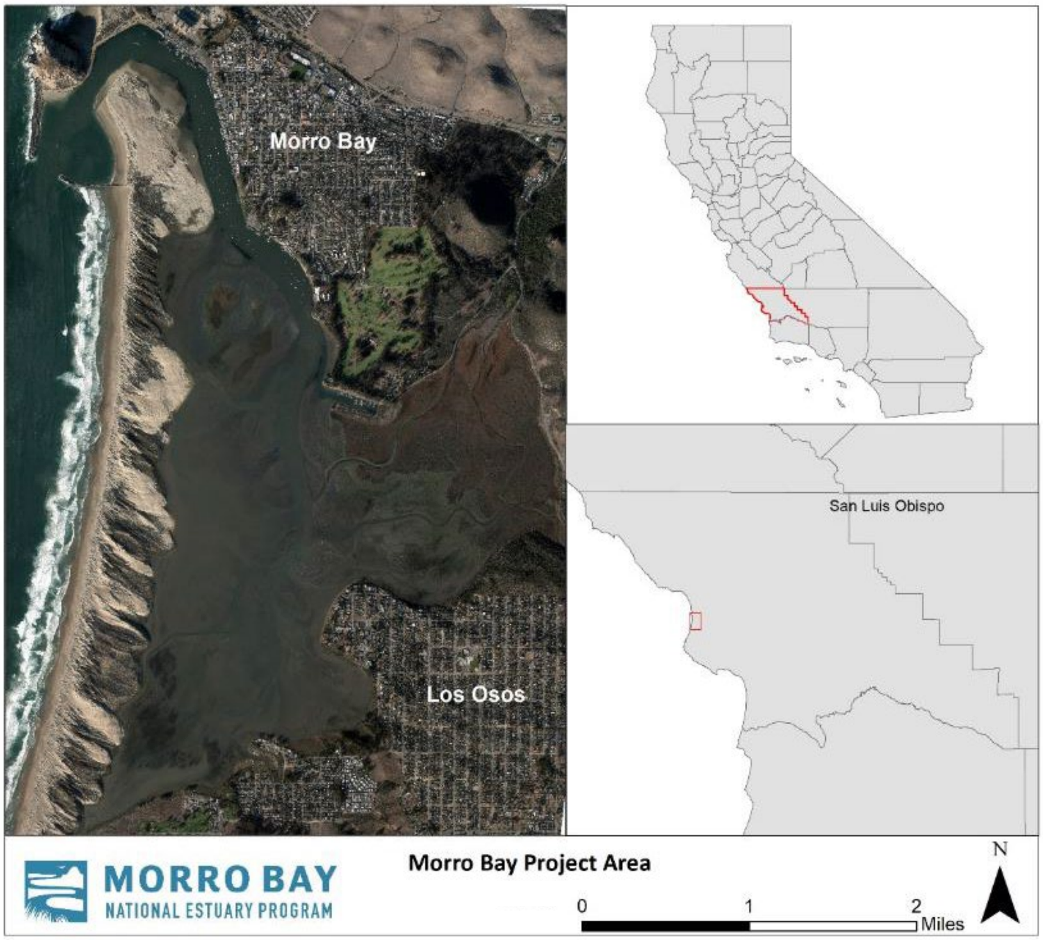

Figure 1. Morro Bay and location within San Luis Obispo County.

Morro Bay Estuary and Harbor

The Morro Bay estuary is comprised of approximately 2,300 acres of shallow, semi-enclosed intertidal and subtidal habitat. The estuary is bordered to the west by a four-mile vegetated natural sand spit that separates Morro Bay from the Pacific Ocean. Seagrass beds in Morro Bay are dominated by eelgrass (*Zostera marina*) with small patches of widgeon grass (*Ruppia maritima*) interspersed throughout the estuary. To date, Japanese eelgrass (*Zostera japonica*) has not been identified in Morro Bay.

Morro Bay is a popular destination for outdoor recreation and supports a commercial fishing port and aquaculture operations. Recreational activities in the bay include kayaking, sailing, fishing, wildlife observing, and waterfowl hunting. Two commercial aquaculture operations grow Pacific oysters (*Crassostrea gigas*) and operate in conditionally-approved areas of the intertidal mudflats. The Morro Bay harbor is maintained by regular dredging events (see “Dredging Operations”).

Eelgrass Distribution

Mapping Efforts

Morro Bay's eelgrass population has been mapped for decades, but the method and time of year has varied. Many of the early eelgrass acreage estimates used subjective aerial photo interpretations, and discrepancies have not been fully quantified or reconciled for datasets generated prior to 2002. In 2002 and 2003, the Estuary Program contracted true color aerial flights, which were later re-analyzed using multispectral analysis to create a map of intertidal eelgrass similar to methods used in later years. Between 2004 and 2013, intertidal eelgrass was mapped with multispectral aerial images. Flights were typically completed during extreme low tides in November. In 2012, the flight had to be canceled due to weather conditions and was instead completed in May 2013. Merkel & Associates (M&A) surveyed the bay in July 2013 and July 2015 using sidescan sonar, a method that targets mostly subtidal eelgrass.

In 2017, a combination of sidescan sonar and unmanned aerial vehicle (UAV) imagery were seamed together to map intertidal and subtidal eelgrass bay-wide in the spring. Later that winter, Ocean Imaging (OI) collected multispectral aerial imagery to create a classification of intertidal submerged aquatic vegetation, which was groundtruthed by the Estuary Program. Multispectral imaging was again collected by OI in 2019 to identify eelgrass bay-wide and quantify acreage of other exposed and submerged vegetation and substrate types. Further details of this analysis can be found in the Estuary Program's 2019 Eelgrass Report.

UAV Drone Mapping

Since 2017, California Polytechnic State University, San Luis Obispo (Cal Poly) has surveyed eelgrass in Morro Bay annually using a UAV. This method of mapping is less expensive than multispectral imaging, allowing surveys to be conducted more frequently. For each survey, a UAV technician flies a drone over the bay at a standard height of 400 feet during a series of negative tide windows. Thousands of photos are stitched together and georeferenced to create a bay-wide image. The eelgrass is then quantified in ArcGIS, a Geographic Information System (GIS) software, by manually digitizing eelgrass beds into individual polygons.

Researchers at Cal Poly collected imagery of intertidal eelgrass in the mid-bay in May and of the entire bay in December 2022 and January 2023 using a DJI Phantom 4 Pro drone with a 20 megapixel camera. Surveys covering the entire bay require four to five days of extreme low tides of approximately -1ft relative to mean low low water (MLLW) to expose the intertidal reaches of the bay and regions of intertidal eelgrass. Several thousand images of the bay were taken using a high-resolution camera (1.32 in/pixel) at a relatively low altitude (400 ft), resulting in very detailed imagery. These images were stitched together using Agisoft Metashape Professional to create an orthomosaic of the bay.

The orthomosaic compiled from the drone flyovers in 2022 has not yet been converted into an eelgrass acreage map, as a new method for generating these maps is currently under development. Historically, Estuary Program staff manually digitized eelgrass into individual polygons in GIS. This process has taken approximately 1,000 hours and would likely take even longer with expanded acreage. The new method would automatically classify eelgrass using a machine learning model, saving time while maintaining accuracy (see "Research Efforts"). The model has currently been tested on the 2019 acreage but has yet to be applied to the latest imagery.

To support digitizing and verify results, staff completed extensive ground truthing of the bay from December 2022 to January 2023 using GPS units with sub-meter accuracy.

Figure 2A, 2B. Resolution of photos captured with Cal Poly's UAV drone during spring of 2022. Figure 2A shows oyster farm infrastructure, and Figure 2B shows how the imagery is useful for detecting eelgrass that is partially submerged in water.

Eelgrass Acreage Data

The following table and figure present Morro Bay's eelgrass acreage over time and the method of data collection. It is important when comparing these data to keep in mind that the mapping methodology has changed over time. Between differences in mapping techniques (e.g., drone mapping, sonar) and differences in estuary conditions during mapping events (e.g., water clarity, tide height), the extent of eelgrass coverage captured can vary. Previous versions of this report are available at http://www.mbnep.org/library and include additional historical data information and sources.

Table 1. Eelgrass acreages and mapping methods, 1960 to 2021.

Year	Time of Year	Eelgrass Acreage	Method
1960	Unknown	335	Field surveys (Haydock)
1970	Unknown	452	Aerial photos (CA Fish & Game)
1988	Unknown	404	Aerial photos (Josselyn), reinterpreted (Chesnut)
1994	Late Sept to early Nov	435	Quadrat sampling (Chesnut)
1995	Late Sept to early Nov	260	Quadrat sampling (Chesnut)
1996	Late Sept to early Nov	165	Quadrat sampling (Chesnut)
1997	Late Sept to early Nov	98	Quadrat sampling (Chesnut)
1998	Unknown	125	Aerial photos (Tetra Tech)
2002	November 25, 2002	149	True color aerial images, reanalyzed (Estuary Program with Golden State Aerial and Ocean Imaging)
2003	November 21, 2003	167	True color aerial images, reanalyzed (Estuary Program with Golden State Aerial and Ocean Imaging)
2004	November 24, 2004	267	Multispectral aerial images (Estuary Program with Ocean Imaging)
2006	November 6, 2006	287	Multispectral aerial images (Estuary Program with Ocean Imaging)
2007	November 24, 2007	344	Multispectral aerial images (Estuary Program with Ocean Imaging)
2009	November 13, 2009	240	Multispectral aerial images (Estuary Program with Ocean Imaging)
2010	November 4, 2010	176	Multispectral aerial images (Estuary Program with Ocean Imaging)
2013	May 28, 2013 for multi-spectral imagery, July 2013 for sonar	15	Multispectral aerial images (Estuary Program with Ocean Imaging) and sonar (M&A)
2015	July 2015	13	Sonar (M&A)
2017	April 2017	14	Sonar and UAV (M&A)
2017	December 3, 2017	13	Multispectral aerial images (Estuary Program with Ocean Imaging)
2017	December 1 to 4, 2017	9	UAV (Cal Poly, Sea Grant)*
2018	December 6, to 8, 20 and 21, 2018	16	UAV (Cal Poly, Sea Grant)*
2019	November 26, December 11 to 13, 23 and 24, 2019, January 8, 2020	37	UAV (Cal Poly)*
2019	November 24, 2019	42	Multispectral aerial images (Estuary Program with Ocean Imaging)
2020	November 14 to 16, December 14 and 15, 2020	146	UAV (Cal Poly)*
2021	December 2, 3, and 4, 2021 January 1, 2022	500	UAV (Cal Poly)*

*Note that the UAV imagery and manual digitization process has approximately a 10% error associated with it.

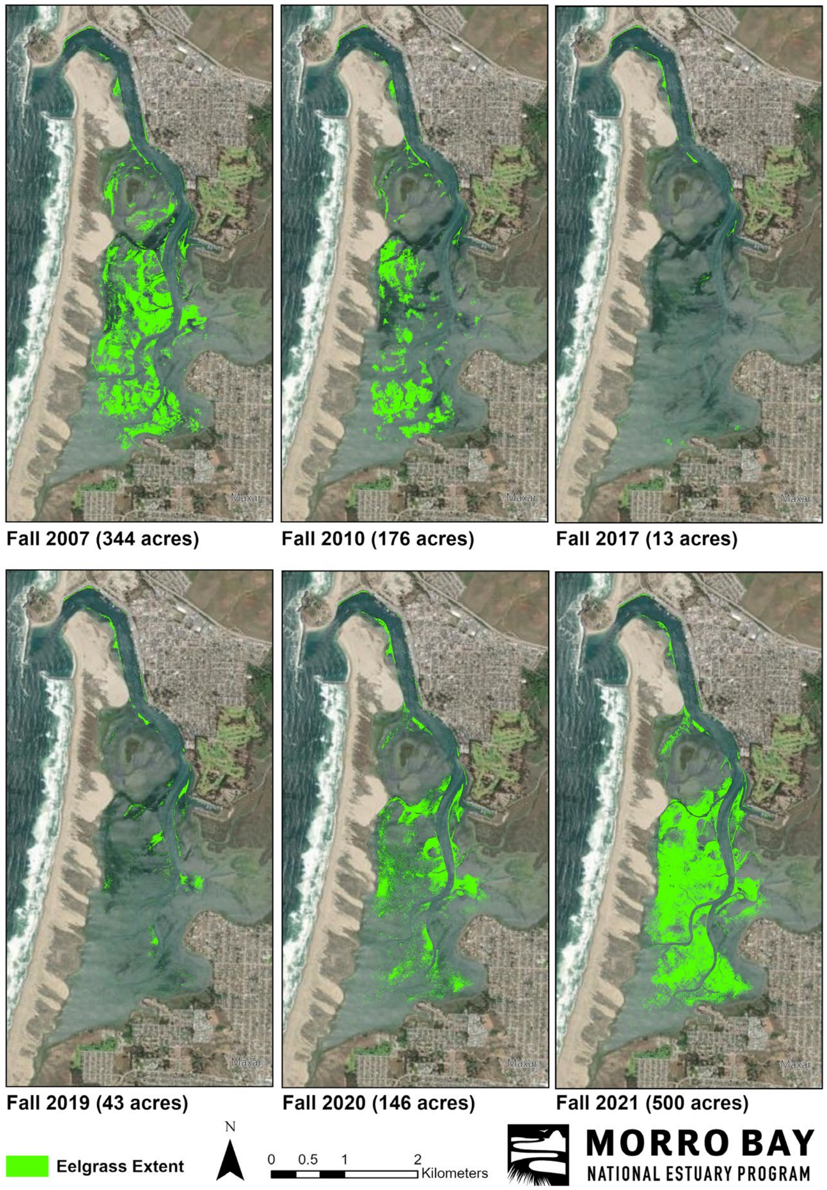

Figure 3. Changes in intertidal eelgrass density in Morro Bay from 2007 to 2021. Note that the eelgrass extent from 2007 to 2019 was analyzed with multispectral imagery (Ocean Imaging) and extent from 2020 and 2021 was analyzed using manual quantification of drone imagery (Cal Poly).[†]

Given restoration efforts and significant natural establishment, there has been a major resurgence of eelgrass habitat with 500 acres mapped in December 2021. We are encouraged to see such a large expansion in eelgrass coverage throughout the bay in a short time. From 2007 to 2016, eelgrass in Morro Bay declined by more than

[†] Eelgrass acreage from 2020 and 2021 was analyzed using manual quantification of Cal Poly's UAV drone imagery due to the cost and labor associated with multispectral imagery analysis. Because of differences in methodology over time, acreages of eelgrass cannot be directly compared from year-to-year.

90% with only 13 acres mapped in 2017. Eelgrass began to re-establish in 2017 in areas where it previously declined. In 2020, 146 acres were mapped. For a subset of the bay, including some restoration sites and adjacent intertidal areas, an additional drone flyover was conducted in late April 2021 and May 2021 to help track eelgrass coverage during the spring.

Restoration Efforts

Eelgrass was harvested from healthy donor beds in Morro Bay and transplanted with the support of trained staff from Tenera Environmental, Inc. (Tenera). Transplanting occurred at two locations in the back of the estuary. Planting took place in March 2022, during which 300 eelgrass plants were transplanted from a donor bed at Coleman Beach. Eelgrass was planted using bamboo stakes as an anchoring method. Due to expansion of eelgrass acreage above restoration targets, fewer transplantings were conducted in spring than in previous years, and these efforts were halted in the fall of 2022. A California Department of Fish and Wildlife (CDFW) Scientific Collection permit was obtained prior to collection and transplanting efforts. Restoration efforts during 2022 are summarized in the table below. Restoration locations from 2020 to 2022 are visualized spatially in relation to the 2021 eelgrass extent in Figure 4.

Table 2. Eelgrass restoration sites completed during 2022.

Site	Location	Date Planted	Approximate Elevation	Donor Bed	Planting Type
T38	35.327815, -120.855958	3/30/2022	0 ft.	Coleman	6 bamboo plantings
T39	35.327736, -120.857409	3/30/2022	0 ft.	Coleman	6 bamboo plantings

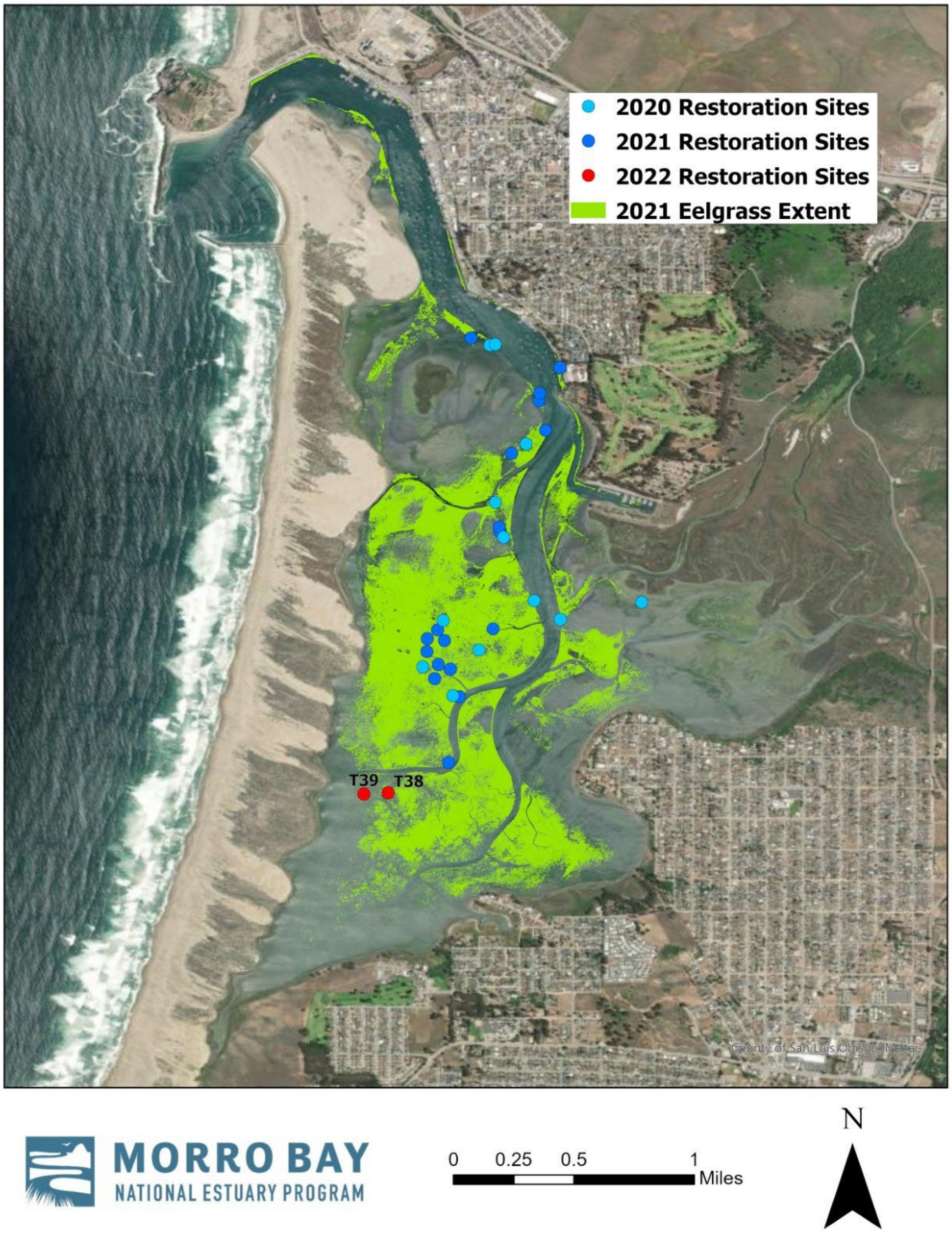

Figure 4. Map of eelgrass transplanting locations from 2020 to 2022, with the 2021 eelgrass extent in green.

Eelgrass Transplanting

Eelgrass rhizomes were collected from the Coleman donor bed for the 2022 restoration effort. Eelgrass was harvested on foot and by hand at low tides. No more than three rhizomes per square meter were collected, as required by the Estuary Program's scientific collection permit from CDFW. Harvesting and transplanting occurred in the spring, as previous experimental efforts showed higher success during the spring as opposed to the summer. Pre- and post-density eelgrass counts of the donor beds were collected before and after harvesting.

Figure 5. Eelgrass collection at Coleman Beach in March 2022.

For both of the restoration sites, three-foot bamboo stakes were used to transplant eelgrass. Each piece of bamboo had 25 rhizomes secured to it with jute string. Bamboo was then placed in the intertidal zone off the main channel and anchored to the sediment with garden stakes. The sites were accessed by boat and planting was conducted via scuba at high tide since the substrate is too muddy to navigate on foot. PVC plot markers were established at each planting so they could be revisited for monitoring.

Figure 6. Preparation and scuba planting of eelgrass bamboo pieces by Tenera staff, Spring 2022.

Monitoring of Restoration Sites

The two eelgrass restoration sites were monitored by Tenera in July and October 2022. Both T38 and T39 were monitored using scuba and/or snorkel. At three months post-planting, all six of the bamboo pieces at T38 experienced increased shoot counts, averaging 77% higher than during the initial planting. However, transplanting at T39 was less successful, and eelgrass had died back at five out of the six bamboo stakes.

At six months post-planting, shoot counts had declined at T38 but still remained higher than at the initial planting for all but one stake. Eelgrass health at T39 had improved significantly, as indicated by shoot count increases in five out of the six stakes, half of which had more than doubled since planting.

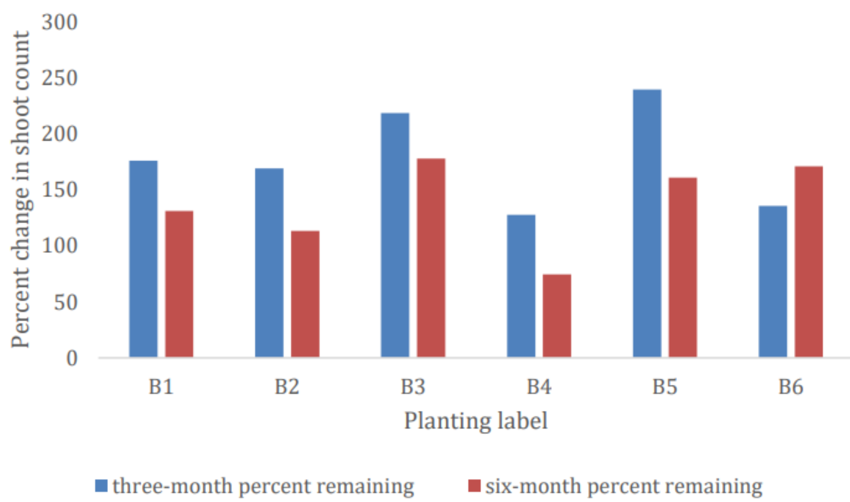

Figure 7. Percent change in shoot counts after three and six months post-planting at site T38.

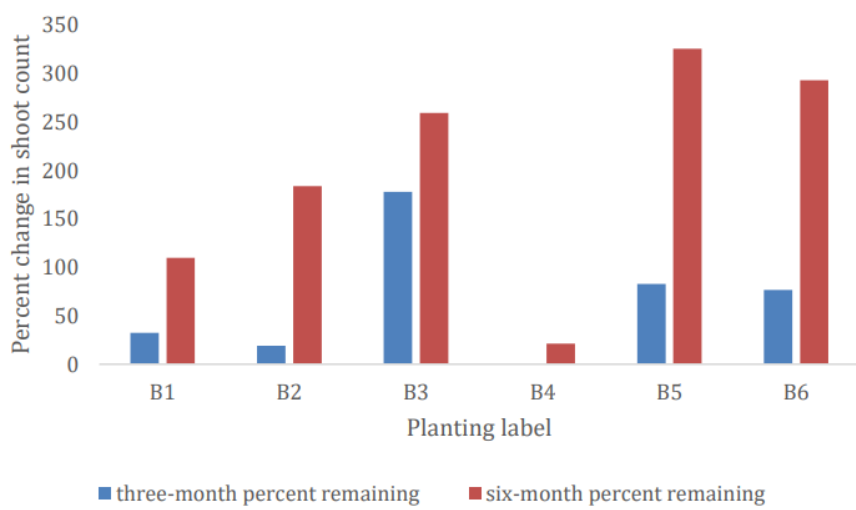

Figure 8. Percent change in shoot counts after three and six months post-planting at site T39.

The 2022 restoration marked the last transplanting efforts in the estuary unless eelgrass acreage declines back below the restoration target of 313 acres.

Other Monitoring Efforts

In addition to monitoring the restoration plots, there have been several supplementary monitoring efforts to track eelgrass changes throughout the bay. The Estuary Program established permanent transects beginning in 2005 to measure average shoot density at sites spanning the length of the bay. California Sea Grant and Cal Poly established bed condition monitoring beginning in late 2015 to measure average density and overall condition of remaining eelgrass. Cal Poly and California Sea Grant established permanent plots in 2018, which the Estuary Program monitored in 2018, 2019, 2021, and 2022.

Permanent Transects

History

Permanent transects were established to track changes in eelgrass shoot density throughout Morro Bay. There are currently six permanent transects, some having been established as far back as 2005. Four transects (Coleman, Reference, Chorro, Pasadena) were monitored annually from 2006 to 2010. No data were collected in 2011 due to staffing logistics. In November 2012, a fifth transect was established near the State Park Marina. From 2012 to 2016, some sites were not surveyed due to poor weather or tide conditions. In December 2017, a new transect was established on the eastern side of the channel at Tidelands Park, called “Embarcadero.” The transect now called “Reference” was originally named “Tidelands” but has since been renamed to avoid confusion.

Figure 9. The six current permanent transect monitoring locations: Coleman, Embarcadero, Reference (previously named Tidelands), Marina, Chorro, and Pasadena.

Methods

Monitoring was conducted during extreme low tides (-0.4 feet and below) during the late fall, as this period provides the best tidal windows for accessing sites. At each site, a GPS unit was used to identify the transect location (most sites have no permanent markings), and a meter tape was set out along a 50-meter transect. A 0.5-meter x 0.5-meter quadrat was used to take measurements at points along the tape. Percent coverage of eelgrass, macroalgae (predominantly *Gracilaria* and *Ulva*), and bare substrate were measured. If eelgrass was present, shoots were counted to determine density.

While there are six permanent transect locations, some sites have more than one transect. If an eelgrass bed was fairly wide, additional transects were established that run parallel to each other to measure eelgrass at various depths. Note that for analysis, all data from a site in a particular year were combined to represent eelgrass at that general location.

Initially the effort included an eelgrass biomass measurement. From 2005 to 2012, eelgrass samples were collected adjacent to each transect. However as eelgrass declined, it became too damaging to collect samples, and the biomass study was stopped.

Results

Average shoot density for each site is summarized in Figure 10.

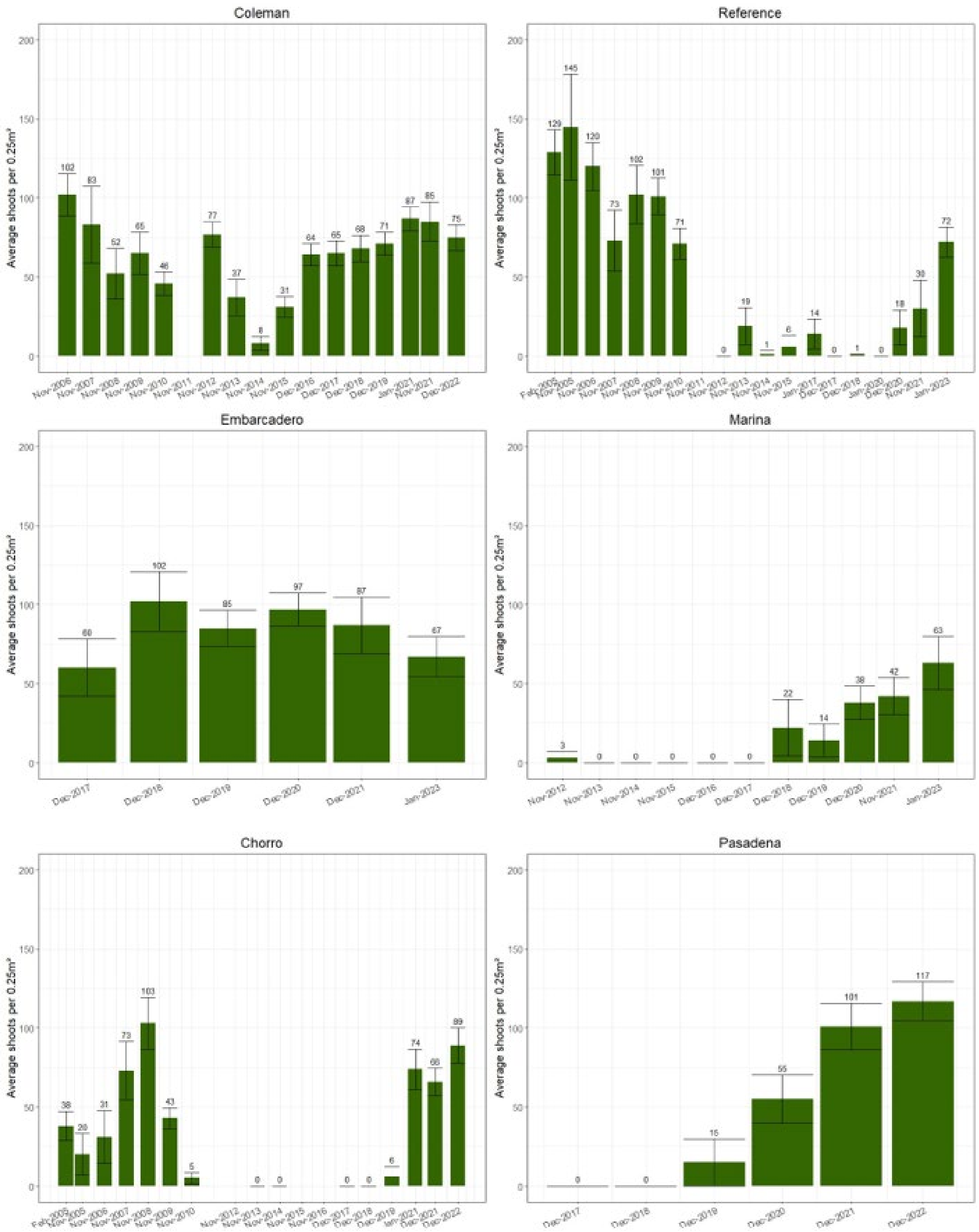

Figure 10. Average shoot density counts per year at six sites. Shoots were counted within a 0.5 m x 0.5 m quadrat. Error bars represent the 95% confidence interval.

Eelgrass density has rebounded to pre-decline levels at Coleman, Reference, and Chorro, the three sites where surveys were conducted before 2007. During 2022, average densities were higher than the previous sampling effort at four out of six sites, and all sites had higher densities than those recorded in 2017. For example, sites like Marina, Chorro, Pasadena, and Reference had no eelgrass present at the peak of the decline and reached their highest density since 2017 during this year's monitoring. The sites that had a sustained eelgrass presence during the decline, Coleman and Embarcadero, are not currently experiencing the same trajectory of increased density but are maintaining the density observed for the past several years.

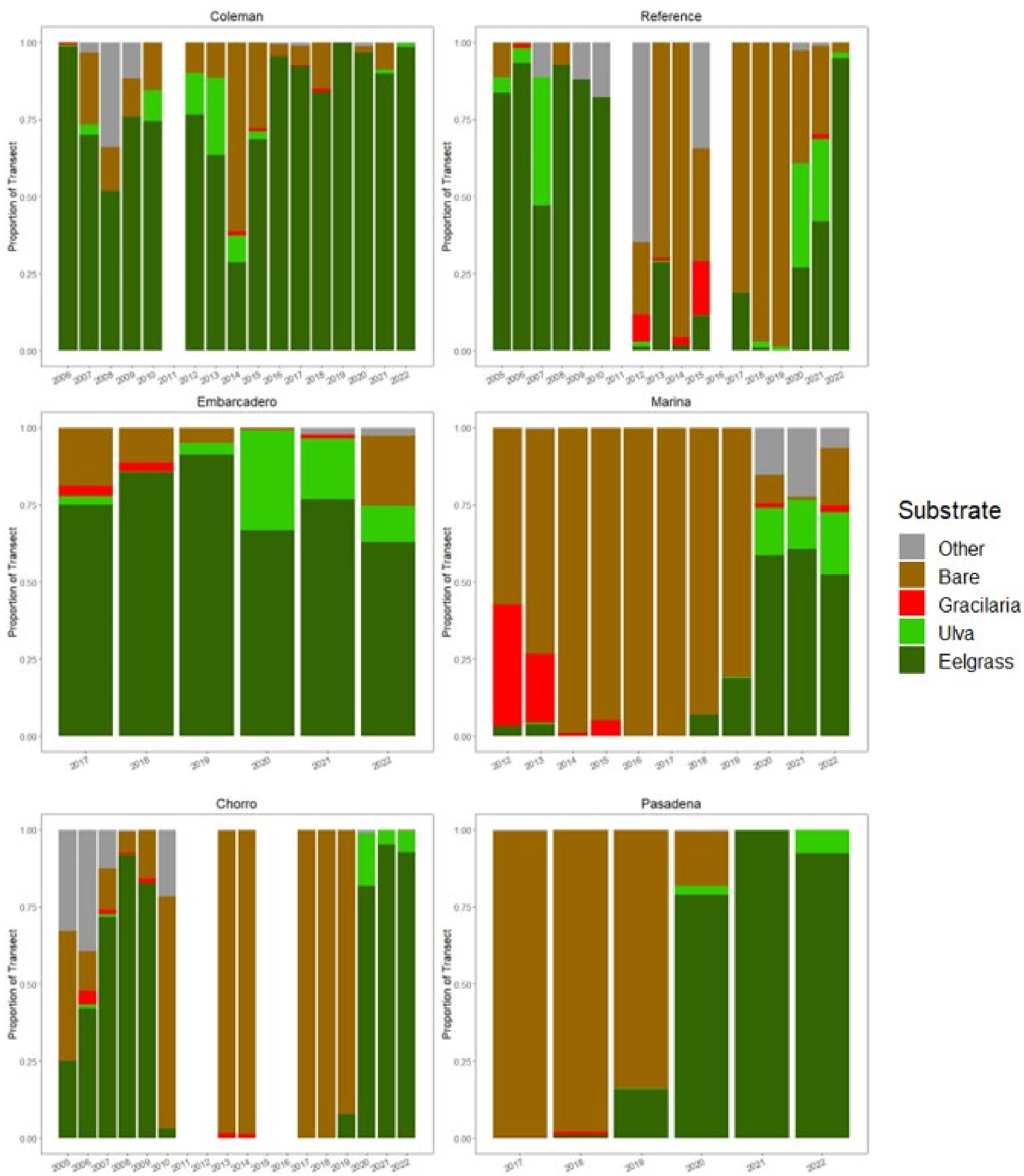

Figure 11. Proportional compositions of the primary recorded percent coverage types, averaged over all quadrats for a given year. Each vertical bar represents one year's sampling efforts.

Proportional compositions are summarized in Figure 11. The percent cover of eelgrass (dark green bars) observed at all sites closely follows the fluctuations in density seen in Figure 10. However, these plots show how additional macroalgae taxa fluctuated in abundance as well. The percent cover of *Ulva* (light green bars) across many of the sites has notably increased starting in 2020. Fortunately, the appearance of *Ulva* does not seem to be stifling eelgrass growth, as both organisms are currently experiencing increases in coverage. Of note, the density and percent cover of eelgrass at Reference was more than double that of last year's monitoring.

Permanent Transect Photos and Observations

Photo monitoring documents site conditions, although they have not been taken every year.

Coleman Transect

Average eelgrass density slightly decreased at this transect for the second year in a row but is still over ten times the density observed in 2014. Current shoot density is comparable to pre-decline levels seen in 2007.

Figure 12. Permanent transect monitoring at Coleman Transect, 2016 to 2022.

Reference Transect

Eelgrass has made a significant comeback at this transect after having been virtually absent since 2017. Small patches of eelgrass began appearing in 2019 at higher elevations than previously observed and have transformed the landscape to consist of eelgrass “islands” separated by small channels. Shoot density is similar to the pre-decline density observed in 2007.

Figure 13. Permanent transect monitoring at Reference Transect (previously “Tidelands”), 2017 to 2022.

Embarcadero Transect

This transect was established in 2017 and is the newest of the six permanent transect monitoring sites. Eelgrass density in 2022 was the lowest recorded at this site since 2017 and marks the second year of decline in a row. The Embarcadero transect had been a harvest site for restoration efforts for multiple years.

Figure 14. Permanent transect monitoring at Embarcadero Transect, 2017 to 2022.

Marina Transect

After this transect was established in 2012, no eelgrass was present from 2013 to 2017. Patchy eelgrass began appearing in 2018 and 2019 and has formed into one continuous bed. The shoot density observed in 2022 is the highest recorded after a decade of monitoring.

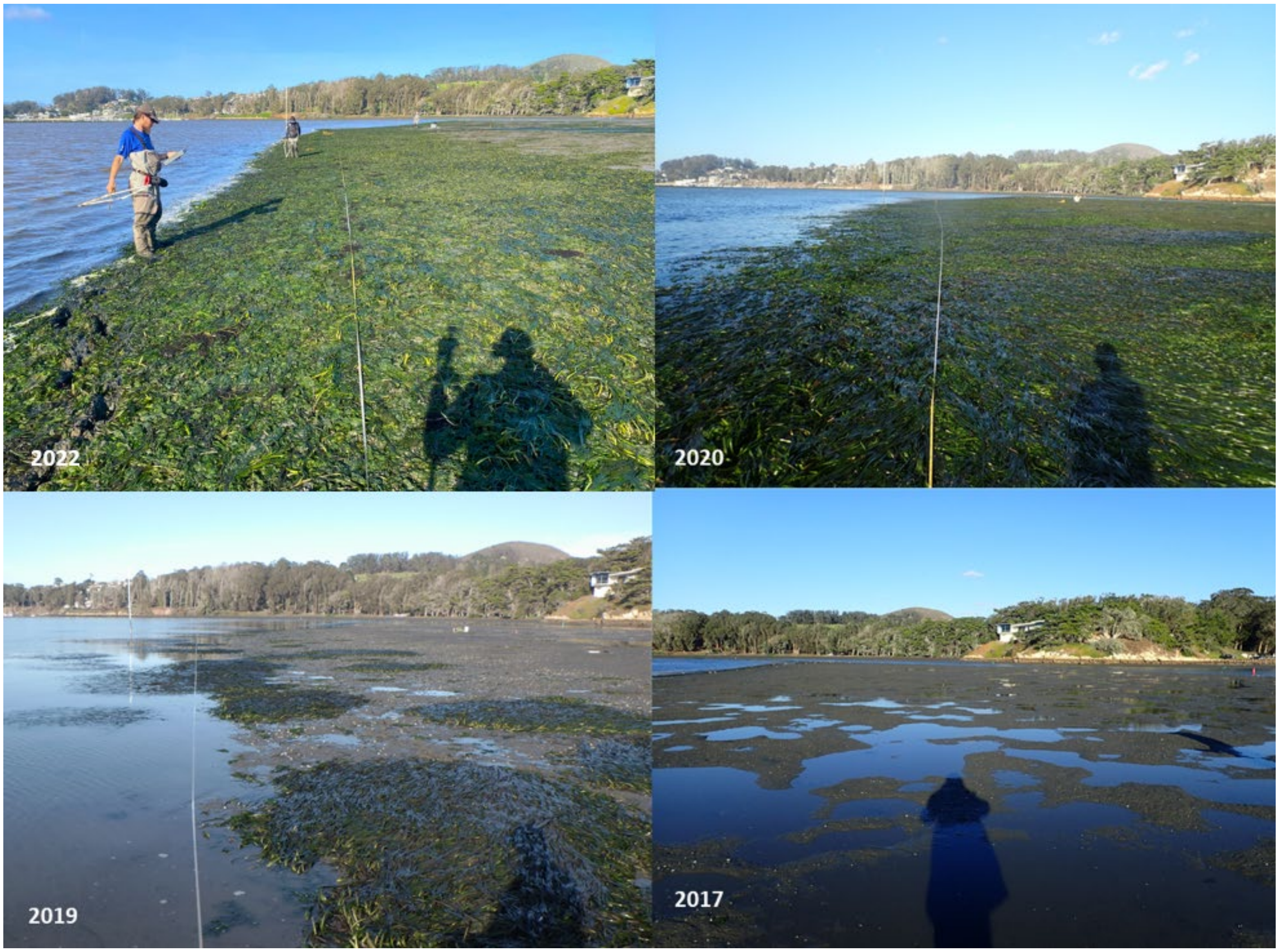

Figure 15. Permanent transect monitoring at Marina Transect, 2017 to 2022.

Chorro Transect

Shoot density at the Chorro transect returned to pre-decline levels in 2021 and has reached the highest density observed at this site since 2008. Eelgrass had not been recorded here since 2010 but reappeared in 2019. Surveys were not conducted at this transect in 2011 to 2012 and 2015 to 2016 due to staffing limitations and time constraints.

Figure 16. Permanent transect monitoring at Chorro Transect, 2017 to 2022.

Pasadena Transect

The Pasadena transect had the highest observed shoot density of 2021 and 2022. The photos below show the dramatic transformation that took place at this site over the past five years. In this relatively short time frame, eelgrass density has increased from 0 shoots/0.25 m^2 to 117 shoots/0.25 m^2. The Pasadena transect was established in 2005, however the original transect location was lost and it had to be re-established at new coordinates in 2017. Due to the uncertainty of its original location, only data collected at Pasadena since 2017 has been included in the report.

Figure 17. Permanent transect monitoring at Pasadena Transect, 2018 to 2022.

Permanent transects were initially established to track eelgrass density from sites throughout the bay. While density data at permanent sites can provide insight into the coverage of eelgrass at a particular location, it is not always the optimal method of monitoring eelgrass health. For example, there are often instances of eelgrass near the site (even within just a few meters), but because it was not on the transect, it is not captured in the data collection. Most transects are not permanently marked which makes it challenging to return to the exact location each year. Due to challenges with this methodology, a different method of monitoring was needed to more fully capture the health of existing eelgrass. The Estuary Program collaborated with Cal Poly and Sea Grant to develop a new monitoring protocol called Bed Condition Monitoring. However, permanent transect monitoring has continued, as it is the longest running eelgrass dataset for Morro Bay. This dataset helps to document pre- and post-decline conditions.

Bed Condition

History

Bed condition monitoring was established in 2015 as a joint effort between Dr. Jennifer O'Leary of California Sea Grant and the Estuary Program. This method measures eelgrass conditions in terms of density, blade length, evidence of necrotic tissue, and competition with algae and other organisms.

Monitoring occurs at four significant beds in Morro Bay along a 150-meter, seven-quadrat survey. Historically, both intertidal and subtidal eelgrass beds were surveyed, and monitoring occurred twice per year, once in late fall and again in the spring. Due to a lack of optimal tides, the fall monitoring and subtidal monitoring efforts have been halted. Since 2019, only the spring intertidal sampling has been conducted.

Methods

While in the field, eelgrass health is assessed using a combination of methods. Within each quadrat, stipe counts are conducted to determine eelgrass density, and plant and algae material are identified using the point-intercept method at 25 points. Between quadrats, eelgrass presence/absence is recorded along every meter of the transect to estimate the patchiness of the eelgrass bed.

An integral component of the Bed Condition protocol involves taking pictures of eelgrass plants and using photo processing to aid in the determination of blade health. At each site, five stipes are chosen from distinct locations within every quadrat. Each stipe is photographed with all the blades spread out against a whiteboard, so the full area of each blade is visible. These photos are then used to calculate percent cover estimates of eelgrass health indicators using ImageJ software.

Figure 18. Bed condition monitoring sites at Coleman Beach, North Sandspit, Reference Bed and Windy Cove.

Results

The Estuary Program conducted spring 2022 monitoring at Coleman Beach, Reference Bed, Windy Cove, and North Sandspit sites. North Sandspit and Reference Bed were both established at the beginning of the project but have had gaps between sampling years due to tide limitations. Spring monitoring had not been conducted at North Sandspit since 2017 and the Reference Bed site was modified to include an additional transect running perpendicular to the historic transect, which has experienced significant erosion and now contains only 18 meters of contiguous eelgrass. The figure below displays the results of preliminary data analysis using only the spring intertidal data from 2016 to 2022 and excluding sites that lacked adequate replication over several years.

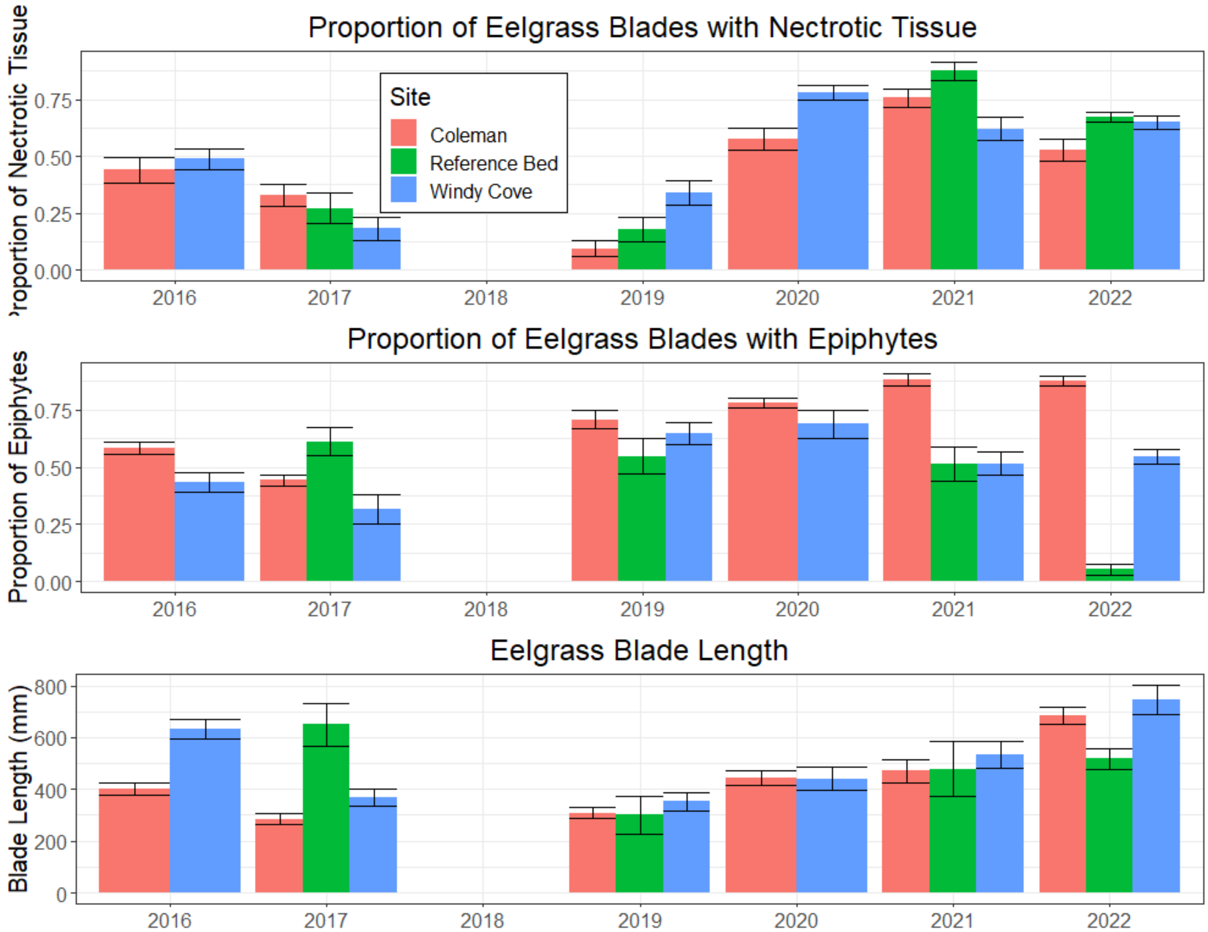

Figure 19. Blade condition results from spring intertidal sampling events. No sampling was conducted in 2018. Reference Bed was not sampled in years where a green bar is absent. Error bars represent the standard error.

The preliminary results show that the average proportion of blades containing necrotic tissue more than tripled between 2019 and 2021 but has fallen approximately 10% in 2022. In general, it appears that the abundance of necrotic tissue fluctuates more on a year-by-year basis than it does between sites. On the other hand, the proportion of blades with epiphyte coverage typically varies more across sites than it does between years. The site closest to the mouth of the bay, Coleman, consistently has the highest epiphyte coverage. It is believed that a higher rate of grazing in the back bay keeps epiphyte coverage down in those beds, while the lack of regular grazing in the front bay allows for epiphytes to grow continuously. It is also possible that water clarity and light penetration play a role in epiphyte distribution, as the presence of epiphytes can be linked to higher rates of primary productivity.

Blade length has increased steadily over the past several years. Average blade lengths from Coleman and Windy Cove are over twice as long as they were in 2019, indicative of sustained growth and retention of eelgrass at these sites.

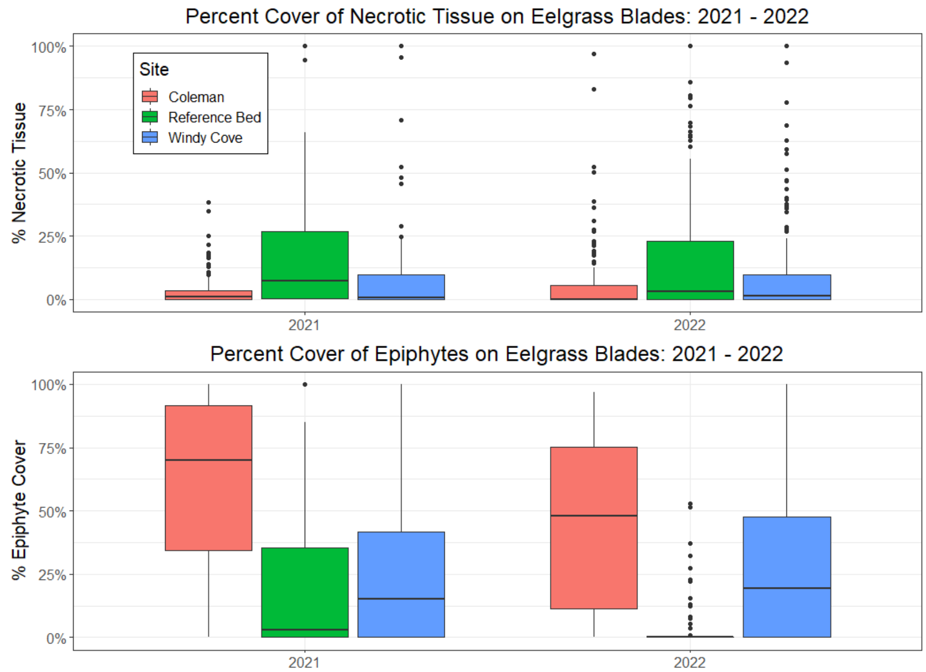

Figure 20. Results from processing pictures of eelgrass taken during the 2021 and 2022 monitoring efforts.

Figure 20 displays the percent cover of necrotic tissue and epiphyte coverage for all photos processed from Spring 2021 and Spring 2022. Photos that were blurry, dark, or had low resolution were excluded from the final dataset if they could not be adequately enhanced through editing. The results show that there is consistency in the spatial distribution of necrotic tissue and epiphyte coverage between the last two years of monitoring. Reference Bed had the highest incidence of necrotic tissue and Coleman had the highest epiphyte coverage in both years. These results corroborate the results of the field data (Figure 19), demonstrating that there is a correlation between the prevalence of these health indicators across eelgrass beds (as measured in the field) and the average percent coverage of these indicators on the eelgrass blades themselves (as measured through photo processing).

It is important to note that while necrotic tissue was present on the majority of blades at all sites, the actual percent cover of necrotic tissue typically made up less than a quarter of the total blade area. This is just one example of how photo processing provides a more complete picture of eelgrass health when used in conjunction with the field data.

Another interesting takeaway was the dramatic drop in epiphyte coverage observed at Reference Bed in 2022. This site was modified with an additional transect that resulted in different quadrat placement than in previous years. However, the new quadrats were all within the same contiguous eelgrass bed that was monitored in previous years. When analyzing the results for the historic and new transects at Reference Bed, eelgrass at both transects experienced a notable decrease in epiphytes. The changes could be due in part to high amounts of grazing or crowding as recorded by the presence of epifauna, which includes many invertebrate species that feed on epiphytes or compete with them for space on eelgrass blades. In 2021, the percent coverage of epifauna at Reference Bed was 8%, which was over four times higher than the epifauna coverage at the other two sites. It is possible that the combination of low epiphyte cover and high epifauna cover relative to the other sites may have led to this decline. In 2022, epifauna cover at Reference Bed had dropped well below 1%, potentially reflecting the lack of available food for grazing invertebrates.

Permanent Plots

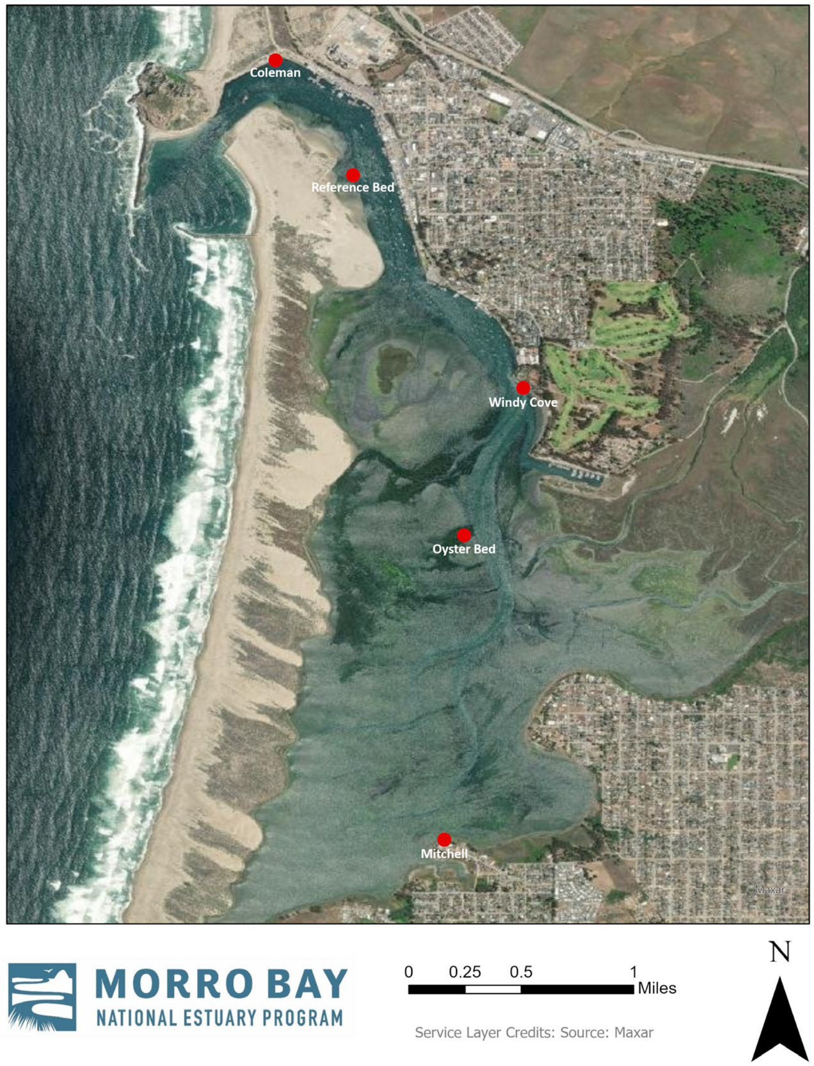

Figure 21. Eelgrass permanent plot monitoring locations.

History

In response to the decline of eelgrass in Morro Bay, permanent plots were installed in 2018 at five sites ranging from the front bay to the back bay (Figure 21). Three of these sites (Coleman, Reference Bed, and Windy Cove) are sites that had persistent eelgrass coverage through the period of recent eelgrass decline (2007 to 2016), while Oyster Bed and Mitchell represent areas where eelgrass coverage was lost.

Based on hydrological studies, there is a gradient of water quality parameters across the Morro Bay estuary. The area from the bay mouth to Windy Cove is largely influenced by oceanic water, and the water south of Windy Cove is less frequently exchanged with oceanic water and is notably warmer and saltier in the dry season (Walter et al. 2018). The five sites were established across this gradient of conditions to offer insight into the spatial variability of eelgrass health. With the resurgence of eelgrass acreage, 2022 marked the last round of Permanent Plot monitoring. The Oyster Bed site has been included in the Bed Condition monitoring project to continue the collection of eelgrass health data at this location.

Methods

Three plots were installed at each site by driving PVC markers into the sediment with anchor-screws, marking the corners where a one-meter by one-meter quadrat is placed. These markers remain permanently at each site, allowing the same plot of eelgrass to be monitored over time. The plots were monitored seasonally during 2018 and 2019, and once in the spring in 2021 and 2022.

Figure 22. Density counts and blade length measurements. Stipes are counted in the center four quadrat squares and the longest blade for each stipe is measured with a meter stick, pictured at Reference Bed in spring 2022.

Monitoring the permanent plots provides an opportunity to assess the health and condition of eelgrass over time. When monitoring the permanent plots, there are a variety of indicators that are being assessed. These indicators include eelgrass density, blade length, presence of necrotic tissue, tissue erosion, evidence of grazing, an account of what fauna and flora are within each plot, and the percent cover of epifauna and epiphytes living on the eelgrass blades.

Results

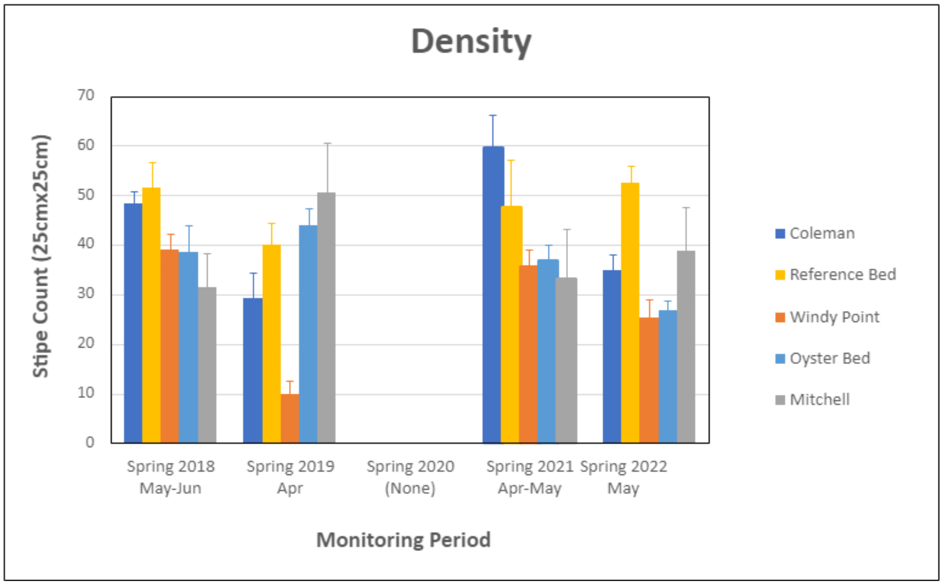

Figure 23. Average stipe count from 2018 to 2022, within a 25 cm x 25 cm quadrat.

Density is the primary parameter used to determine the abundance of eelgrass at a site and is a commonly used indicator of eelgrass condition. Over the course of the study, density was variable across all sites and ranged from approximately 10 to 60 stipes/0.25 m^2 (Figure 26). The steep decline in density observed at Windy Cove in spring 2019 was likely due to erosion within one of the plots, skewing the data from that year's survey. The Mitchell site, located the furthest back in the bay, had fairly high density despite exhibiting poor health when assessed with other metrics. The Reference Bed site, closer to the forebay, seems to be the site with the most consistent density.

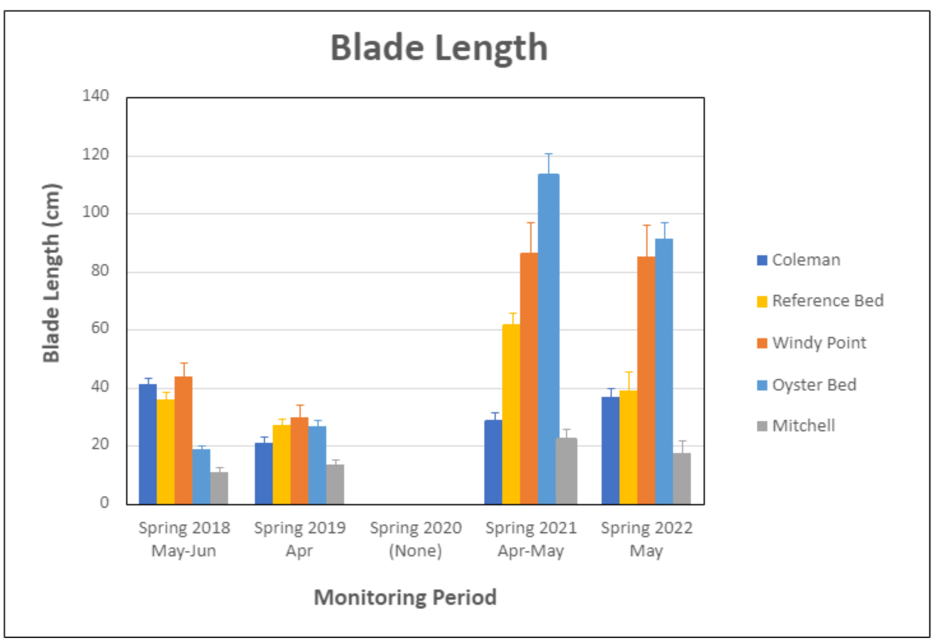

Figure 24. Average lengths of eelgrass blades from 2018 to 2022, within a 25 cm x 25 cm quadrat.

Blade length, another indicator of eelgrass condition, notably increased at Reference Bed and Windy Point between the first and second half of the monitoring timeframe (Figure 24). This could be indicative of more favorable conditions for eelgrass, as the timing corresponds with the expansion of eelgrass acreage. Coleman, the site closest to the mouth of the bay, had persistent eelgrass cover throughout the period of decline and did not experience an increase in blade length. Eelgrass at the Mitchell site consistently had the shortest blade lengths.

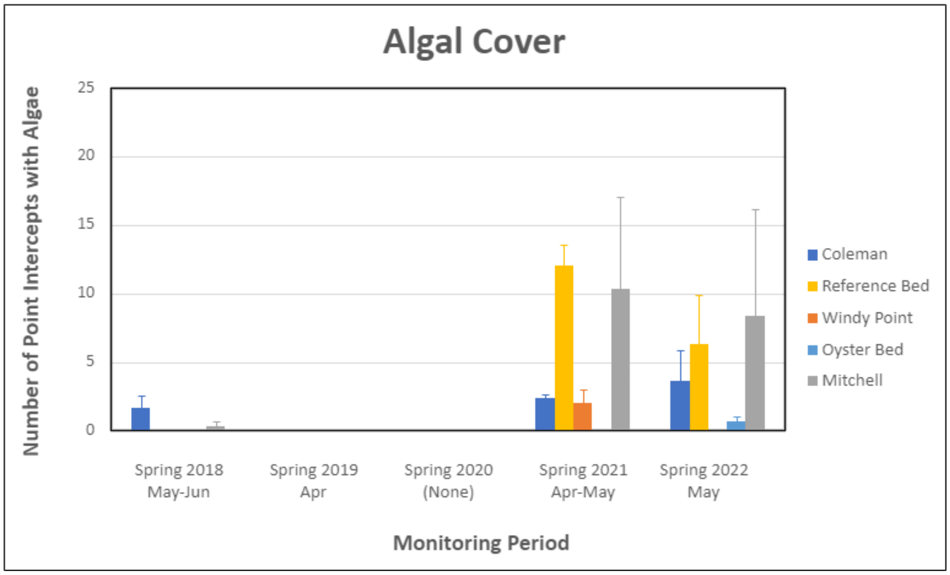

Figure 25. Average number of quadrat intercept points (out of 25) with algae directly under the point from 2018 to 2022.

Algal coverage results from this monitoring effort are consistent with observations from Permanent Transect monitoring. All Permanent Plot sites had either nonexistent or very low algal cover in 2018 and 2019 but experienced a notable increase during spring 2021. Mitchell and Reference Bed have sustained this elevated algae coverage in spring 2022, with the highest variability in coverage observed across the three Mitchell plots.

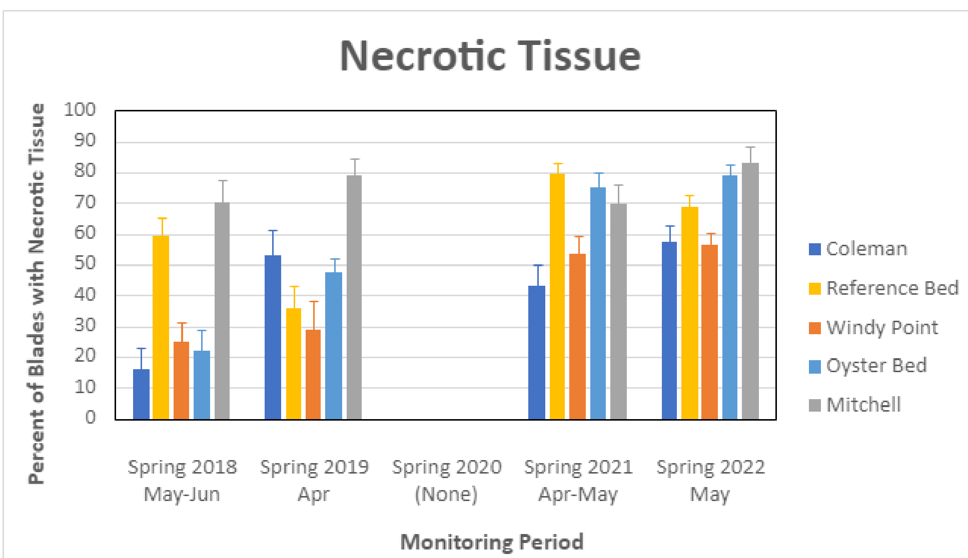

Figure 26. Average percent of eelgrass blade area covered with necrotic tissue from 2018 to 2022, within a 25 cm x 25 cm quadrat.

Additional indicators of eelgrass health, including epiphyte coverage and presence of necrotic tissue, display variability along the gradient of the bay. Epiphyte coverage is indicative of the general system primary productivity, however excessive coverage can reduce the photosynthetic capabilities of eelgrass blades. As seen in the Bed Condition results, epiphyte coverage is higher in the front bay and lower in the back bay. Coleman typically has the highest epiphyte coverage while Mitchell has the lowest. Conversely, Mitchell had the highest incidence of necrotic blades, which typically indicate poor health since necrotic blades are brittle, eroded, and likely are not actively photosynthesizing. In 2022, all sites except for Reference Bed had the highest percentage of blades with necrotic tissue than any previous spring monitoring effort (Figure 26).

Figure 27. Stipe from Mitchell during the Spring 2022 monitoring. Most of the blades at the site were covered in spots of brown, necrotic tissue (circled in red).

Considering the indicators evaluated, several factors indicate that the location of the Mitchell site is less hospitable to eelgrass growth and recovery. This site has higher necrotic tissue and shorter blade lengths than other sites, indicating poor quality eelgrass, which is understandable given its location at the edge of pre-decline eelgrass extent. Through the permanent plot monitoring, we have found that eelgrass is able to grow across a range of conditions, and thus shows potential for high resilience.

Additional Activity

Dredging Operations

The Morro Bay harbor is a designated Harbor of Safe Refuge and is the only safe harbor between Santa Barbara and Monterey. Maintenance of this important harbor requires frequent dredging operations. The harbor mouth is dredged annually by the Army Corps of Engineers (ACOE) to maintain a channel depth of approximately 40 feet.

ACOE began their annual dredging in Morro Bay on May 7, 2022 and the project was completed on May 31, 2022. During active dredging, ACOE contracted Merkel & Associates (M&A) to conduct weekly water sampling efforts upstream and downstream of the dredge footprint as well as at the disposal location. Water quality parameters included dissolved oxygen, light transmittance, turbidity, pH, temperature, and salinity. Action levels for all parameters were defined as a 20% or greater change between upstream and downstream locations, and dissolved oxygen levels were maintained at a minimum of 5 mg/L. In addition, two one-liter water samples were collected at all sampling locations once during the cycle. These samples were then analyzed for total suspended solids (TSS) and total chlordane.

The post-project report indicated one slight turbidity exceedance occurred on May 18, which did not require adaptive action measures since the dredging was stopped for refueling. No other water quality exceedances were encountered during dredging activities. Adequate dissolved oxygen was maintained throughout the project, ranging between 5.7 mg/L to 9.0 mg/L. TSS values ranged from 2.4 mg/L to 5.8 mg/L, which falls within typical non-rainy season values for Morro Bay. The pesticide Chlordane was not detected at any station during sampling (M&A, 2022).

Embarcadero Projects

Eelgrass grows intermittently along the Morro Bay Embarcadero, and impacts to eelgrass must be considered before any construction may occur. Surveys to monitor eelgrass changes have typically been completed by Tenera using scuba divers and/or sonar before, during, and after construction projects. In 2022, two surveys were conducted to support construction projects on the Embarcadero. The conclusions of the surveys were as follows:

- A survey for the construction of a public coastal access walkway and new floating dock at 801 Embarcadero. The project will connect with the Harborwalk Plaza walkway. No eelgrass was found where the dock and walkway would be added, however 11% of the construction area is considered eelgrass habitat since it falls within five meters of surrounding eelgrass patches, as defined by the California Eelgrass Mitigation Policy. A follow-up pre-construction survey completed during the active growing season will likely be necessary to determine if control areas should be established. These control areas are used to determine if restoration is needed to offset impacts to eelgrass.
- A survey for the City of Morro Bay to refurbish the Tidelands boat launch ramp. Two large patches of eelgrass, one on each side of the concrete ramp, would likely be temporarily disturbed by the work, however nothing would prevent the repopulation and expansion of eelgrass after the work is completed. The end of the ramp will likely need to be extended by 10 to 20 feet, which will not impact eelgrass as it is too deep to provide suitable eelgrass habitat.

Partnerships

The Estuary Program is continuing their partnership with Cal Poly and Cuesta College to support eelgrass research efforts. The effort also involves CDFW, NOAA, and U.S. Fish and Wildlife Service (USFWS) partners. These partnerships promote sharing of data and expert opinions to help guide eelgrass activity.

Research Efforts

Various research efforts are underway related to Morro Bay eelgrass. They are briefly summarized, including an estimate of when results will be available.

Automated Eelgrass Classification using Drone Imagery

As mentioned earlier in the "UAV Drone Mapping" section, a machine learning model for the classification of eelgrass has been under development. This project is a collaborative effort between researchers at Stanford and Cal Poly and its successful quantification of eelgrass acreage in 2019 was the subject of a recent publication (Tallam et al 2023). The researchers use a state-of-the-art image segmentation machine learning technique to delineate eelgrass beds by assigning each pixel in the orthomosaic of drone imagery a classification of "eelgrass" or "non-eelgrass."

The model performed very well on the 2019 imagery, receiving an F1 accuracy score of 80.9% and was able to accurately identify and annotate eelgrass when compared to the hand-digitized map. In some cases, the model exhibited higher precision than the map annotated by hand. In a small number of cases, false positives were detected due to the similarities in appearance of green algae mats and eelgrass beds. The researchers believe this issue can be resolved by employing a multi-class image classification model, where each type of vegetation would be assigned a respective class, as opposed to solely "eelgrass" versus "non-eelgrass." As the model is further optimized, it has the potential to dramatically reduce the effort spent on digitizing eelgrass acreage maps, reducing both the time and cost of eelgrass mapping and allowing for more frequent surveys.

Water Quality Monitoring

Dr. Ryan Walter from Cal Poly's Physics Department continues to maintain water quality instrument packages at the front bay and the back bay, as well as a weather station in the back bay. Funding for these stations are provided by the Central and Northern California Ocean Observing System (CeNCOOS) and the Estuary Program. A real-time data stream is available here: https://www.cencoos.org/data/shore/morro. Additionally, Dr. Walter maintains temperature sensors at the mouth of the bay and back of the bay.

Dr. Emily Bockmon of Cal Poly's Chemistry Department oversaw numerous ocean acidification monitoring and carbonate chemistry sampling efforts. In 2020, two autonomous pH sensors were deployed, one at the bay mouth T-Pier and the other at a water quality sensor array in the back bay. Data is automatically uploaded from the sensor to the web and can be viewed here: https://data.cencoos.org/#metadata/100050/station. Data calibration, processing, and sensor maintenance are ongoing.

Figure 28. Dr. Emily Bockmon's students collect water samples for carbonate chemistry analysis while anchored to the back bay weather station.

Dr. Bockmon and her students also conduct monthly carbonate chemistry sampling at seven shore locations, one of which was added this past year. Nutrient sampling was added at three of the shore sampling locations in 2021 and an additional three locations were added in 2022.

Microclimate Ocean Acidification and Hypoxia Experiment

In addition to their ongoing research efforts, Dr. Ryan Walter and Dr. Emily Bockmon conducted a two-week study focused on ocean acidification and hypoxia inside and outside of eelgrass beds in July 2021. The work was funded by a Restore America's Estuaries Coastal Watersheds Grant and results were available in 2022.

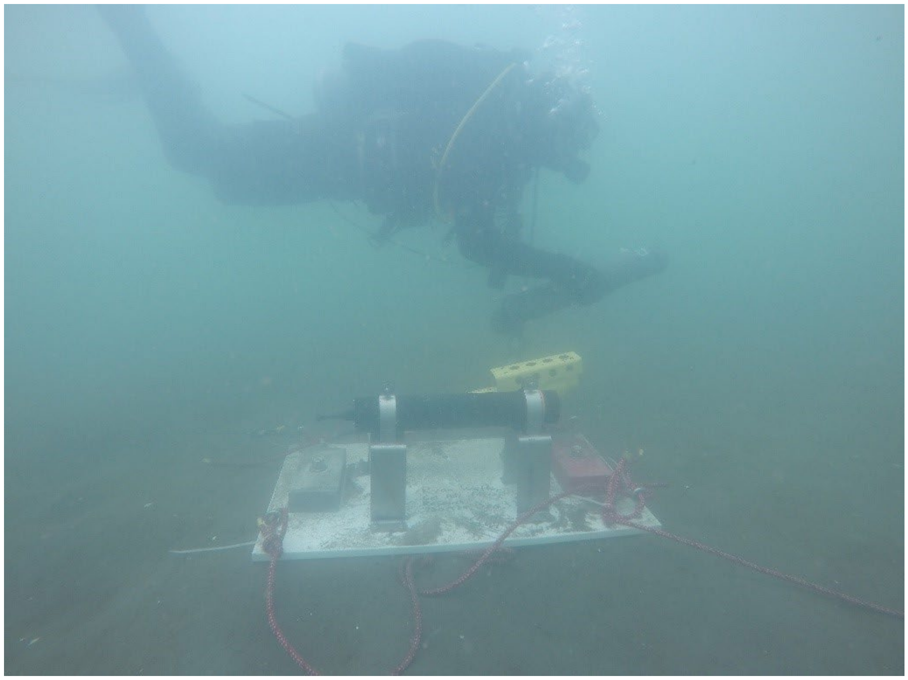

Figure 29. Cal Poly Senior Research Scientist Ian Robbins collects a water sample near the sensor array to calibrate the pH sensors deployed outside of the eelgrass bed. Photo courtesy of Dr. Ryan Walter.

To assess the impacts of eelgrass on modifying water chemistry and hydrodynamics, two oceanographic moorings were deployed and equipped with sensors that measured temperature, salinity, depth, dissolved oxygen, pH, current speed, and current direction. One mooring was situated inside a large subtidal eelgrass bed, while the other was placed in the adjacent unvegetated channel.

Results from the study show that conditions outside of the eelgrass are typically warmer and saltier than within the eelgrass bed. This is primarily attributable to the drag placed on moving water masses within the eelgrass bed which prevents the warmer and saltier back bay water from fully encroaching upon the bed while the tide is falling. The dissolved oxygen and pH results indicate higher variability in the eelgrass bed, with oxygen concentration frequently falling below that observed outside the bed. This is a sign of enhanced biological activity in the eelgrass bed compared to outside the bed. These results highlight how eelgrass can modify the local environment and create microclimates which are important for the health of the eelgrass and the organisms that rely on it.

Topo Bathymetrtric LiDAR Survey

The Estuary Program contracted with NOAA's Office of Coastal Management and NV5 Geospatial in 2022 to conduct a light detection and ranging (lidar) survey throughout the bay. The Digital Elevation Model (DEM) from the most recent survey was compared with previous DEMs from 2010 and 2019 to assess the rates of elevation change as eelgrass acreage has fluctuated. Dr. Ryan Walter led a study using the 2010 and 2019 surveys and found that eelgrass loss had contributed to erosion at 90% of sites that had previously supported eelgrass beds, with a mean elevation loss of 0.1 m (Walter et al. 2020). In contrast, sites near the mouth of the bay that had retained eelgrass during the decline had experienced a mean elevation increase of 0.32 m. This is consistent with findings from a number of studies that have shown that seagrasses support sediment retention.

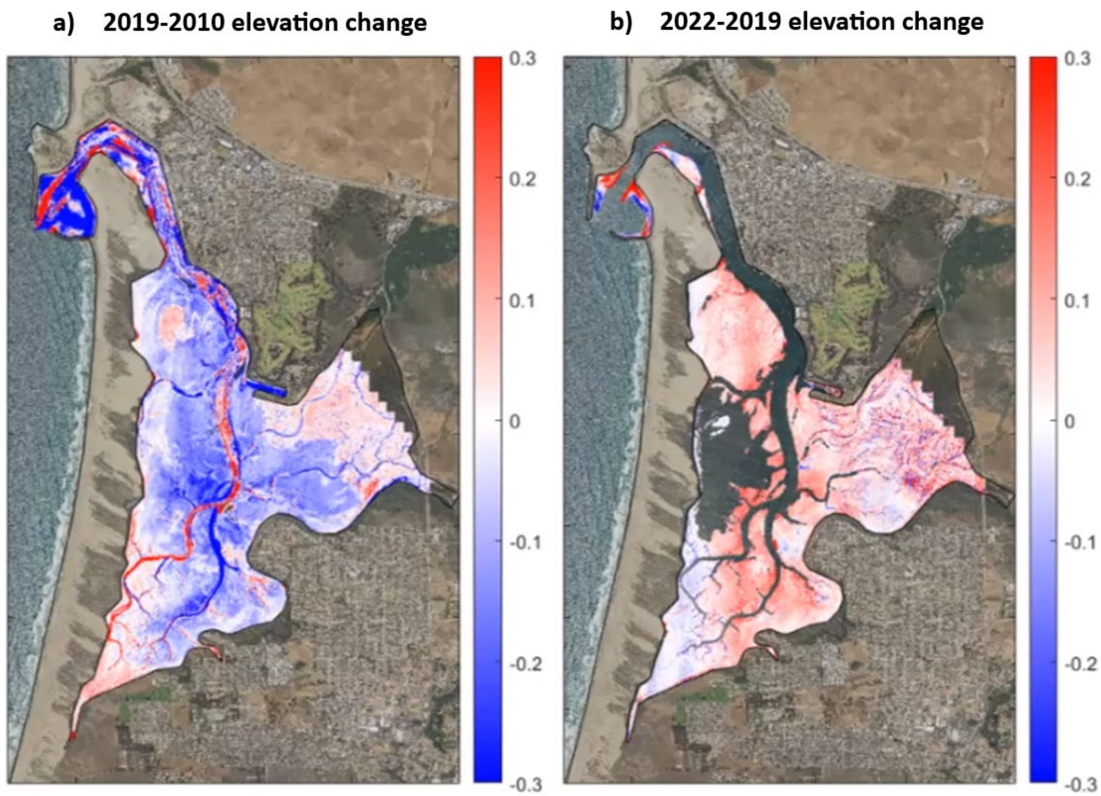

Figure 30. The change in elevation observed at different stages in eelgrass acreage fluctuations: a) Decline (2010 to 2019) and b) Recovery (2019 to 2022). Red coloration indicates elevation gain (accretion), and blue indicates elevation loss (erosion).

The changes observed upon comparing the 2019 and 2022 DEMs are consistent with the results from the original study. As eelgrass acreage increased from 43 acres in 2019 to 500 acres in 2021, the estuary has returned to a state of net elevation gain (accretion). The expanded eelgrass coverage likely slows down waves and currents that would otherwise promote erosion. While further analysis is needed, Dr. Walter hypothesizes that cycles of erosion and accretion may be a significant driver in eelgrass acreage changes. The erosion observed during the eelgrass decline may have rid the estuary of excess sediment, which exposed seed banks and supported the proliferation of eelgrass at a more favorable depth range, allowing for massive regrowth throughout the bay.

Eelgrass Wasting Disease Research

Students and faculty from Cuesta College have been studying the occurrence of the slime mold *Labyrinthula spp.* on eelgrass in Morro Bay since 2018. This project, led by Drs. Laurie McConnico and Silvio Favoreto, is focused on the distribution of *Labyrinthula spp.* throughout the estuary and understanding its role in eelgrass wasting disease.

Eelgrass blade sampling is conducted annually in Morro Bay by Cuesta College faculty and students. Approximately 20 to 25 individual blades are collected from the mouth, mid-bay, and back bay. Students process and culture fragments of each blade to detect the presence of *Labyrinthula spp*. and a separate portion of each eelgrass blade is dried and preserved for subsequent sequencing and DNA quantification.

Although data analysis for this project is still underway, the past four years of data indicate that *Labyrinthula spp.* behaves as an opportunistic organism in the Morro Bay estuary rather than a primary pathogen. Opportunistic microbes take advantage of a weakened state to promote disease but are unable to establish infection in healthy hosts. In 2022, 40 DNA samples were processed to investigate the eelgrass microbiome in association with wasting disease. Preliminary results show that blades with necrotic spots harbor twice the number of microbial species as healthy blades, and the microbial community changes depending on where the eelgrass samples were collected in the bay.

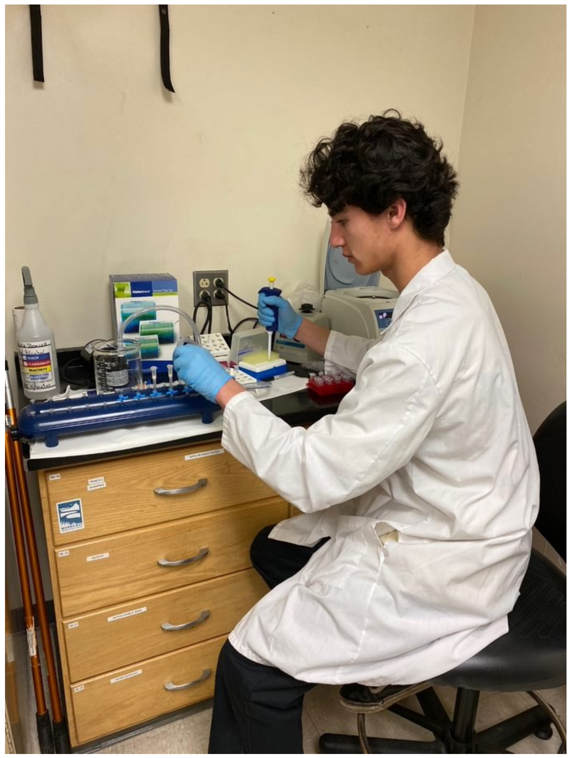

Figure 31. A Cuesta student aids Dr. Laurie McConnico and Dr. Silvio Favoreto in sequencing the *Labyrinthula spp* from samples of eelgrass tissue.

In addition to studying *Labyrinthula spp.*, Dr. McConnico and Dr. Favoreto further refined the Excess Green Index (EGI) method, designed to compare the health of eelgrass samples using non-invasive, quantitative, image-based analysis. The method is based on RGB deconstruction and analysis of high-definition images obtained from cultured blade fragments. Last year, they found that EGI is negatively correlated with the visual necrosis score and can be used as an indicator for a sample's photosynthetic capabilities. EGI eliminates the guesswork of visual scores but is more time consuming since measures are performed every two to three centimeters along the blade. To speed up this process, researchers at Cornell University have been working on an artificial intelligence approach designated EeLISA (Eelgrass Lesion Image Segmentation Application) that can quickly analyze images of eelgrass blades to differentiate between healthy and diseased tissue. Dr. Favoreto has been in contact with Cornell on the possibility of submitting Cuesta's images to be processed by their AI tool.

Further sampling and analyses are expected to take place during 2023 and will be used along with the data from previous years to assess temporal changes in the slime mold. These long-term data sets will be critical to better understand the role *Labyrinthula spp*. and other microbes play in eelgrass health within the Morro Bay estuary.

Black Brant Population and Behavior Changes

The black brant (*Branta bernicla nigricans*) is a small goose that feeds primarily on eelgrass. Morro Bay is an important stop on its annual migration between summer nesting sites in Alaska and wintering sites in Baja California. The brant populations in Morro Bay have historically been associated with eelgrass availability and were likely impacted by the eelgrass decline. However, the recent increase in eelgrass acreage has not yet resulted in a brant increase of similar magnitude.

John Roser, a local biologist, has been counting brant in Morro Bay for nearly 25 years. To estimate the presence of brant in the bay, mid-winter counts are conducted each January and can be compared to historic counts as far back as 1931. Counts from the 1930s through the 1960s averaged between 6,000 to 7,000 brant, with some counts reaching as high as 12,000 brant. The more recent counts, displayed in Figure 32, are all below these historic averages. Brant numbers in Morro Bay experienced a significant decline from the early 2000s until 2015 but have started a modest recovery.

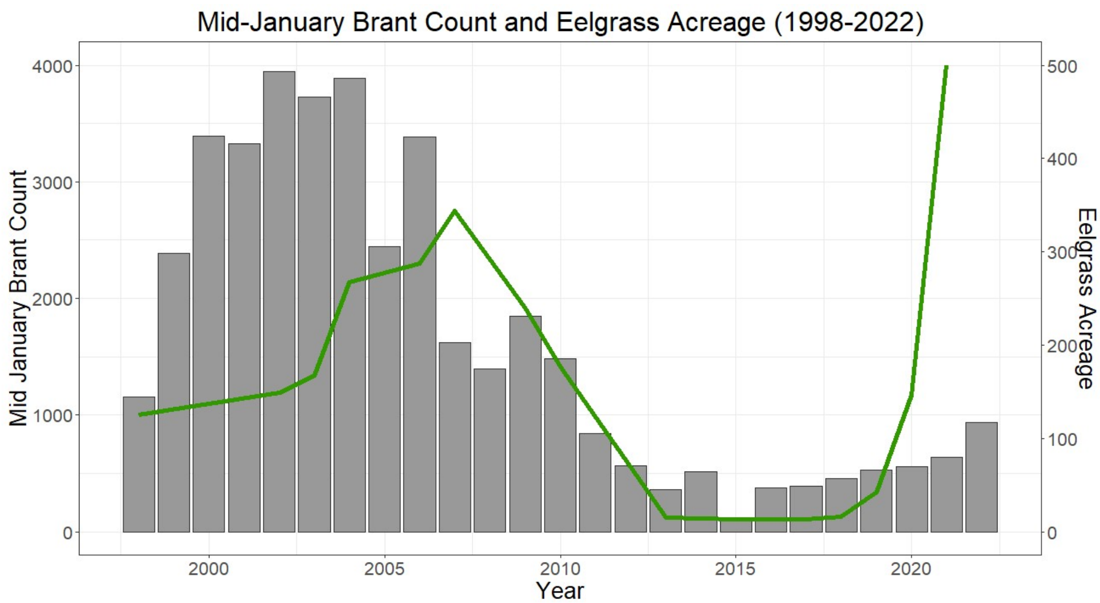

Figure 32. Results of the Mid-January Brant count from 1998 to 2022 compared with eelgrass acreage. Brant counts are available through 2022 but the latest eelgrass acreage data comes from drone flights in 2021.

We hope to see brant return in larger numbers if eelgrass continues to thrive, however the changing climate has altered the number of brant that choose to migrate from Alaska. Warmer temperatures in Alaska allow for adequate food availability throughout the year, causing proportionally less brant to make the 3,000-mile migration. While the number of brant stopping by Morro Bay is fairly low, it is worth noting that their overall population numbers across the Pacific Flyway are stable.

Upcoming Projects

Eelgrass Acreage Mapping

In spring 2023, the Estuary Program will contract Merkel & Associates to conduct a baywide eelgrass map utilizing a combination of interferometric side scan sonar (ISS) to capture subtidal eelgrass habitat and low-altitude UAV aerial imagery along the remaining intertidal portions of the bay exposed at low tide. The hybrid data collection approach will result in an eelgrass distribution map covering the entirety of the bay.

Additionally, the Estuary Program will partner with Cal Poly for a bay-wide UAV drone survey during fall 2023. Although high resolution imagery will be acquired, the full manual quantification of eelgrass coverage in GIS is not expected to take place. The imagery will support Cal Poly's machine learning project, which seeks to develop algorithms to automate the classification of eelgrass from the drone imagery. This effort will be accompanied by two methods of ground-truthing. The first method involves collecting photos on the ground accompanied by highly accurate GPS points to verify the presence of eelgrass or other types of vegetation. This method has been used historically along with previous drone maps and has been essential for hand-digitizing the acreage maps. The new method of ground-truthing involves a lower-altitude drone flight along segments of the bay to obtain clearer imagery, which can be fed into the automated classification algorithm to double-check its accuracy.

Continuation and Development of Monitoring Projects

In 2023, the Estuary Program plans to conduct monitoring of permanent transects and bed condition locations. In addition, an algae-focused monitoring project is currently in development and will begin in 2023. The increased prevalence of macroalgae has become a potential concern for long-term eelgrass health. Monitoring will take place three times per year to capture the seasonality of macroalgae abundance. In the field, percent cover of different algae types will be recorded and samples of macroalgae will be collected for dry-weight processing. This will allow for biomass measurements to be obtained, which are the best way to estimate the true amount of algae at each site.

Additional Research Activity

Dr. Ryan Walter of Cal Poly will continue to maintain the water quality instrument package at the mouth of the bay and in the back bay throughout 2023. Dr. Bockmon of Cal Poly will also continue to oversee the operation of the autonomous pH sensors at the mouth and back bay locations. Her team also intends to collect monthly shoreline carbonate chemistry and nutrient samples.

Additional research efforts by Cal Poly, Cuesta College, and others will continue to collect data to further our understanding of suitable conditions for eelgrass in the bay.

Conclusions

Eelgrass plays a vital role in the health of the Morro Bay ecosystem. While the acreage of eelgrass in Morro Bay has fluctuated in the past, the last decade has included the most precipitous decline and recovery on record. While we have not yet determined the exact explanation for the recovery, it is likely the result of a combination of shifts in elevation and water quality, natural recruitment, and restoration efforts. The Estuary Program plans to continue monitoring eelgrass health and acreage to further develop our understanding of eelgrass bay-wide and to assess how specific eelgrass beds are faring over time.

The past several years have marked a major transitionary period in Morro Bay's eelgrass beds, and the Estuary Program is in the process of investigating the impacts of this transition. Eelgrass coverage climbed to record highs in 2021, yet broader changes in climate will continue to modify conditions within the estuary. Data indicates that migratory patterns are changing, sedimentation and erosion continue to modify estuarine bathymetry, and macroalgae abundance has significantly increased during the spring and summer. While eelgrass and algae appear to be coexisting at the moment, these two primary producers have similar requirements for survival and may be in direct competition if conditions take an unfavorable turn. For this reason, a project devoted to monitoring the coverage and biomass of macroalgae will be initiated in 2023. Consistent monitoring will be key in adapting to and addressing future changes.

In 2023 and beyond, we will build upon our existing knowledge of eelgrass and its complex relationships with macroalgae proliferation, sedimentation, wasting disease, and more. While 2022 marked the final year of our current eelgrass restoration efforts, we will continue to stay up-to-date on restoration strategies so we can respond quickly and efficiently in case of a subsequent decline or die-off. The Estuary Program and its many partners will continue to work towards a better understanding of the estuary as a whole and apply that understanding to supporting a sustainable eelgrass population in Morro Bay.

References

Bernstein B, Merkel K, Chesney B, Sutula M. 2011. Recommendations for a Southern California Regional Eelgrass Monitoring Program. Technical Report 639. Prepared for the National Marine Fisheries Service. Southern California Coastal Water Research Project. Costa Mesa, CA

Chesnut J. 1999. Eelgrass Habitat in Morro Bay. Morro Bay National Estuary Program.

Cuesta College. Nov 2019. Role of *Labyrinthula spp.* in the development of eelgrass wasting disease in the Morro Bay Estuary. Final Community Project Report, Project Number 7219RF. Prepared for the Morro Bay National Estuary Program.

Cuesta College. 2021. 2020 *Labyrinthula spp.* Summary. Prepared for the Morro Bay National Estuary Program.

Fleischman, T. June 2022. AI reveals scale of eelgrass vulnerability to warming, disease. Cornell Chronicle.

Harenčár J.G., G. Lutgen, Z. Taylor, N. Saarman, J.M. Yost. 2017. How population decline can impact population genetics: A case study of eelgrass (*Zostera marina*) in Morro Bay. Estuaries and Coasts. Accepted with revision.

Hauxwell J, Cebrian J, Valiela I. 2003. Eelgrass (*Zostera marina)* loss in temperate estuaries: relationship to land-derived nitrogen loads and effect of light limitation imposed by algae. Marine Ecology Progress Series 247, 59-73.

Kitajima A. Jan 2016. Morro Bay National Estuary Program's Data Summary Report 2015. Morro Bay National Estuary Program.

Merkel & Associates. Sept 2014. Re: Morro Bay Eelgrass Recovery Program 2014 Eelgrass Transplant Report. Prepared for the Morro Bay National Estuary Program. M&A #12-090-05.

Merkel & Associates. Sept 2015. 2015 Monitoring Report, Morro Bay Eelgrass Recovery Program. Prepared for the Morro Bay National Estuary Program.

Merkel & Associates. June 2022. Re: Post-Construction Water Quality Monitoring Report In Support of the Morro Bay 2022 Maintenance Dredging Project. Prepared for the U.S. Army Corps of Engineers. M&A #05-024-42.

Morro Bay National Estuary Program. July 2017. Morro Bay Eelgrass Report 2014-2016.

Morro Bay National Estuary Program. April 2019. Morro Bay Eelgrass Report 2018.

Morro Bay National Estuary Program. February 2021. Morro Bay Eelgrass Report 2019.

Morro Bay National Estuary Program. December 2021. Morro Bay Eelgrass Report 2020.

Morro Bay National Estuary Program. October 2022. 2021-2022 Morro Bay Eelgrass Restoration & Monitoring Report. Prepared for the Restore America's Estuaries Coastal Watershed Grant.

Nordlund L.M., Koch E.W., Barbier E.B., Creed J.C. 2017. Seagrass ecosystem services and their variability across genera and geographical regions. PLOS ONE 12(1): e0169942. https://doi.org/10.1371/journal.pone.0169942

Ocean Imaging. November 2020. 2019 Morro Bay Submerged Aquatic Vegetation (SAV) Mapping in Morro Bay Utilizing Multispectral Imagery - Final Report (Revision 4). Prepared for the Morro Bay National Estuary Program.

Ralph PJ, Durako MJ, Enriquez S, Collier CJ, Doblin MA. 2007. Impact of light limitation on seagrasses. Journal of Experimental Marine Biology and Ecology 350, 176-193.

Roser J. April 2019. Brant Counts for Morro Bay, California, 2018 - 2020 Season. *Unpublished.*

Tenera Environmental. October 2022. Eelgrass planning survey for the Libertine Pub at 801 Embarcadero, Morro Bay, California. Document ESLO2022-15.

Tenera Environmental. November 2022. Eelgrass Planning Survey for the City of Morro Bay Tidelands Launch Ramp Project, 2022-H2P. Document ESLO2022-17.

Walter R.K., Rainville E.J., O'Leary J.K. 2018. Hydrodynamics in a shallow seasonally low-inflow estuary following eelgrass collapse. Estuarine, Coastal, and Shelf Science 213, 160-175. https://doi.org/10.1016/j.ecss.2018.08.026.

Walter R.K., O'Leary J.K., Vitousek S., Taherkhani M., Geraghty C., Kitajima A. 2020. Large-scale erosion driven by intertidal eelgrass loss in an estuarine environment. Estuarine, Coastal, and Shelf Science 243. https://doi.org/10.1016/j.ecss.2020.106910.

This project has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement CE-99T43601 to the Bay Foundation of Morro Bay. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does the EPA endorse trade names or recommend the use of commercial products mentioned in this document.