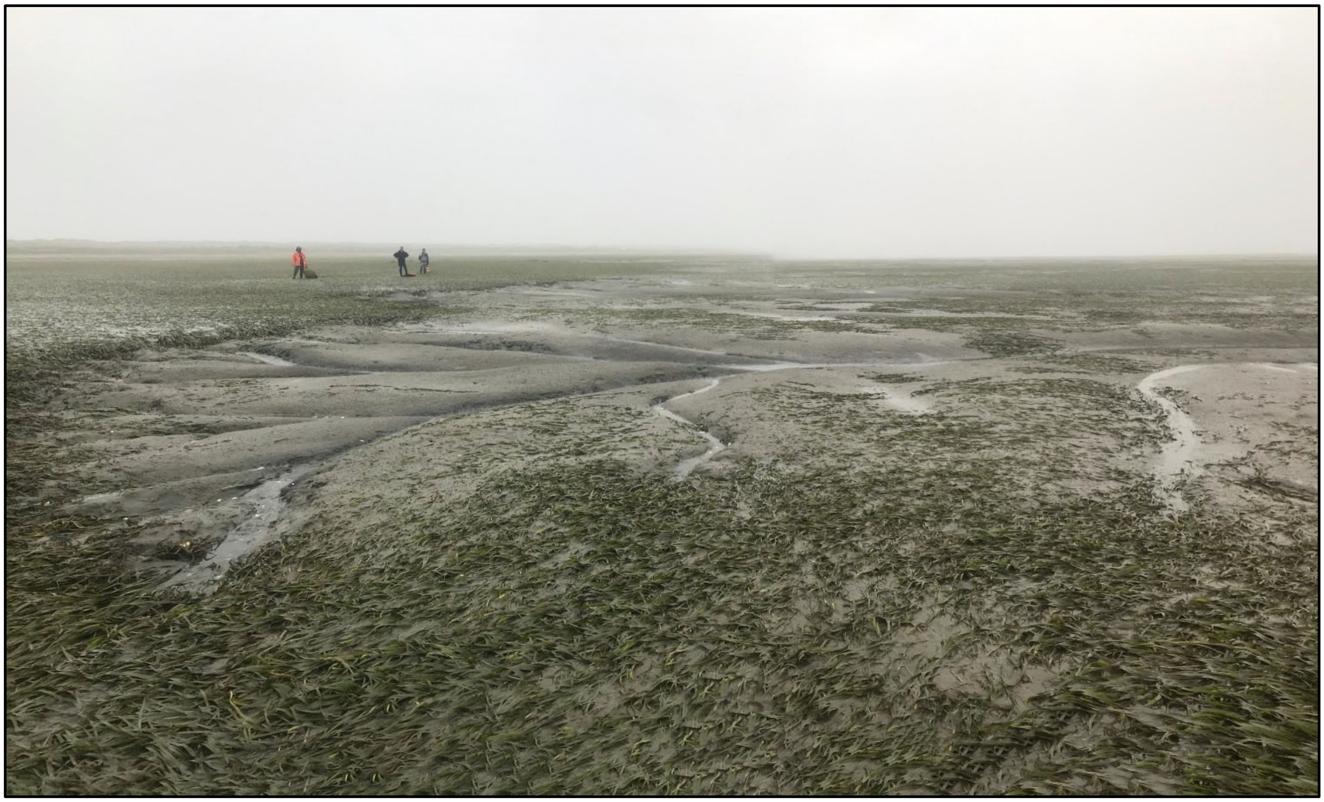
Humboldt Bay and Eel River Eelgrass Monitoring and Pilot Study Project (2020-2023)



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Background

This pilot study has been developed to provide insights into the current status of common eelgrass (*Zostera marina*) habitat within portions of Humboldt Bay and the Eel River Estuary, as well as to investigate trends in eelgrass distribution and abundance relative to baseline conditions previously assessed by the 2009 NOAA Humboldt Bay and Eel River Estuary Benthic Habitat Project (Schlosser & Eicher 2012). To accomplish these goals, several tasks were identified and prioritized through collaborative discussions with NOAA's West Coast Regional Office (Branch Chief, Jeffrey Jahn and Essential Fish Habitat Coordinator, Matt Goldsworthy) and the California Sea Grant Extension-Humboldt Office (former Extension Specialist Dr. Joe Tyburczy). The tasks that were ultimately selected for this study include a reconnaissance-level investigation of recently noted eelgrass losses occurring in South Humboldt Bay (Task 1); an inventory and analysis of eelgrass distribution trends within Humboldt Bay and the Eel River Estuary sloughs (Task 2); and pilot investigations of eelgrass loss and tidal flat erosion at focal study sites in South Humboldt Bay and Mad River Slough (Task 3).

Oblique view facing northwest of the pilot study site in South Humboldt Bay, CA (foreground) where eelgrass losses have been occurring and Pacific Ocean (background).

This study was funded by the California Coastal Office Division of NOAA Fisheries and administered through a cooperative agreement with California Sea Grant with the intent of providing additional information on recently noted significant declines in eelgrass habitat distribution within Humboldt Bay and the Eel River Estuary. As eelgrass is a habitat area of particular concern (HAPC) under the Pacific Groundfish Fisheries Management Plan (PFMC 2022), and Humboldt Bay supports approximately 35% of the known eelgrass in California, widespread eelgrass losses are of significant management concern. As such, characterizing the observed declines and exploring the causative agents is important to supporting making informed management decisions regarding this resource and managed species reliant upon eelgrass.

Eelgrass Ecology and Regional Context

Eelgrass is widely distributed throughout temperate estuaries and coastal embayments in both the northern Pacific and Atlantic oceans. Eelgrass plants are comprised of narrow, green, strap-like leaves that range in length from less than 40 to more than 130 cm (Keiser, 2004). Leaves are buoyant and grow from shoots called turions that emerge from branching root-like rhizomes. Eelgrass reproduces both sexually and asexually through flowering and rhizome branching respectively. Dependence on sexual reproduction is greatest in areas prone to physical disturbance (Phillips et al., 1983). Flowering occurs primarily in the spring and early summer with seed production and dispersal occurring from midsummer into fall (Phillips, 1984). The upper limit of eelgrass growth is primarily controlled by desiccation stress and wave exposure (Koch, 2001; Boese et al., 2003), while the maximum depths are typically limited by light attenuation (Dennison, 1987).

Eelgrass performs a multitude of ecosystem services. It provides a critical food source for spring staging Black Brant (*Branta bernicla nigricans*) (Moore and Black, 2006) and supports a rich detrital food web. Eelgrass meadows also provide structure and nursery habitat for a diverse range of fish and invertebrates including commercially-important species such as Dungeness crab (*Metacarcinus magister*) and Pacific herring (*Clupea pallasi*) (Phillips, 1984), as well as federally managed fish species (PFMC 2022). Where eelgrass forms more extensive beds, turbulence and current velocity are reduced, facilitating the deposition of fine sediment (Fonseca and Fisher, 1986).

Eelgrass is the dominant and only vascular macrophyte of the lower intertidal and shallow subtidal zones of Humboldt Bay and grows in a wide range of unconsolidated sediments primarily within the spectrum of fine gravel to clay. The invasive Japanese eelgrass (*Zostera japonica*) is typically limited in its occurrence within intertidal areas above common eelgrass within some areas of the Eel River Estuary and potentially within Humboldt Bay. This species is not the focus of the present study and, unless otherwise noted, eelgrass refers to common eelgrass (*Z. marina*).

Across the Pacific Northwest, eelgrass has been found to grow within a range of tidal elevations spanning from -6.6 meters to 1.8 meters relative to Mean Lower Low Water (MLLW) (Phillips

1984). Gilkerson (2008) determined the depth range capable of supporting eelgrass in Humboldt Bay and found substantial variation with respect to the maximum depth distribution of eelgrass. Further, it was determined that this maximum depth difference varied predictably by location within the bay. The maximum depths capable of supporting eelgrass were substantially shallower in North Bay relative to South Bay (-1.3 m MLLW vs -2.1 m MLLW; Gilkerson 2008). The eelgrass beds with the shallowest maximum depth are generally found in areas closest to sources of freshwater runoff with high-suspended sediment loads (e.g. Eureka Slough and Salmon Creek). More recent surveys completed in Humboldt Bay have resulted in eelgrass being found at depths up to -2.5 m below MLLW in the North Bay Channel (Merkel & Associates 2022). Based on a combination of field surveys and classification of aerial imagery (Judd 2006; Gilkerson 2008) the upper limits of continuous eelgrass habitat were estimated to range from approximately 0.3 to 0.4 m MLLW, while patchy eelgrass associated with semi-enclosed depressions and intertidal channels capable of retaining water during low-tide was found to extend up to 1.4 m MLLW.

The relatively shallow maximum depth distribution of eelgrass in Humboldt Bay is likely a reflection of the relatively high-suspended sediment yields associated with Humboldt Bay tributaries, in addition to the adjacent Eel River. During the latter part of the 20th century, the Eel River was believed to discharge the highest suspended sediment yield relative to watershed area of any river system unaffected by volcanic eruptions or active glaciers within the continental United States (Brown and Ritter, 1971). Eelgrass depth distribution in Humboldt Bay is also limited by the presence of steep channel slopes and high current velocities that occur within the bay's major channels. The majority of Humboldt Bay eelgrass habitat, by area, is distributed in North Bay and South Bay areas where expansive, low-gradient intertidal and shallow subtidal mudflats support extensive eelgrass meadows. Eelgrass habitat distribution within Entrance Bay is extremely limited primarily as a result of wave exposure. However, areas adjacent to North Bay Channel and small intertidal flats along the Samoa Peninsula and near the mouth of Elk River support small eelgrass beds.

In 2009, a total of 5,646 acres of eelgrass habitat were mapped in Humboldt Bay and 41 acres of eelgrass habitat was identified within the lower Eel River Estuary. These surveys were conducted as part of the Humboldt Bay and Eel River Benthic Habitat Project which leveraged color and infrared aerial photography captured during extreme low tide to map benthic habitats using the Coastal and Marine Ecological Classification Standard (CMECS; Schlosser and Eicher 2012). This was a cooperative effort involving NOAA Fisheries and California Sea Grant and represents the most comprehensive assessment of eelgrass and other benthic habitats ever completed within these systems. Within the lower Eel River Estuary, the largest individual eelgrass bed was found within McNulty Slough located northeast of the river mouth. Eelgrass was also found to occur within Salt River (a tidally influenced tributary located south of the mainstem Eel River) and adjacent smaller, un-named sloughs as well as Morgan Slough and Seven Mile Slough.

The results of the 2009 benthic habitat mapping confirmed that Humboldt Bay contains the most extensive eelgrass beds in California, representing approximately 35% of the state's eelgrass resources by area (Merkel & Associates 2017), and has one of the largest concentrations of eelgrass habitat on the entire West Coast, providing critical ecosystem functions at the local, regional, and coast-wide scales.

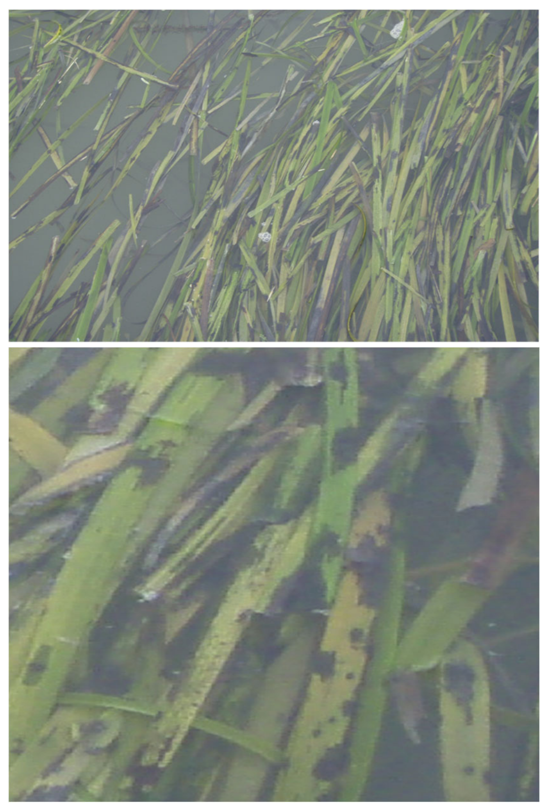
Eelgrass is a sentinel indicator of bay ecosystem health and water quality and may be impacted by a wide range of factors including suspended sediment, excess nutrients and other types of pollution, physical disturbance, shading from overwater structures, dredging activities and disease. Continuing infrastructure and resource development activities along the shoreline and adjacent uplands, as well as within the bay can impact eelgrass habitat. As climate change proceeds, the upper edges of eelgrass beds are likely to face increasing temperature and desiccation stress during low tide. Sea level rise may cause the lower margins of eelgrass beds to recede, as increasing water depth decreases the amount of sunlight available for photosynthesis which is an important factor that currently restricts the depth range of eelgrass in Humboldt Bay.

General distribution of eelgrass in California with the relative extent of eelgrass in each system indicated by size of location marker. Systems with less than one acre of eelgrass are not shown. (Merkel & Associates unpublished data)

The Humboldt Bay Eelgrass Comprehensive Management Plan (Merkel & Associates 2017) developed for the Humboldt Bay Harbor, Recreation, and Conservation District identified the lack of ongoing bay-wide monitoring of eelgrass as a critical shortcoming. In the past, intermittent monitoring efforts were conducted at several sites within the Bay in an effort to better understand variability in eelgrass bed dynamics, such as eelgrass shoot density, percent cover and above ground biomass. Additionally, several baywide mapping efforts have been conducted, beginning in 1959 and culminating most recently with the completion of the 2009 NOAA Humboldt Bay and Eel River Benthic Habitat Project (Schlosser and Eicher 2012). However, given the substantial differences in survey methodology between the 2009 benthic habitat assessment and previous baywide mapping efforts, it is difficult to draw robust conclusions about changes in Humboldt Bay's eelgrass distribution or abundance through time. Further, the lack of coupling between previous ground-based monitoring programs and aerial mapping efforts limits our capacity to harness historic data for purposes of understanding how changes in bed condition and overall eelgrass abundance may be related.

Insights gleaned from comprehensive eelgrass monitoring programs conducted in San Francisco Bay, San Diego Bay, Mission Bay, Morro Bay and the outer coast of the southern California Bight, as well as monitoring conducted in the Pacific Northwest and Alaska indicate that eelgrass distribution and abundance along the entire eastern Pacific has become much more variable over the past decade than it has been previously. Eelgrass in Humboldt Bay is believed to have experienced significant declines attributable to recent variation in climatic conditions since 2009, although only limited data existed upon which to draw inference regarding the magnitude and nature of loss prior to this study.

The Humboldt Bay region is also experiencing the most rapid rate of relative sea level rise along the entire US west coast (Anderson 2018) and has suffered recent declines in intertidal eelgrass cover attributed to a prolonged marine heat wave event that began in the winter of 2013-2014 and was later reinforced by the 2015-2016 El Niño event (Di Lorenzo & Mantua, 2016 and Jacox et al. 2019) and increased virulence of the pathogenic protist *Labyrinthula zosterae*, leading to outbreaks of eelgrass wasting disease. Although the extreme thermal anomalies associated with the 2013-2016 marine heat wave have largely abated since 2016, declines in eelgrass cover, erosion of tidal flats, and expansion of the channel networks across eelgrass dominated flats is ongoing within the bay and represents an emerging and understudied threat to the Humboldt Bay Ecosystem.



August 2013 shed leaf wrack and diseased eelgrass in Humboldt Bay. (Photos provided by Vicky Frey, CDFW)

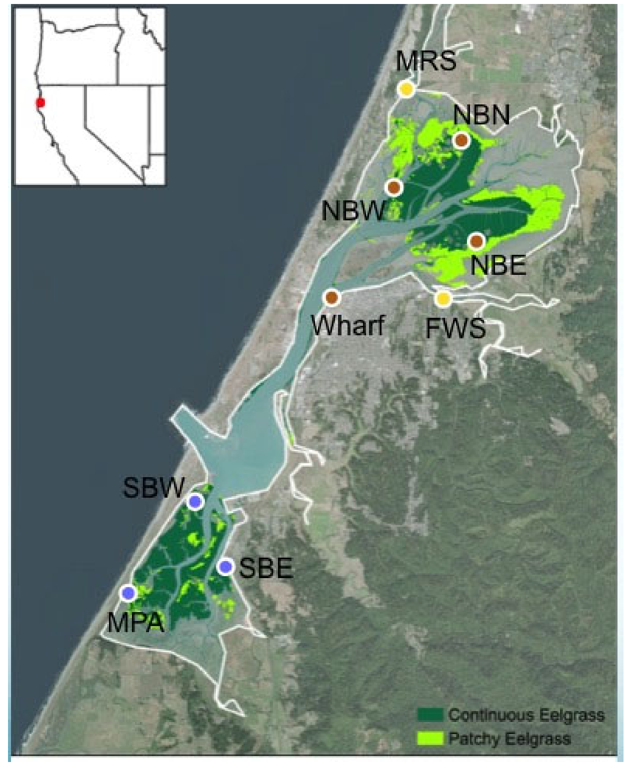
In Humboldt Bay, changes in eelgrass have been most apparent along the upper margins of the beds where eelgrass transitions from more continuous to patchy coverage. In 2013 eelgrass wasting disease was noted to have hit Humboldt Bay (V. Frey, pers. comm.) and has been subsequently observed to occur with variable intensity every year since. Insights gained from several pilot studies involving collection of high resolution aerial imagery of eelgrass habitat in Humboldt Bay during 2016, suggest that Humboldt Bay was impacted by thermal stress associated with the historically-unprecedented positive temperature anomalies that swept across much of the eastern Pacific Ocean between 2014 and 2016, which is believed to have exacerbated wasting disease outbreaks within the bay. However, with only anecdotal observations and limited data to draw from, resource managers have lacked the capacity to detect in a timely fashion even fairly marked changes in eelgrass abundance and distribution in Humboldt Bay.

In 2017 a bay-wide eelgrass monitoring program was initiated through collaboration among California Sea Grant, Humboldt State University, the California Department of Fish and Wildlife (CDFW), and the Wiyot Tribe with funding from the California Ocean Protection Council. Permanent 100m transects were established in the high, mid, and low intertidal at 9 sites (4 in North Bay, 3 in South Bay, and 2 in sloughs). For each transect the percent cover, shoot density, shoot length, above ground biomass, and leaf area index of eelgrass was measured using standard on-the-ground methods using stratified random placement of quadrats along the transect. This sampling was conducted in June when there are excellent low tides, weather is generally clear, and though eelgrass has started growing by then, the growth of green macroalgae (that can be difficult to distinguish from eelgrass in aerial imagery) is minimal. This was done to maximize the utility of corresponding Unmanned Aerial Vehicle (UAV) aerial surveys that were conducted by Merkel & Associates in anticipation that the aerial survey data would eventually be incorporated as part of the monitoring program to provide a broader and archival tool for tracking long-term temporal changes in the eelgrass beds.

The first three years of data (2017-2019) from this on-the-ground monitoring showed significant interannual variation (similar in 2017 and 2019, but higher in 2018) in eelgrass abundance (shoot density, leaf area index) but little directional change in abundance or distribution at the monitoring transects. However, UAV imagery taken in 2018 near one of the monitoring sites in South Bay revealed an area of active tidal flat erosion and associated eelgrass loss that was not apparent from the ground at the transect. Follow-up UAV flights and preliminary field investigations completed in July and August 2018 revealed that the erosion and coupled loss of eelgrass was ongoing over several acres of continuous eelgrass meadow within the State Marine Recreational Management Area (SMRMA) in South Bay.

In the Spring of 2020, a nearly complete loss of eelgrass was observed at the ground-based monitoring transect at Mad River Slough (MRS; Frank Shaughnessy, pers. comm.). Though this provided a clear indication that further investigation was urgently needed, the single 100m on-the-ground transect provided little insight to the spatial extent of eelgrass loss in the rest of the slough. Given the observed loss of eelgrass in 2018 and 2020 at these two locations near the extreme southern and northern limits of eelgrass distribution within the bay and considering that more than ten years had passed since baywide eelgrass distribution was last assessed, interest in developing a pilot study began to build.

In the summer of 2020, NOAA Fisheries West Coast Regional Office funded California Sea Grant and Merkel & Associates to develop a pilot study aimed at investigating localized losses of eelgrass in South Bay and Mad River Slough, as well as to expand the scope of the investigation to include assessment of changes in eelgrass distribution within the bay's sloughs and tributaries since the last baywide mapping effort was completed in 2009. In 2022, the scope of the project was amended to include additional baseline mapping and trend analysis of changes in eelgrass distribution within the sloughs of the lower Eel River Estuary, further mapping and monitoring of eelgrass losses at pilot study sites in South Bay and lower Mad River Slough, and completion of additional reconnaissance-level UAV mapping flights to better understand the spatial extent of eelgrass losses and associated intertidal erosion within South Bay. Figure 1 presents the study area locations associated with the tasks completed under this study.



Baywide Eelgrass Monitoring Program transect locations and eelgrass distribution in Humboldt Bay derived from the 2009 Humboldt Bay and Eel River Benthic Habitat Project.

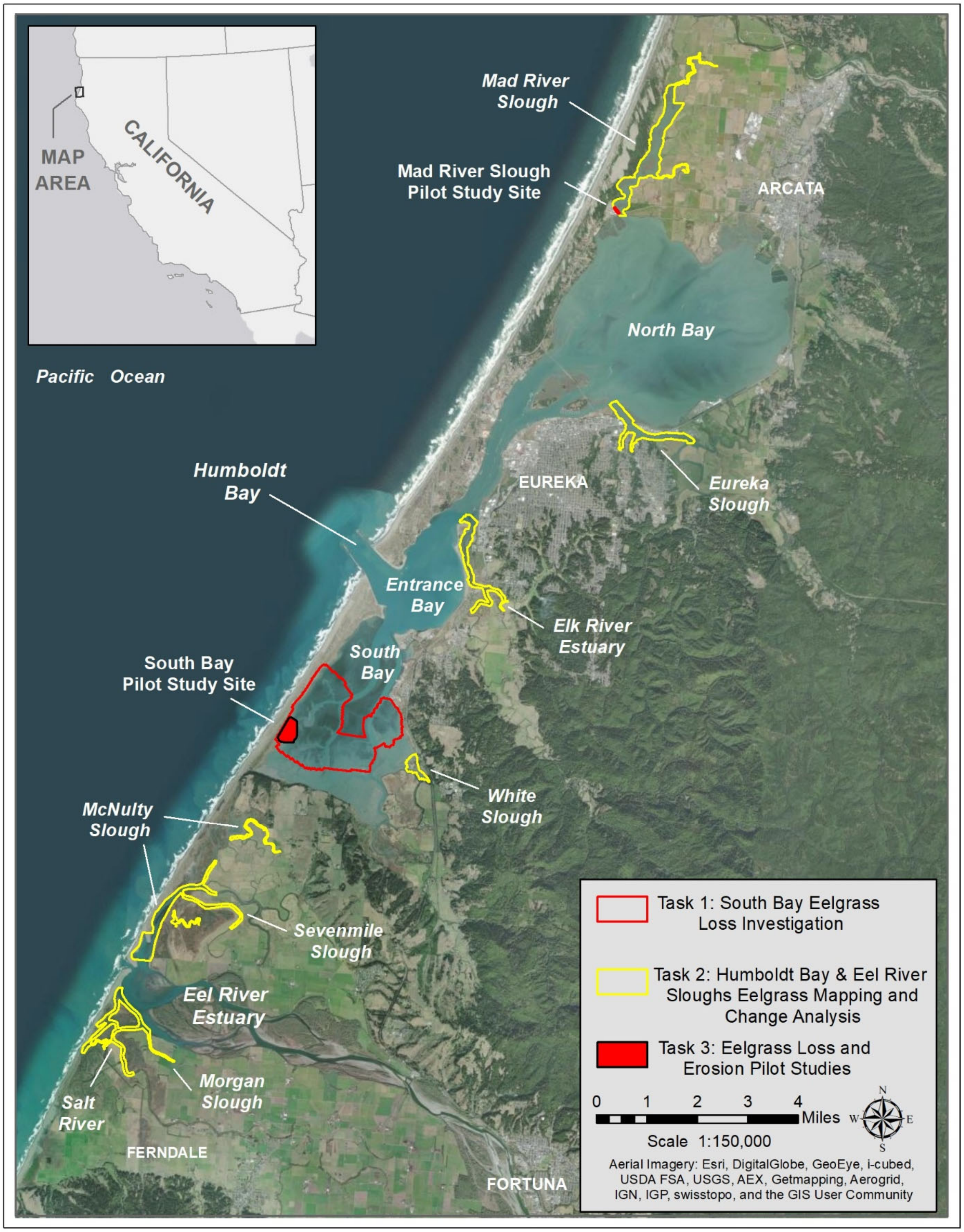


Figure 1. Location of the Humboldt Bay and Eel River Eelgrass Monitoring and Pilot Study Project in Humboldt County, California.

Methods

Task 1: South Bay Eelgrass Loss Investigation

In June 2020, the study initiated with a reconnaissance-level, UAV-based aerial survey of the southwestern portion of South (Humboldt) Bay. Low-altitude color aerial imagery was collected during predicted -1.8 ft, and -1.6 ft Mean Lower Low Water (MLLW) low tides on the mornings of June 7th and June 8th respectively (https://tidesandcurrents.noaa.gov/). Additional imagery was collected within the eastern portion of South Bay on August 11th, 2021 (-0.4 ft MLLW tide) and within the central portion of South Bay on July 29, 2022 (-0.6 ft MLLW tide). A DJI Phantom 4 Pro UAV with 20 mega-pixel (MP) camera provided the primary aerial imaging platform for the project. Flights were conducted from multiple shore positions and from a kayak to maintain visual contact with the UAV during the mapping flights. Automated flight control software was used to ensure the imagery was captured in a consistent manner with respect to flight altitude (390 ft) above ground level (AGL), front lap (70%) and sidelap (60%). Based on the camera specifications and altitude, aerial image resolution of the mapping flights yielded a ground sample raw image resolution of approximately 4 cm/pixel.

Combined UAV-based orthoimagery coverage of the Task 1 study area in South Humboldt Bay flown between June 2020 and July 2022.

Aerial imagery was processed, color-corrected for exposure variation, mosaicked and orthorectified into a series of orthomosaics covering the South Bay study area using Structure from Motion (SfM) photogrammetry software (Agisoft Metashape Professional). A total of four orthomosaics were generated in order to cover the entirety of the South Bay study area (approximately 1,830 acres).

Following image processing, the aerial orthoimagery was visually interpreted to assess changes in eelgrass distribution relative to the mapped distribution of eelgrass derived from the 2009 Humboldt Bay and Eel River Benthic Habitat Project (Schlosser and Eicher 2012). Areas of evident eelgrass loss and associated physical markers which included visual indications of tidal flat erosion and intertidal channel network expansion/extension that have occurred since 2009 were digitized and quantified.

Task 2: Humboldt Bay and Eel River Sloughs Eelgrass Mapping and Change Analysis

From late May 2020 to August 2022, UAV-based aerial mapping surveys were completed throughout the major sloughs and tributaries of Humboldt Bay and the lower Eel River, where eelgrass distribution was previously assessed by the 2009 Humboldt Bay and Eel River Benthic Habitat Project. Low-altitude color aerial imagery was collected during extreme low-tide conditions when tidal water levels were predicted to be at or below 0 feet MLLW based on the closest NOAA tidal gaging station location relative to each slough or tributary (https://tidesandcurrents.noaa.gov/). A DJI Phantom 4 Pro UAV with 20 mega-pixel (MP) camera was flown from multiple shore positions and from a kayak to maintain visual contact with the UAV during the mapping flights within each slough system. Automated flight control software was used to ensure the imagery was captured in a consistent manner with respect to flight altitude (300 ft) above ground level (AGL), front lap (70%) and sidelap (60%). Based on the camera specifications of the Phantom 4 Pro, aerial image resolution of the mapping flights yielded a ground sample raw image resolution of approximately 3 cm/pixel. Aerial imagery was processed, color-corrected for exposure variation, mosaicked and orthorectified into a series of orthomosaics covering each slough and tributary reach mapped within the study, using SfM photogrammetry. Table 1 presents the dates and locations associated with the slough mapping flights completed under Task 2.

Oblique view of Mad River Slough facing north on June 29, 2021.

Table 1. UAV Image acquisition dates and slough areas mapped under Task 2.

Slough/Tributary	Aerial Imagery Acquisition Date(s)
Mad River Slough	5/28/2020, 6/6/2020, 6/29/2021
Eureka/Freshwater Slough	6/9/2020, 6/29/2021, 7/12/2021, 7/13/2021
Elk River	7/7/2020, 6/29/2021
White Slough	7/7/2020
McNulty Slough	7/30/2022, 8/14/2022
Sevenmile Slough	7/30/2022
Salt River Mainstem	8/13/2022
Salt River Sloughs	8/13/2022
Morgan Slough	8/13/2022

Following completion of the mapping flights, ground truthing was conducted by kayak and by wading at low tide to support image interpretation and to assist in distinguishing eelgrass from spectrally similar, comingled macroalgae where it co-occurred with eelgrass. Additional synthetic ground truthing was performed by UAV, by flying and capturing extremely high resolution (e.g. sub-centimeter) imagery from approximately 50 feet AGL to assess areas where ground-based access was impractical. In the upper portion of Eureka Slough where proximity to the Murray Field Airport precluded mapping via UAV, eelgrass distribution was assessed at low tide by kayak. Ground truthing was also completed by wading in upper McNulty Slough within the Eel River Estuary where invasive Japanese eelgrass was first detected in 2008 and subsequently targeted for experimental eradication by Sea Grant and CDFW staff, to confirm whether the eradication efforts remained successful.


Eelgrass observed along the left bank of Eureka Slough during completion of ground truthing efforts on July 11, 2021.

Eelgrass was then digitized through interpretation of the UAV orthoimagery to develop spatial data depicting eelgrass distribution and spatial extent within each slough and tributary included in the study. To address substantial differences in image resolution and support comparison of the newly mapped, higher-resolution eelgrass habitat data (< 5 cm/pixel) captured under this study with the lower-resolution, 2009 Humboldt Bay and Eel River Benthic Habitat imagery data

(50 cm/pixel), both eelgrass spatial datasets were converted from polygon to polyline geometry. This facilitated comparison of the linear extent of eelgrass occurring along each channel bank within each mapped slough and tributary as a means of supporting change analysis and evaluating trends in eelgrass distribution and abundance over time across data sources.

Task 3. Eelgrass Loss and Erosion Pilot Studies in South Bay and Mad River Slough

Two large pilot study sites were established where recent eelgrass losses had been observed in association with headcutting and headward erosion of intertidal channels and flats in the southwestern corner of South Bay at the South Humboldt Bay State Marine Recreational Management Area and active erosion of the right channel bank immediately north of the Mad River Slough Bridge in lower Mad River Slough (Figure 1). These have been tracked through time with a goal of better understanding how and why losses of eelgrass are occurring, and whether natural recovery can be expected where losses are occurring. A combination of ground-based observations, field data collection and UAV-based aerial surveying methods were initiated during May 2020 and continued through June 2023. Ground-based observations included photo-documentation of eelgrass loss and recently exposed/eroded substrate, collection of eelgrass biometric parameters (turion density, incidence of flowering, silt loading, and observations of eelgrass wasting disease), and installation and monitoring of stake arrays to assess sediment erosion. UAV-based aerial surveying methods included capturing overlapping vertical and oblique imagery of the study sites from an altitude of 200 feet AGL and establishing temporary ground control monuments using a real-time kinematic global positioning system (RTK-GPS) unit to establish precise positional control for developing photogrammetric digital surface models (DSMs) of the sites. DSMs were then developed for both pilot study areas and referenced to the local MLLW tidal datum based on the Hookton Slough (South Bay) and Mad River Slough tide gages (https://tidesandcurrents.noaa.gov/). At the South Bay study site, where

Sea Grant and CDFW staff observing an area of active headcutting, associated headward channel erosion, and eelgrass loss at the South Bay pilot site on June 5, 2020.

observed erosion and associated eelgrass losses were more spatially extensive than what was observed at the Mad River Slough study site, residual channel depths in shallow subtidal channels that remained inundated at low tide were assessed by taking manual depth readings with a graduated stadia rod and capturing the sounding positions using RTK-GPS. These depth readings were then integrated with the UAV-based DSM to develop a fused topographic-bathymetric (topobathy) surface of the study area. This was done in an effort to quantify the volume of erosion observed in association with the most active and extensive area of headcut erosion and eelgrass loss in South Bay.

Residual depth in this newly-formed channel was assessed with a graduated stadia rod and RTK-GPS unit to survey shallow subtidal areas of the South Bay pilot site that remained inundated at low tide and could not be assessed using a UAV-based photogrammetric approach. In this photo captured on July 26, 2021, residual channel depth was found to be 27 cm with a total depth of 65 cm relative to surrounding intertidal flats.

At the South Bay pilot site, sediment stake arrays were positioned parallel to two advancing erosional fronts associated with the largest area of active erosion and eelgrass bed loss. At each erosional front, two parallel arrays were established with the first array positioned immediately headward of the scarp at the leading edge of the front, with a second array positioned approximately 3 meters west in the unaffected eelgrass meadow (Figure 2 inset). Sediment stakes were installed at 2-meter intervals on June 6, 2020 and embedded approximately 20 cm into the substrate. Eelgrass biometric data was collected coincident with stake installation in areas west of the advancing erosional fronts where the dense eelgrass meadow was not yet affected by erosion, as well as east of the area of active erosion where small, fragmented eelgrass patches and isolated individual plants persisted (Figure 2). Stake arrays were revisited and stake exposure was measured on May 27, 2021 (n= 355 days; southern array) and June 27, 2021 (n = 386 days; northern array) to characterize erosion and associated elevation loss.

Cement pavers were used as temporary ground control markers to support fine-scale georeferencing of UAV orthoimagery used to develop a photogrammetric DSM of the South Bay pilot site. Ground control markers were installed and surveyed using RTK-GPS and a UAV-based aerial survey of the South Bay pilot site was conducted during a predicted -2.2 ft tide on May 28, 2021. Residual channel depth measurements and eelgrass biometric data were collected on July 26, 2021 during a predicted -1.2 ft tide.

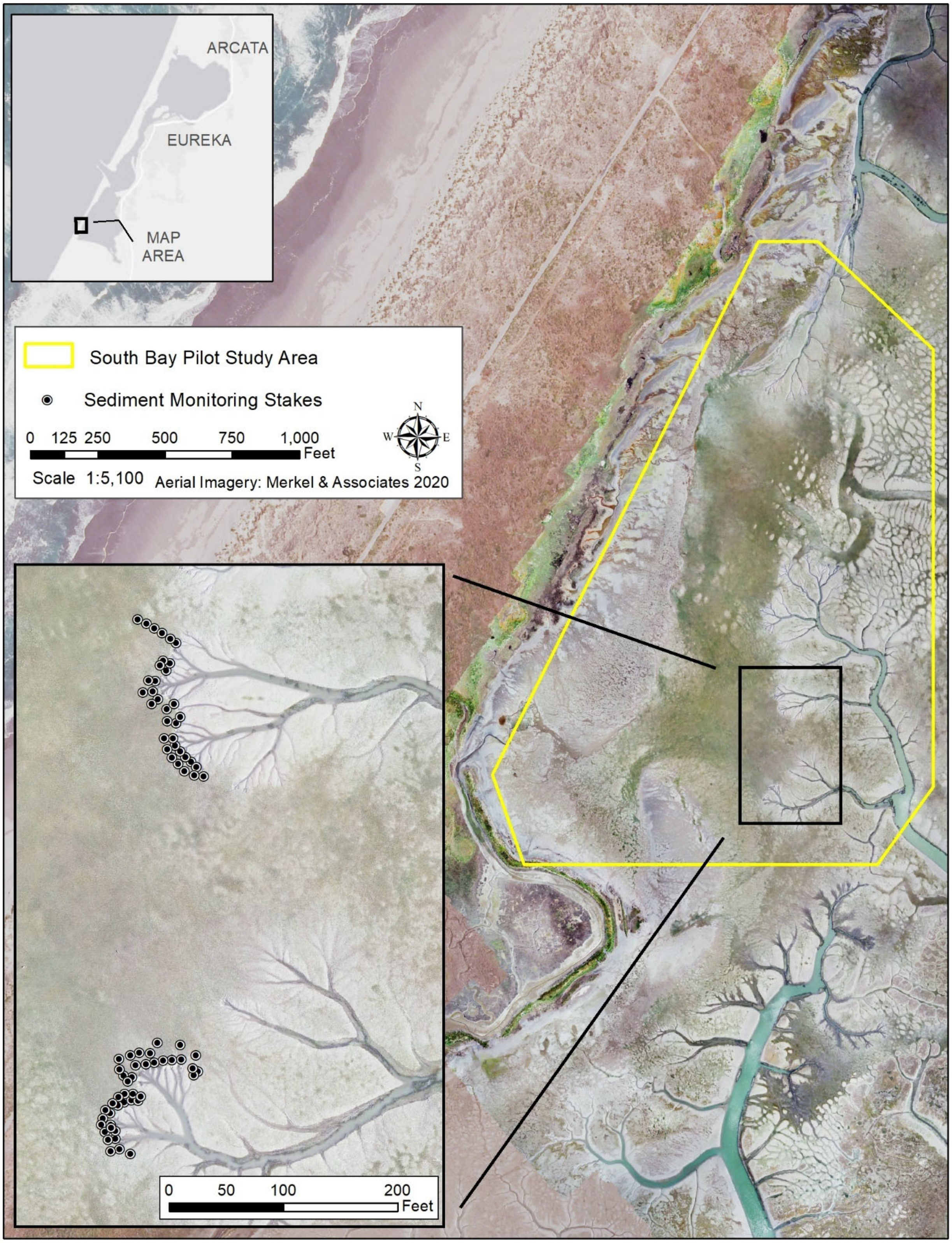


Figure 2. South Bay Pilot Study Area and Sediment Stake Monitoring Arrays in South Humboldt Bay.

Following completion of UAV aerial surveys and associated field data collection efforts in July 2021, SfM photogrammetry software was used to develop an orthomosaic and DSM of the South Bay pilot study area. Subtidal channel reaches that remained inundated during the aerial survey were masked and residual channel depth measurements were used to interpolate channel bathymetry using the Topo to Raster algorithm in ArcGIS 10.8 (ESRI; Redlands, CA). Channel bathymetry and UAV topography were then merged into a continuous topobathy DSM and differenced against the 2009-2011 California Coastal Conservancy Lidar Project digital elevation model (DEM) in an effort to quantify erosion over an approximate 10-year timeframe at the 61-acre South Bay pilot study area.

Sediment stakes at the South Bay pilot study site approximately one year after installation illustrating westward expansion of the erosional front beyond the array on June 27, 2021.

It is important to acknowledge that a DSM differs from a DEM in that a DSM captures the height of vegetation and other features superimposed over the ground surface, whereas a DEM is intended to represent the elevation of a bare surface devoid of vegetation. For the purposes of this study and given that both the 2021 DSM and 2009-2011 Lidar DEM surfaces are believed to reflect the presence of dense eelgrass lying flat over much of the exposed intertidal flats which would have added several centimeters to the surface elevation of both data sources, the DSM and DEM were considered functionally equivalent for purposes of change analysis in this study.

An additional aerial survey of the South Bay pilot site and ground-based eelgrass biometric data collection were completed on July 16, 2022 (-1.6 ft low tide), and a final aerial survey was conducted on June 9, 2023 (-0.9 ft low tide) to continue to map the progression of erosional fronts and to document changes in eelgrass cover within the eroded intertidal flats and channels through time.

At the Mad River Slough pilot site, PVC stakes were positioned in three linear arrays along the right bank of the slough beginning immediately north of the bridge where eelgrass bed retreat was observed in May 2020 prior to the initiation of the study. The primary linear array was established coincident with the long-term eelgrass monitoring transect parallel to the slough channel near the center of the eelgrass depth distribution and was approximately 190 meters in length with stakes positioned at 20-meter intervals. The southern half of the primary stake array was positioned coincident with the area of recent eelgrass bed loss at the monitoring transect, with the northern half of the array extending into the remaining eelgrass bed area at the northern portion of the monitoring transect. The secondary array was located approximately 8m east of the primary array at an elevation approximately 40 cm lower along the channel bank. The secondary array was approximately 50 meters in total length with stakes positioned at 5-meter intervals. A third stake array was established near the center of the primary and secondary arrays perpendicular to the channel to assess changes in the channel cross-section, with sediment stakes positioned at 1-meter intervals. Sediment stakes were installed on June 8, 2020, and embedded into the substrate. Figure 3 depicts the Mad River Slough pilot study site, sediment stake monitoring arrays, and eelgrass distribution derived from the Task 2 slough surveys completed in 2020-2021.

Oblique aerial view of lower Mad River Slough facing northwest, captured on June 29, 2021. The pilot study site is visible on the western bank of the slough (left) immediately north of the bridge where the lighter coloration of the lower portion of the exposed bank illustrates the area subject to recent erosion and eelgrass bed retreat at the site.

On May 26, 2021, temporary ground control monuments were established at the Mad River Slough study site and surveyed using RTK-GPS. A UAV-based aerial survey was then completed on June 11, 2021 (-0.8 ft low tide) to develop an orthomosaic and DSM of the site using structure SfM photogrammetry software. The DSM was then differenced against the 2009-2011 California Coastal Conservancy Lidar Project DEM in an effort to quantify bank erosion over the period between 2009-2011 and 2021.

An additional aerial survey of the Mad River Slough pilot site was completed on June 30, 2022 to document conditions at the site and to monitor for indications of eelgrass recovery. Eelgrass biometric data collection was completed at the site on August 29, 2022.

Figure 3. Mad River Slough Pilot Study Area and Sediment Stake Monitoring Arrays in North Humboldt Bay.

Results

Task 1: South Bay Eelgrass Loss Investigation

Figure 4 presents an overview of the results of the reconnaissance level, aerial surveys completed over 1,830 combined acres of South Humboldt Bay between June 2020 and July 2022. The South Bay pilot study site and South Humboldt Bay SMRMA are also shown for spatial context. Areas of eelgrass loss and gain within the intertidal flats of South Bay relative to 2009 were digitized as polygon features. In total, eelgrass losses were found to extend over 38.46 acres, while eelgrass gains amounted to 16.42 acres within the South Bay investigation area. Headward channel erosion and associated channel network expansion occurring across intertidal flats within South Bay were mapped as linear features, and a total of 24,208 feet (4.6 miles) of new channels were identified during the 2020-2022 study period relative to 2009. Figures 4A-4F present the results of the investigation in greater detail to assist in interpretation.

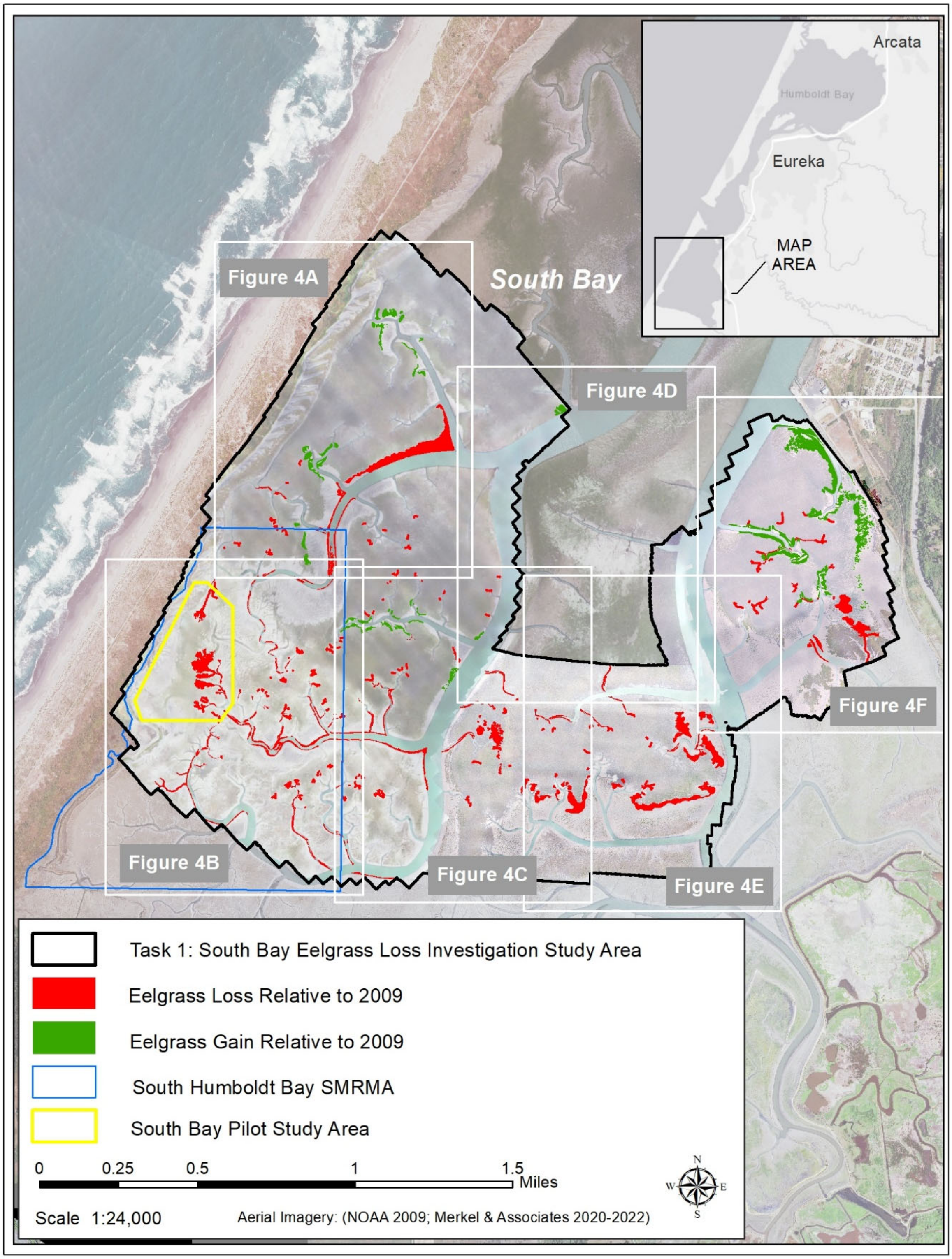


Figure 4. South Bay Eelgrass Loss Investigation Reconnaissance Survey Overview Depicting Areas of Eelgrass Loss and Gain Relative to 2009.

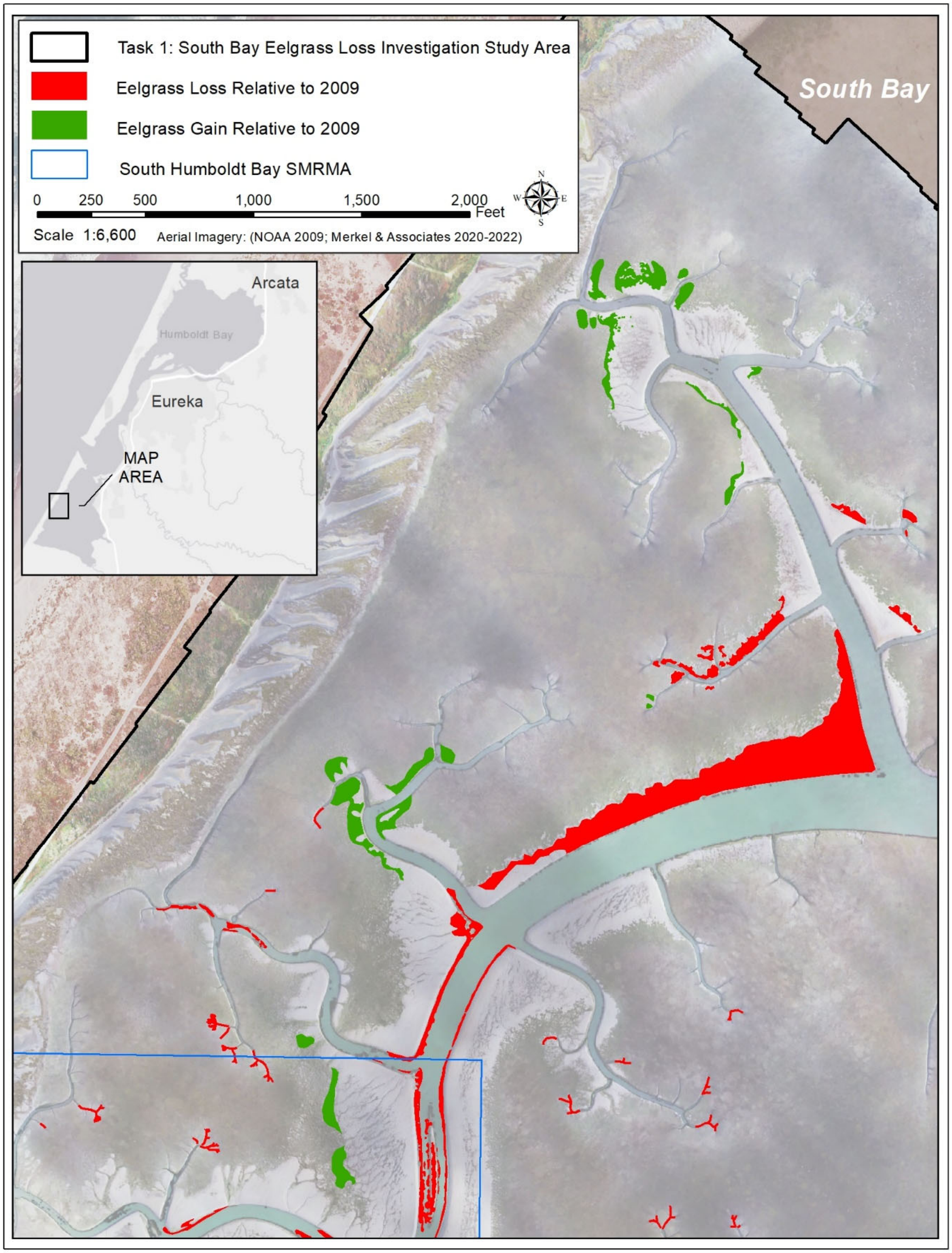


Figure 4A. South Bay Eelgrass Loss Investigation Reconnaissance Survey Results Depicting Areas of Eelgrass Loss and Gain Relative to 2009.

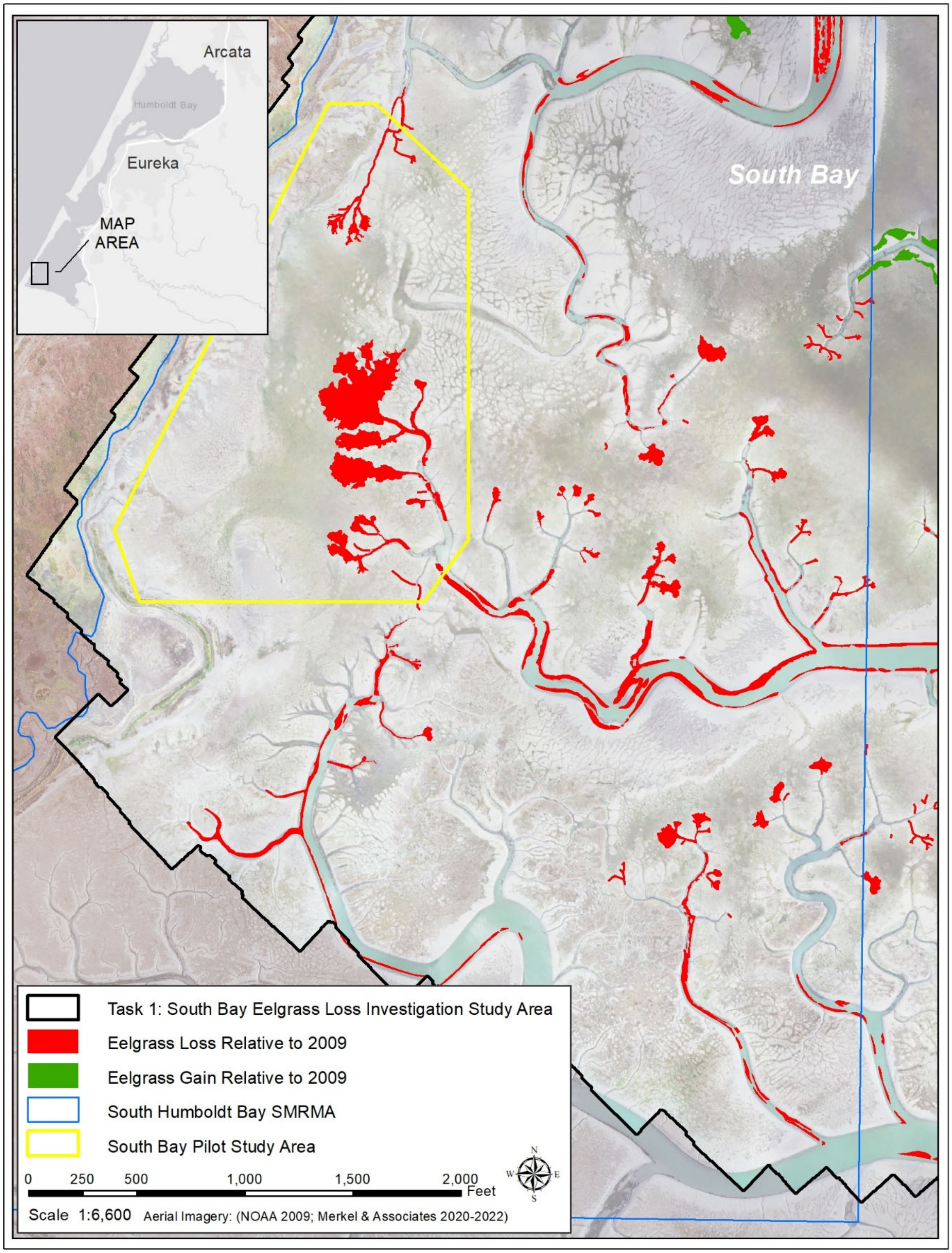


Figure 4B. South Bay Eelgrass Loss Investigation Reconnaissance Survey Results Depicting Areas of Eelgrass Loss and Gain Relative to 2009.

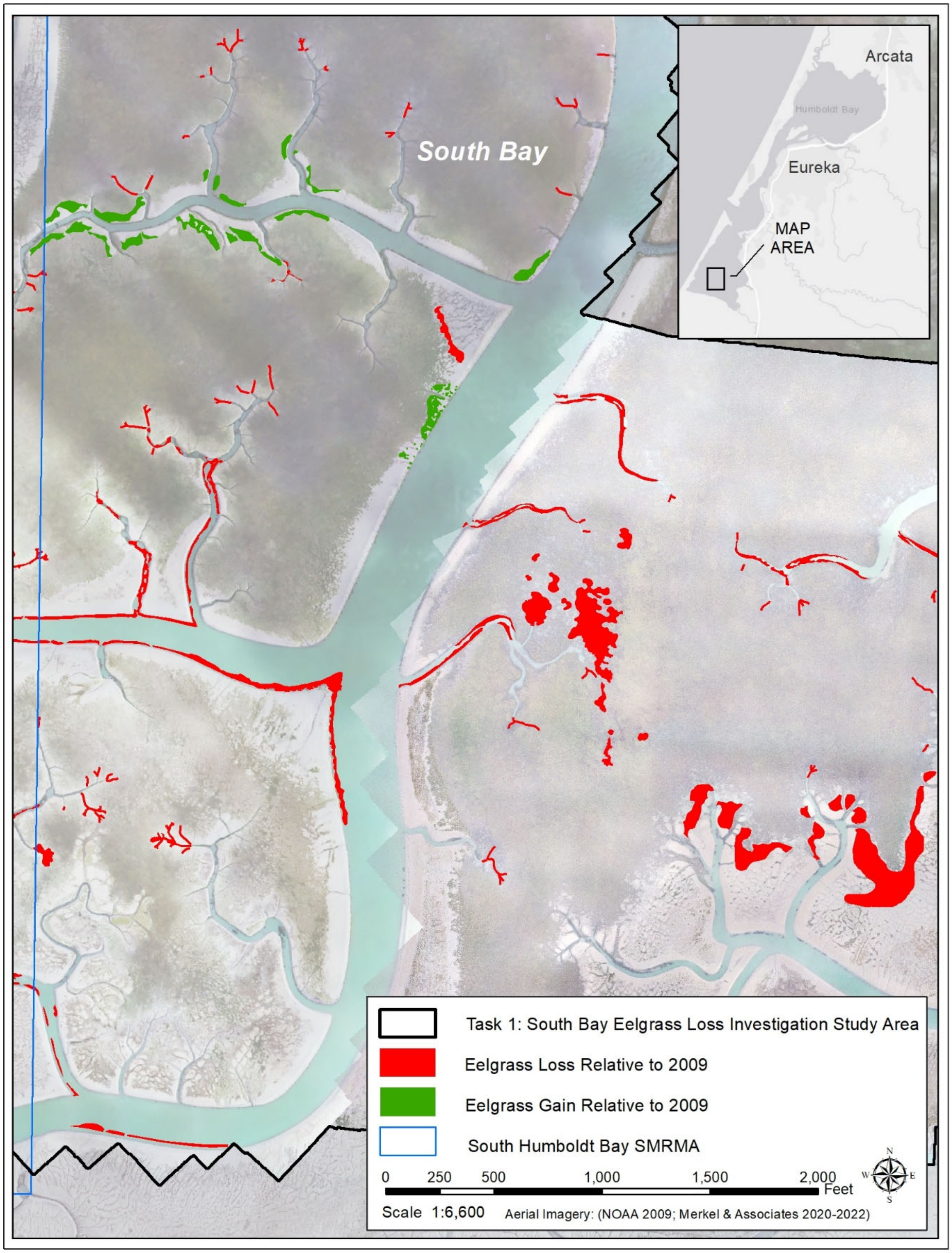


Figure 4C. South Bay Eelgrass Loss Investigation Reconnaissance Survey Results Depicting Areas of Eelgrass Loss and Gain Relative to 2009.

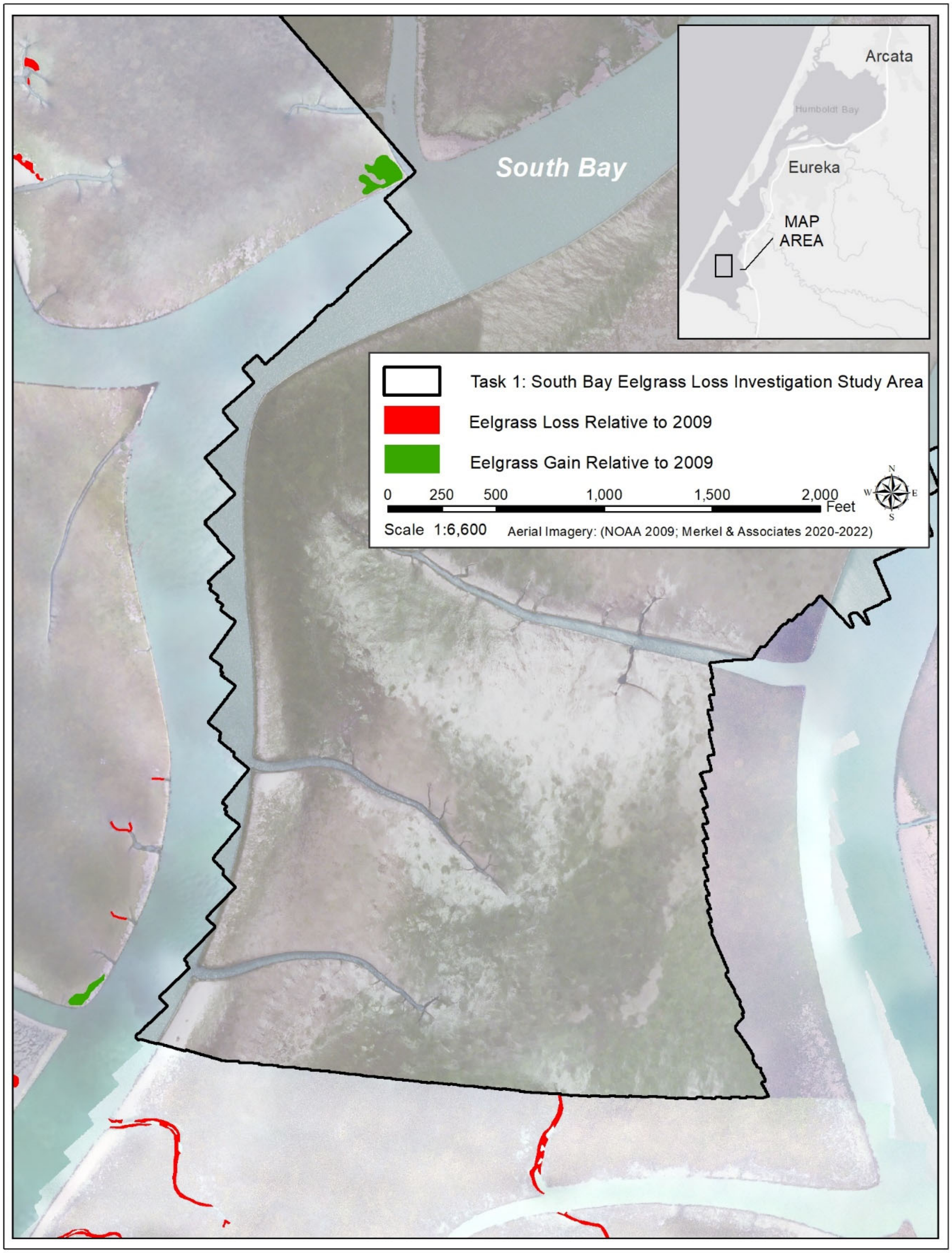


Figure 4D. South Bay Eelgrass Loss Investigation Reconnaissance Survey Results Depicting Areas of Eelgrass Loss and Gain Relative to 2009.

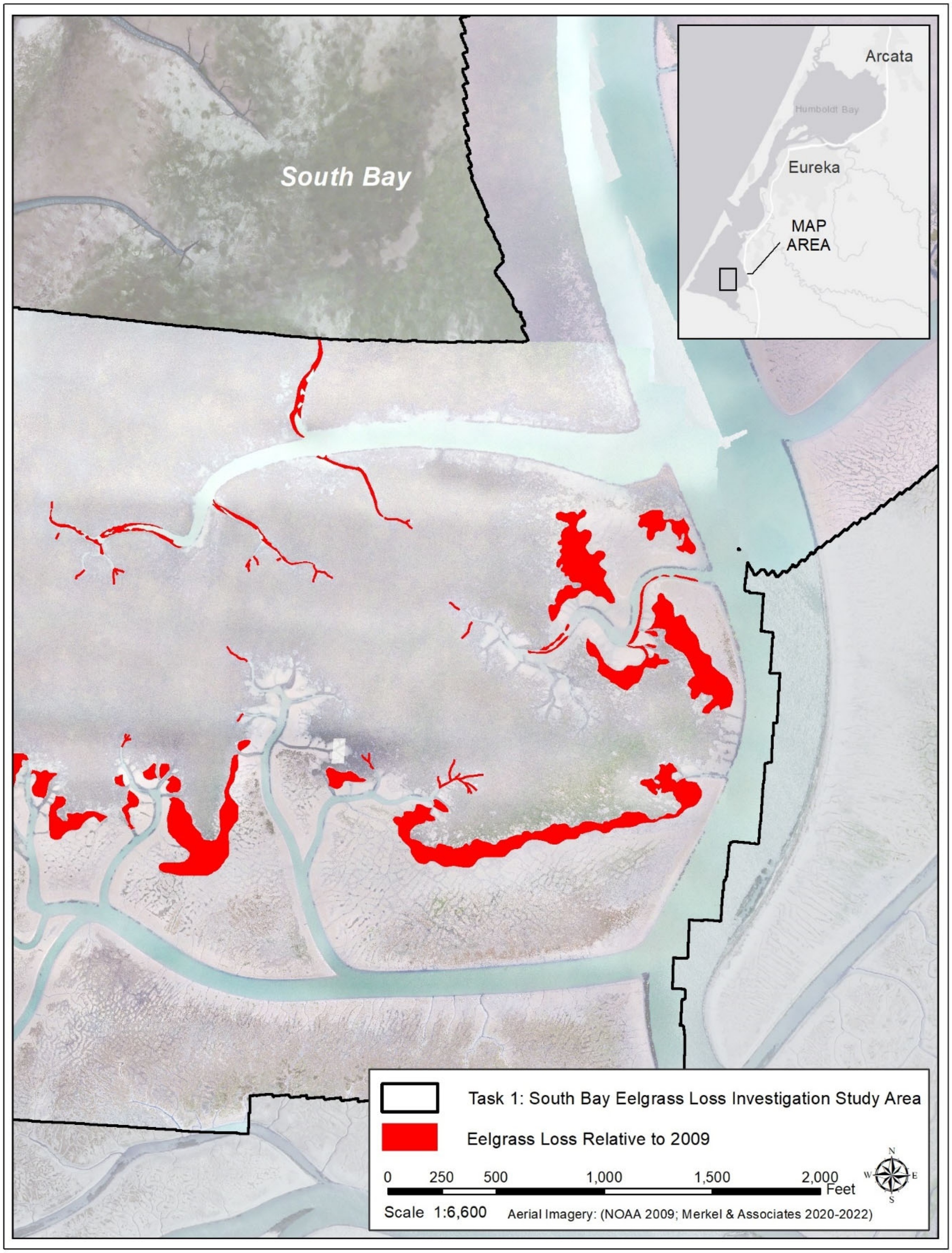


Figure 4E. South Bay Eelgrass Loss Investigation Reconnaissance Survey Results Depicting Areas of Eelgrass Loss Relative to 2009.

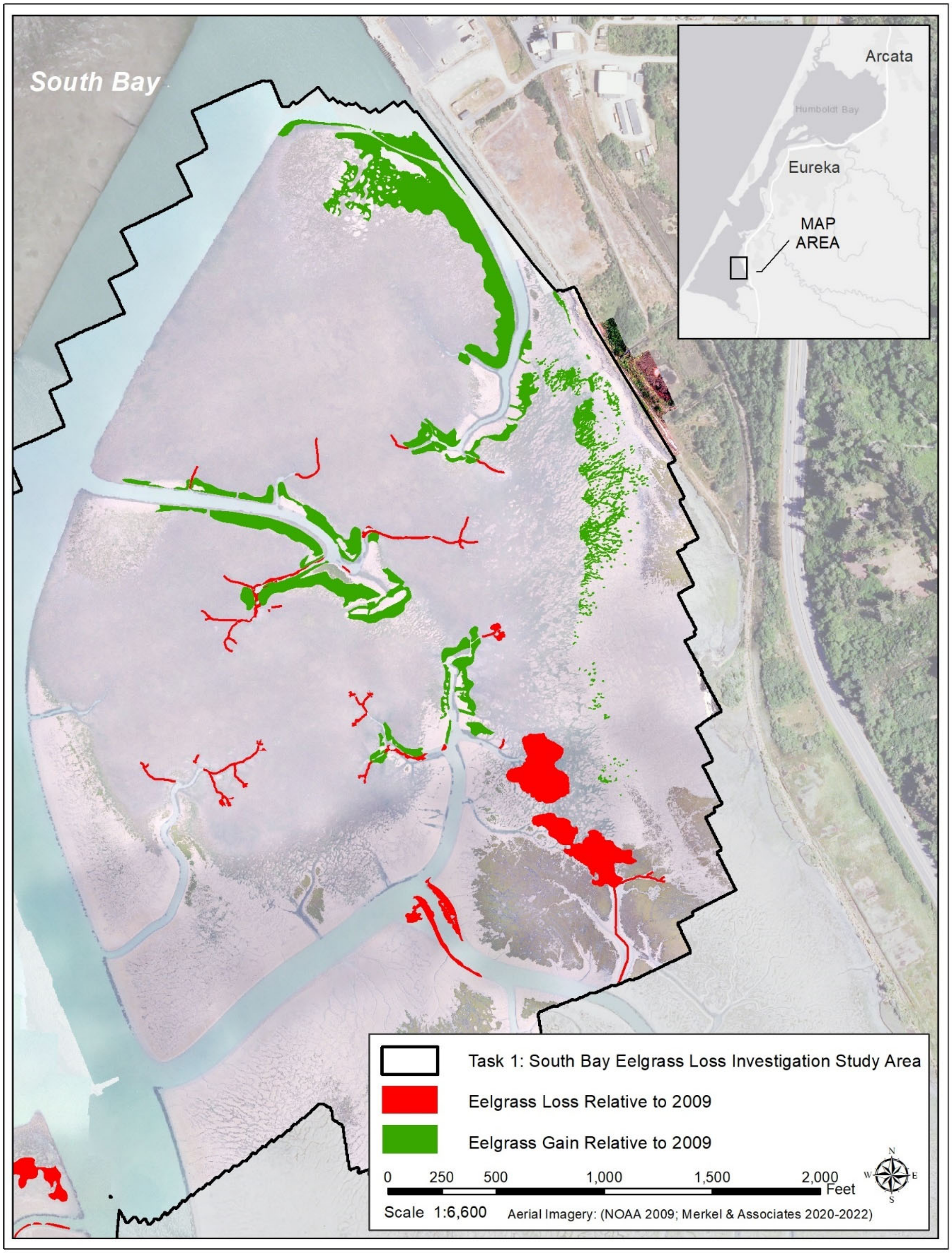


Figure 4F. South Bay Eelgrass Loss Investigation Reconnaissance Survey Results Depicting Areas of Eelgrass Loss and Gain Relative to 2009.

Task 2: Humboldt Bay and Eel River Sloughs Eelgrass Mapping and Change Analysis

Figure 5 presents an overview of the results of the Humboldt Bay and Eel River sloughs eelgrass mapping completed during the 2020-2022 study period. Figures 5A-5I present the mapping results in greater detail to aid in interpretation. Figures 6-10 present the results of the change in eelgrass linear extent analysis within the Humboldt Bay and Eel River sloughs. Table 2 summarizes the results of the 2020-2022 slough eelgrass mapping and change analysis relative to 2009.

In Mad River Slough (Figures 5A-5C), a total of 6.21 acres of eelgrass was mapped between May 2020 and June 2021. Eelgrass was found to occur within the lower 2.3 miles of the slough, with the majority of eelgrass being found within approximately ½ mile of the Mad River Slough Bridge at the southern end of the slough (Figure 5A). The northernmost eelgrass bed was found to occur along the western bank of the slough immediately south of the Lanphere Road Bridge, approximately ½ mile north of the nearest downstream eelgrass patches observed within the slough (Figure 5C). At Eureka Slough, a total of 12.41 acres of eelgrass was mapped between June 2020 and July 2021 within the lower 1.5 miles of the slough (Figures 5D and 5E). In Elk River, a total of 25.62 acres of eelgrass was mapped between July 2020 and June 2021 primarily within the lower 1.5 miles of the river (Figure 5F), with several isolated patches and small beds extending another 0.4 miles upstream into lower Swain Slough (Figure 5G). No eelgrass was documented to occur within White Sough during the completion of the surveys, presumably as a result of unsuitable elevations in combination with insufficient tidal exchange within this portion of the bay.

In the Eel River Estuary, a total of 29.29 acres of eelgrass were mapped, with 28.99 acres occurring within McNulty Slough (Figures 5H and 5I) and 0.30 acres occurring along the left bank (south side) of the mainstem Eel River near the mouths of the Salt River, Morgan Slough, and the Salt River Slough network (Figure 5J). Three small patches of eelgrass (1.2 m^2 combined) were found along the left bank of Salt River within 190 feet of the mainstem Eel River and represent the only remaining eelgrass occurring within either Salt River or Morgan Slough at the time of the study. The aerial coverage of mapping flights completed in 2022 within the Eel River Estuary captured 97 percent of the mapped extent of eelgrass derived from the 2009 Humboldt Bay and Eel River Benthic Habitat Project.

In terms of changes in eelgrass linear extent within the Humboldt Bay slough study areas that was observed to occur between 2009 and the 2020-2022 study period, Mad River Slough exhibited the greatest decline (-77%; Table 2), followed by Eureka Slough (-41%), with Elk River remaining nearly unchanged (-5%). In the Eel River Estuary, only McNulty Slough exhibited an increase in eelgrass linear extent (+20%) primarily as a result of a localized expansion of eelgrass along the right bank of the lower reach of the slough (Figure 5H and Figure 9), while all remaining sloughs and tributaries where eelgrass was previously mapped in 2009 were nearly devoid of eelgrass in July and August 2022. With the nearly complete loss of eelgrass occurring throughout the sloughs in the southern portion of the estuary and only fragmented patches of eelgrass occurring near the slough mouths along the left bank of the mainstem river channel, the southern sloughs were combined for purposes of assessing change in eelgrass linear extent in 2022 (-96%) relative to 2009.

In aggregate, a total of 73.53 acres of eelgrass habitat were mapped during the 2020-2022 study (Table 2). The total change in eelgrass linear extent observed within the Humboldt Bay and Eel River sloughs during the 2020-2022 study period relative to 2009 amounted to a decline of 58 percent.

Table 2. Humboldt Bay and Eel River Sloughs Eelgrass Mapping and Change Analysis Summary Metrics, 2020-2022 versus 2009.

Slough/Tributary	2020-2022 Eelgrass Area (Acres)	2020-2022 Eelgrass Linear Extent (Feet)	2009 Eelgrass Linear Extent (Feet)	Change in Eelgrass Linear Extent (Percent)
Mad River Slough	6.21	9,202	39,265	-77%
Eureka Slough	12.41	17,938	30,418	-41%
Elk River/Swain Slough	25.62	13,083	13,805	-5%
McNulty Slough	28.99	10,415	8,699	20%
Sevenmile Slough	0	0	7,304	-100%
Southern Eel River Estuary sloughs (combined)	0.30	923	23,748	-96%
Totals	**73.53**	**51,561**	**123,239**	**-58%**

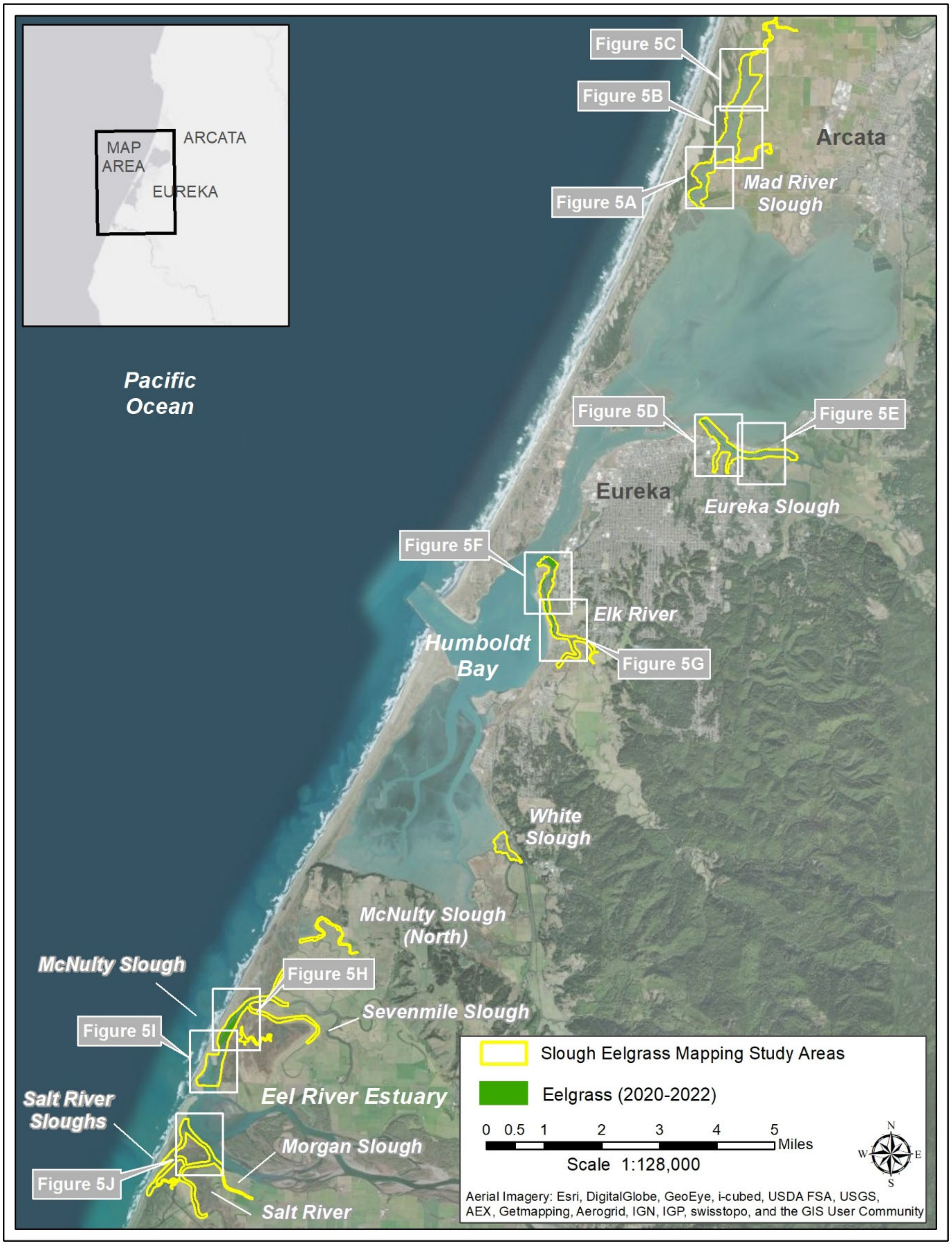


Figure 5. Overview of the Humboldt Bay and Eel River Sloughs Eelgrass Mapping and Change Analysis Study Areas.

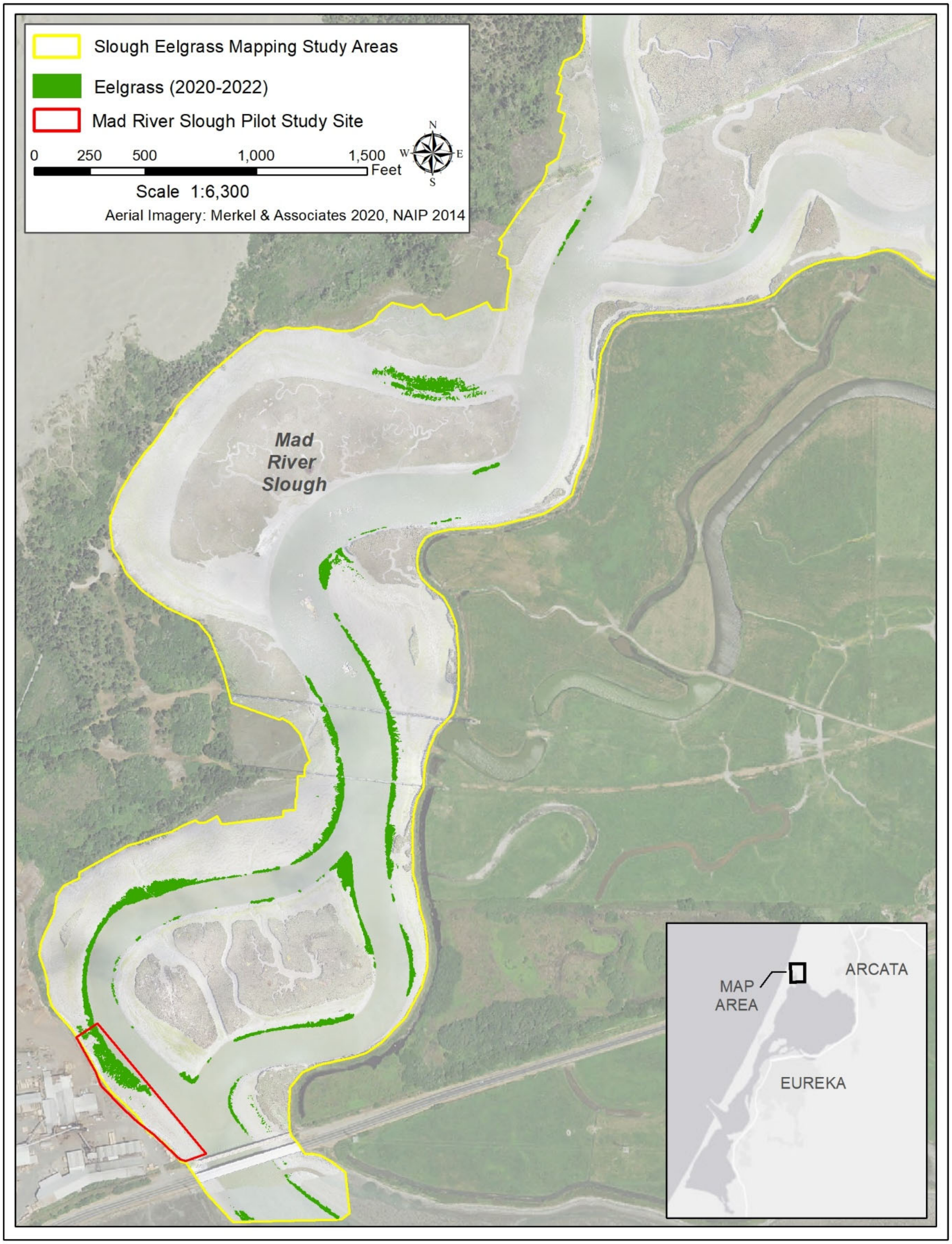


Figure 5A. Lower Mad River Slough Eelgrass Distribution, 2020-2021.

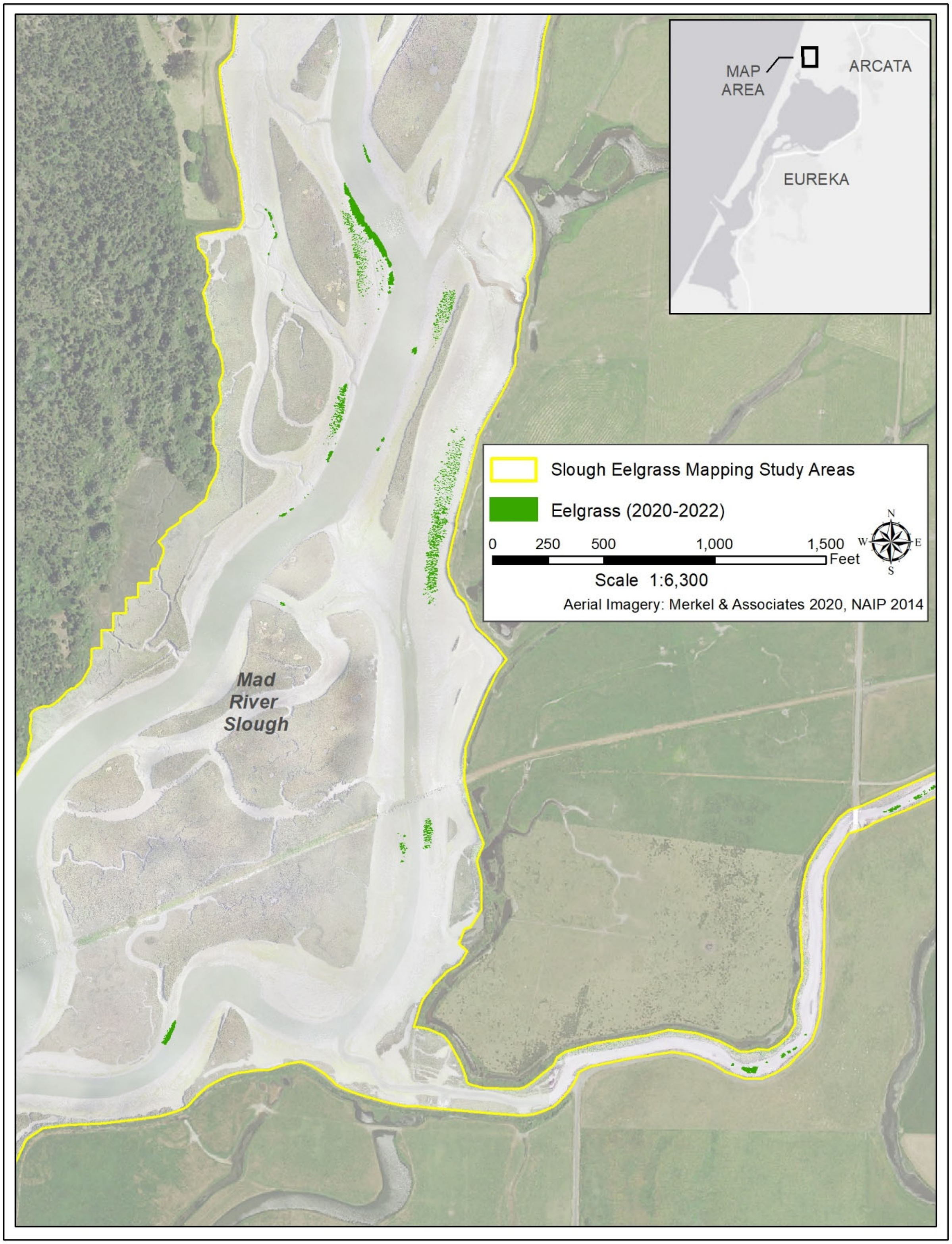


Figure 5B. Central Mad River Slough Eelgrass Distribution, 2020-2021.

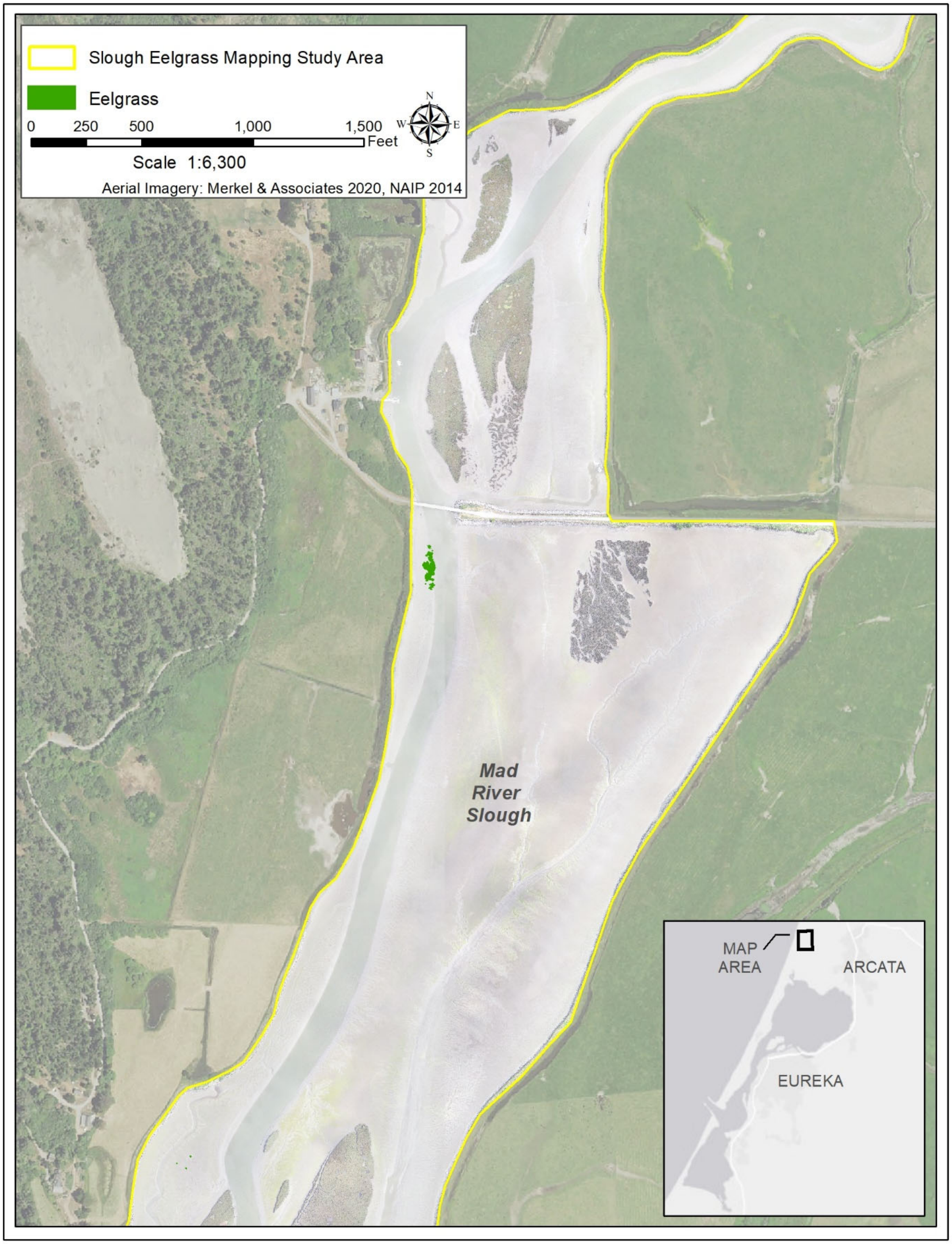


Figure 5C. Upper Mad River Slough Eelgrass Distribution, 2020-2021.

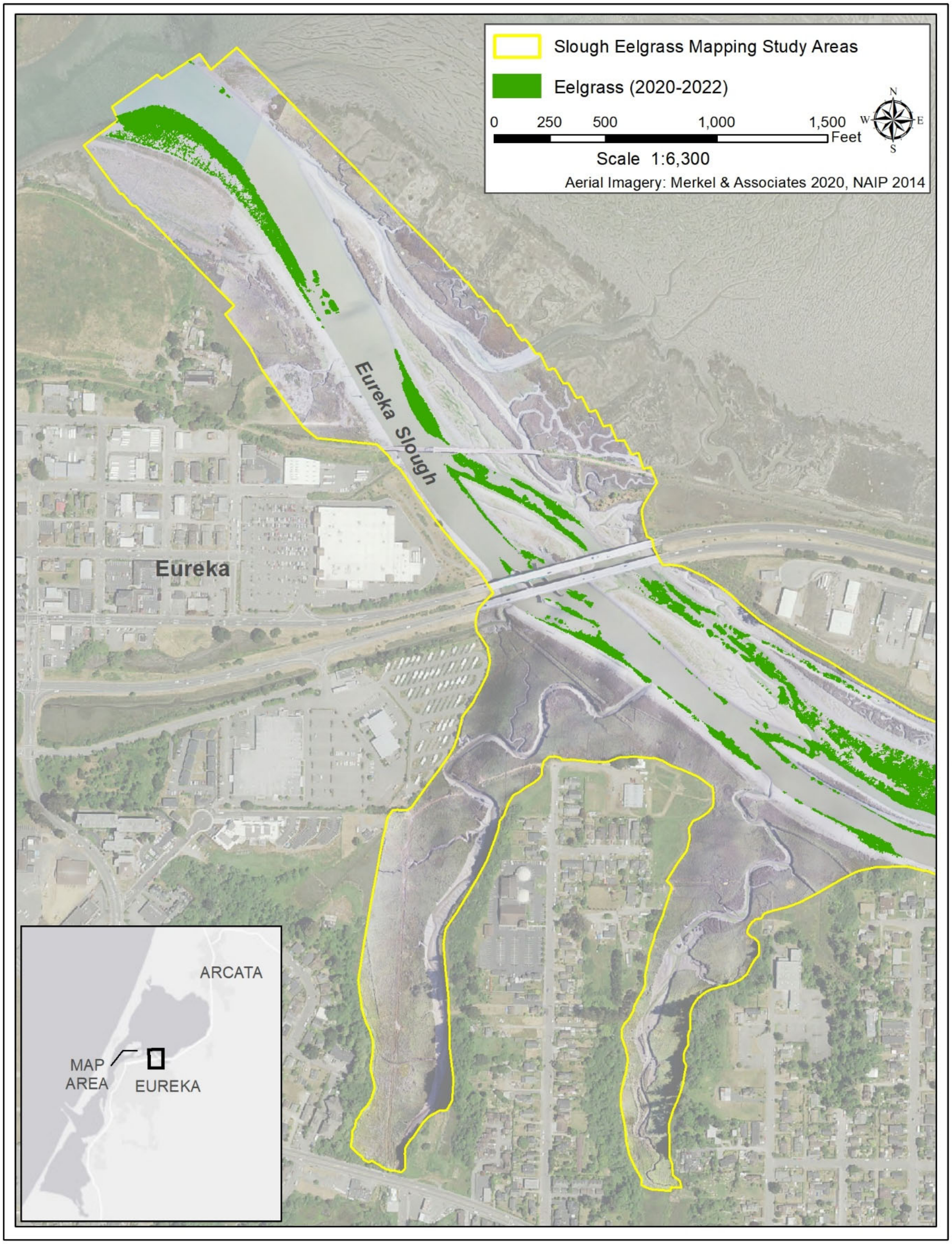


Figure 5D. Lower Eureka Slough Eelgrass Distribution, 2020-2021.

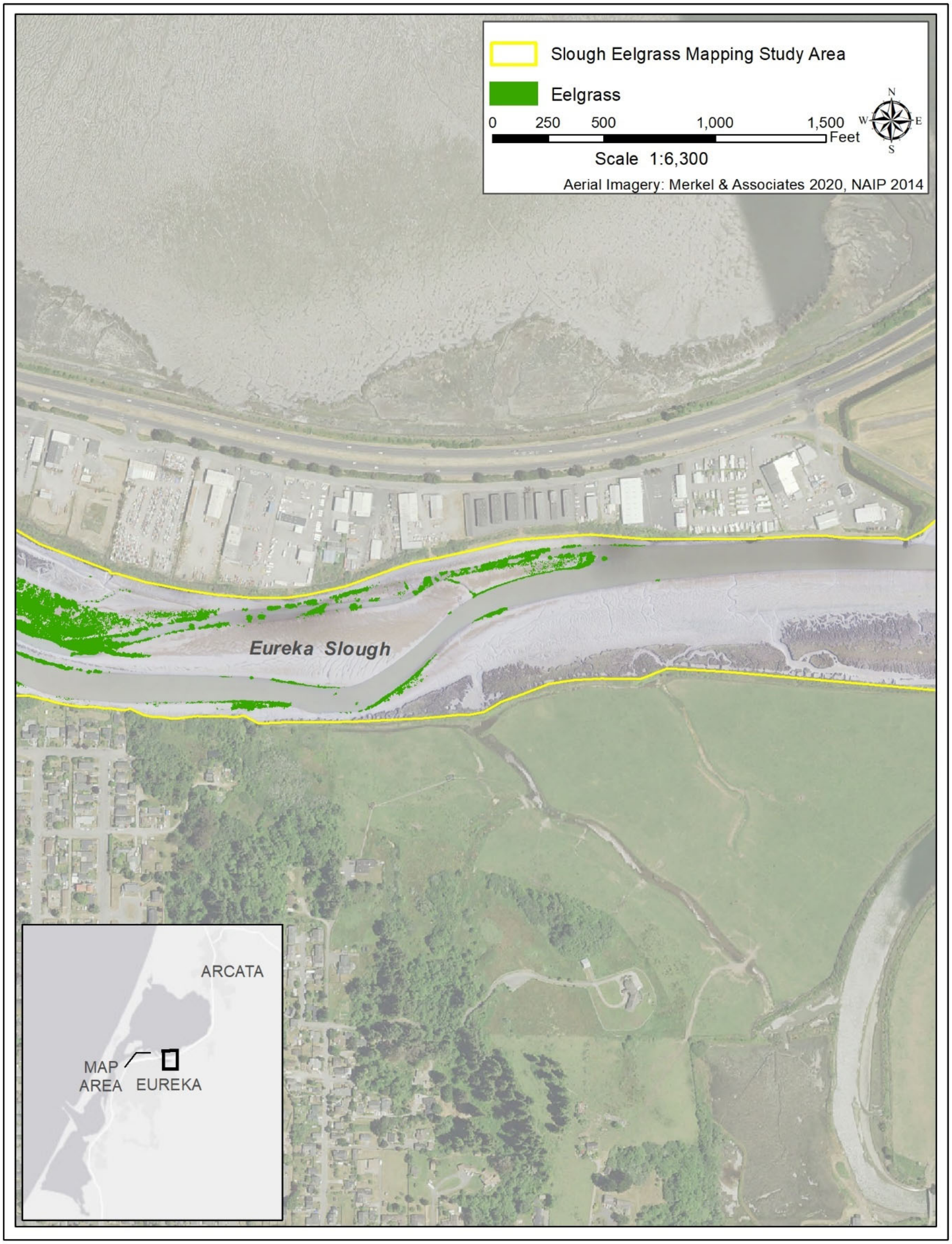


Figure 5E. Upper Eureka Slough Eelgrass Distribution, 2020-2021.

Figure 5F. Lower Elk River Eelgrass Distribution, 2020-2021.

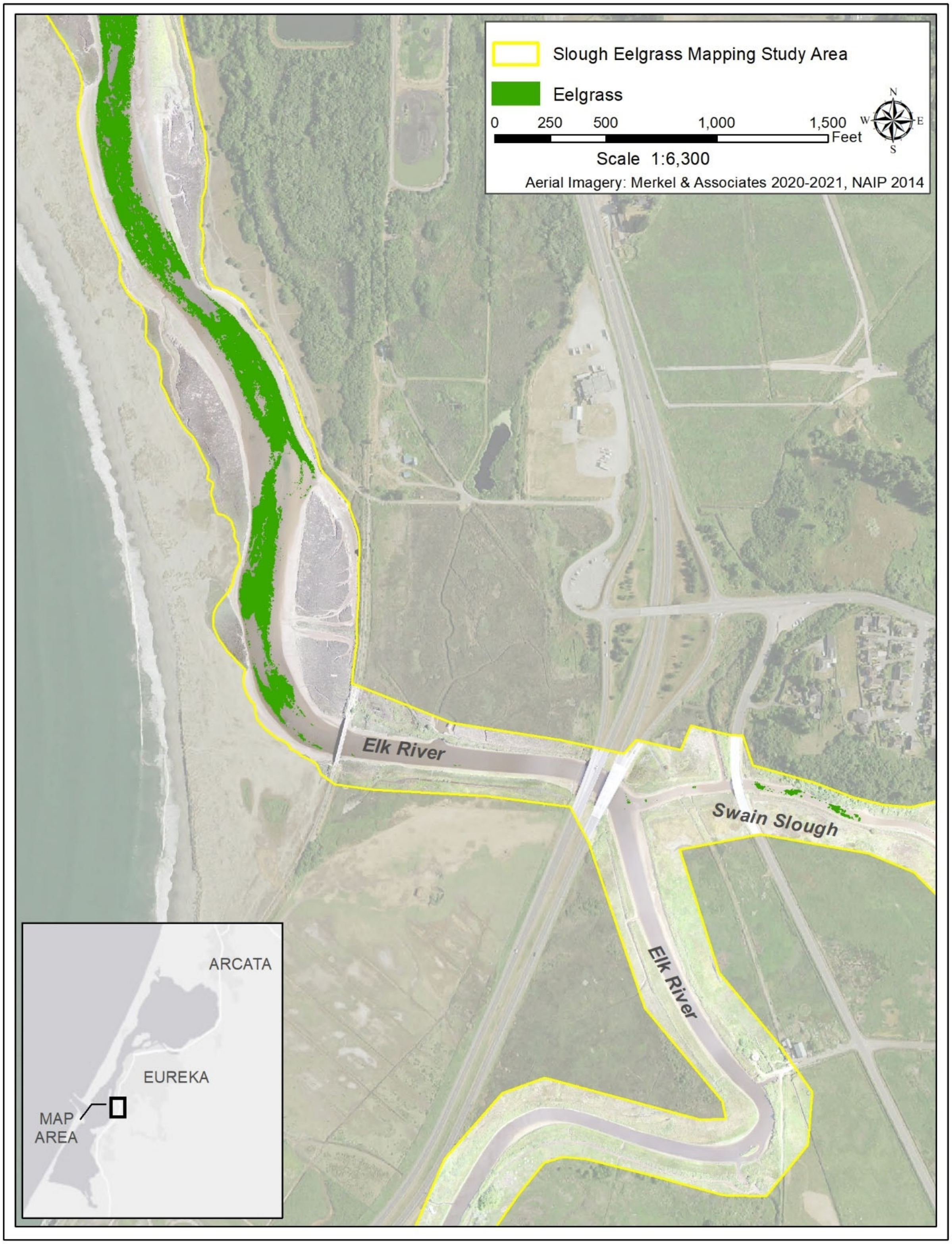


Figure 5G. Upper Elk River and Swain Slough Eelgrass Distribution, 2020-2021.

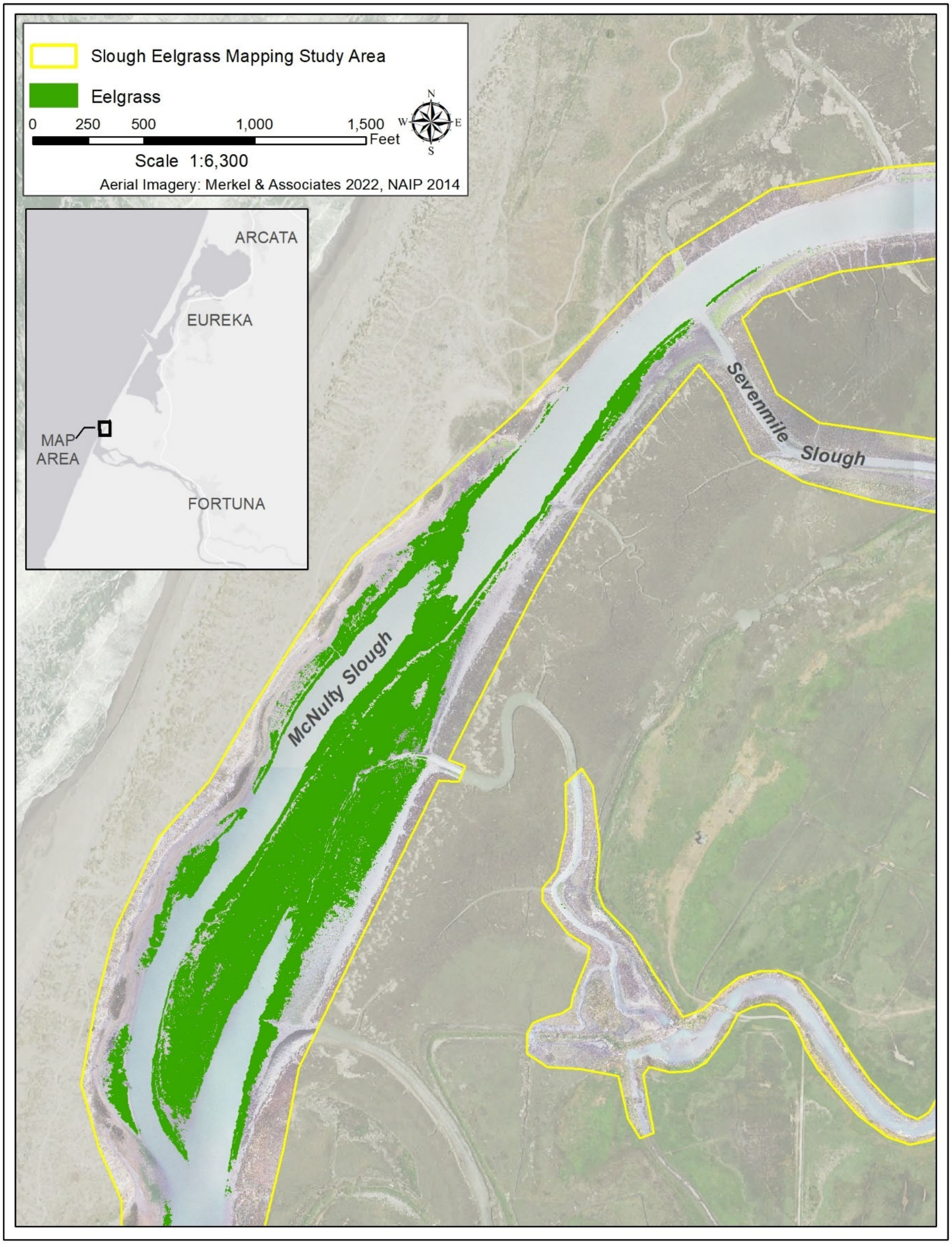


Figure 5H. McNulty Slough Eelgrass Distribution, 2022.

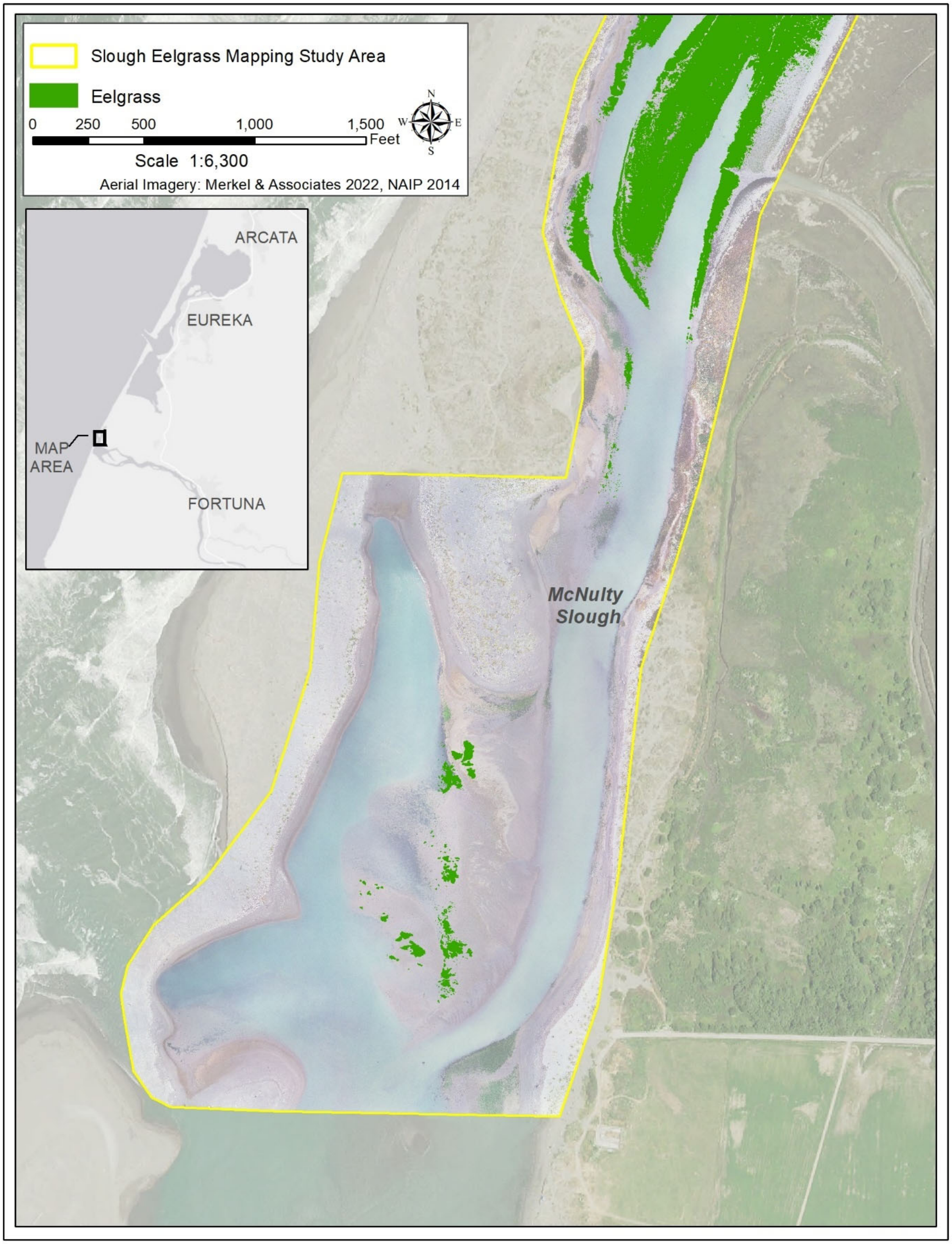


Figure 5I. Lower McNulty Slough Eelgrass Distribution, 2022.

Figure 5J. Southern Eel River Estuary Eelgrass Distribution, 2022.

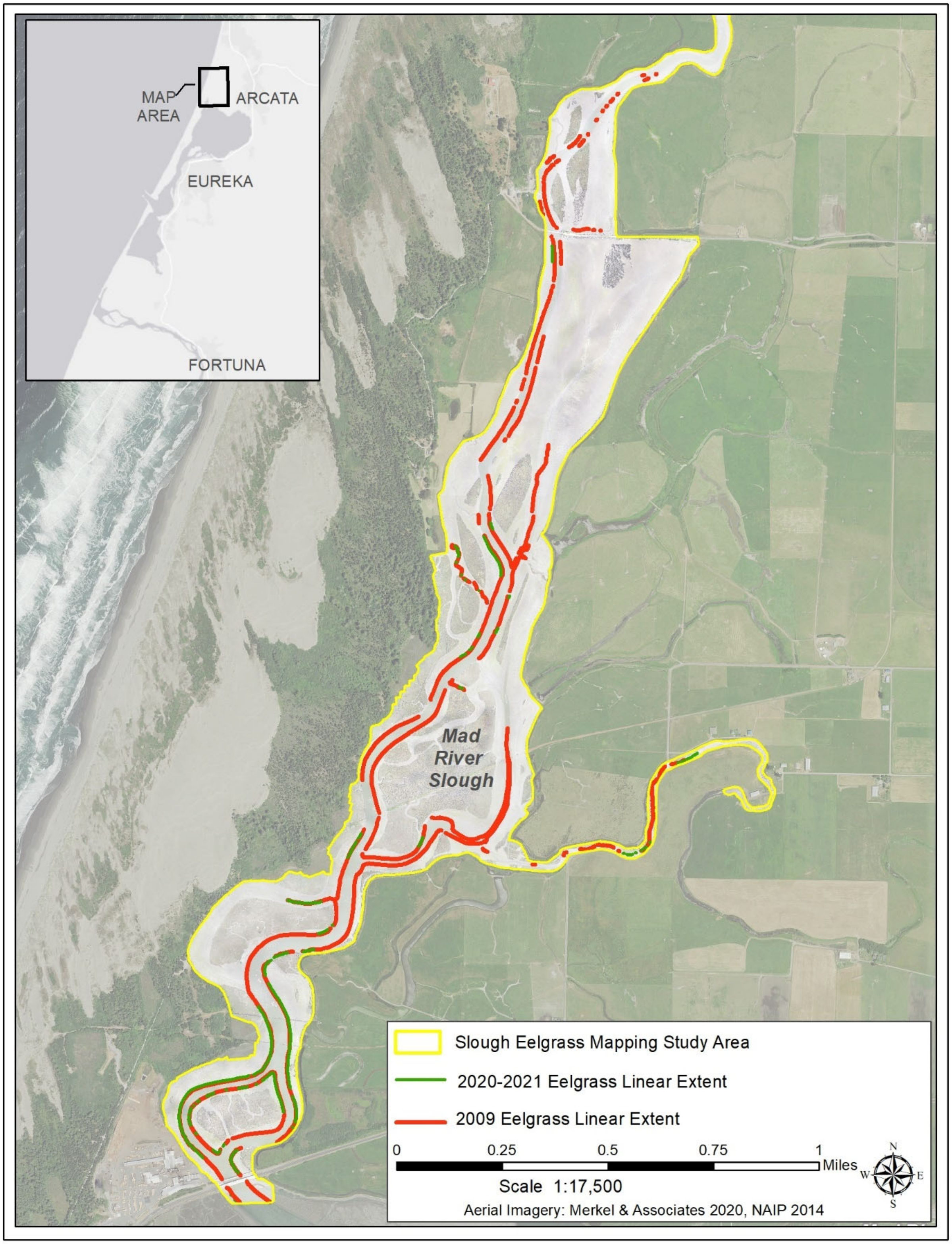


Figure 6. Mad River Slough Eelgrass Linear Extent Change, Analysis 2020-2021 versus 2009.

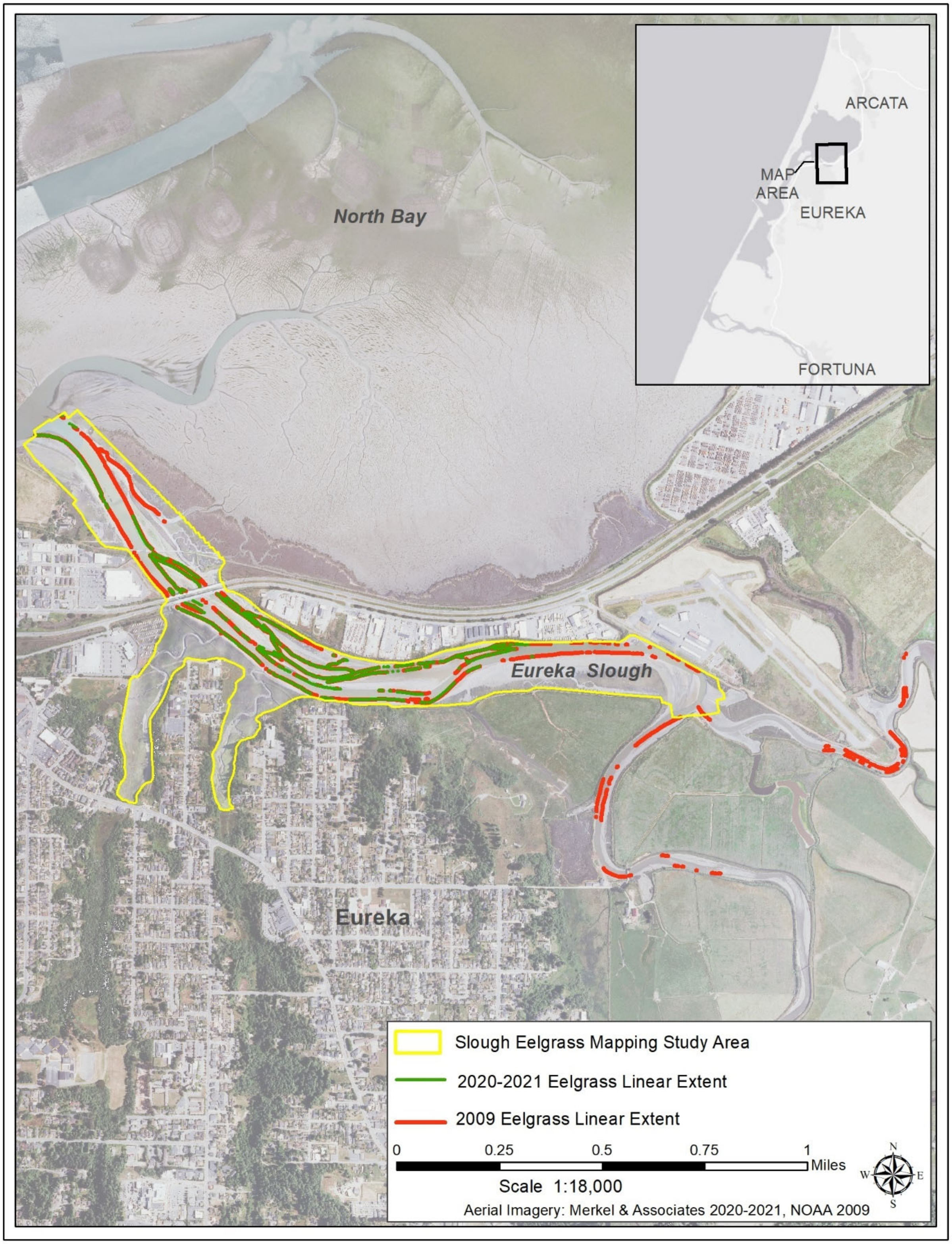


Figure 7. Eureka Slough Eelgrass Linear Extent Change Analysis, 2020-2021 versus 2009.

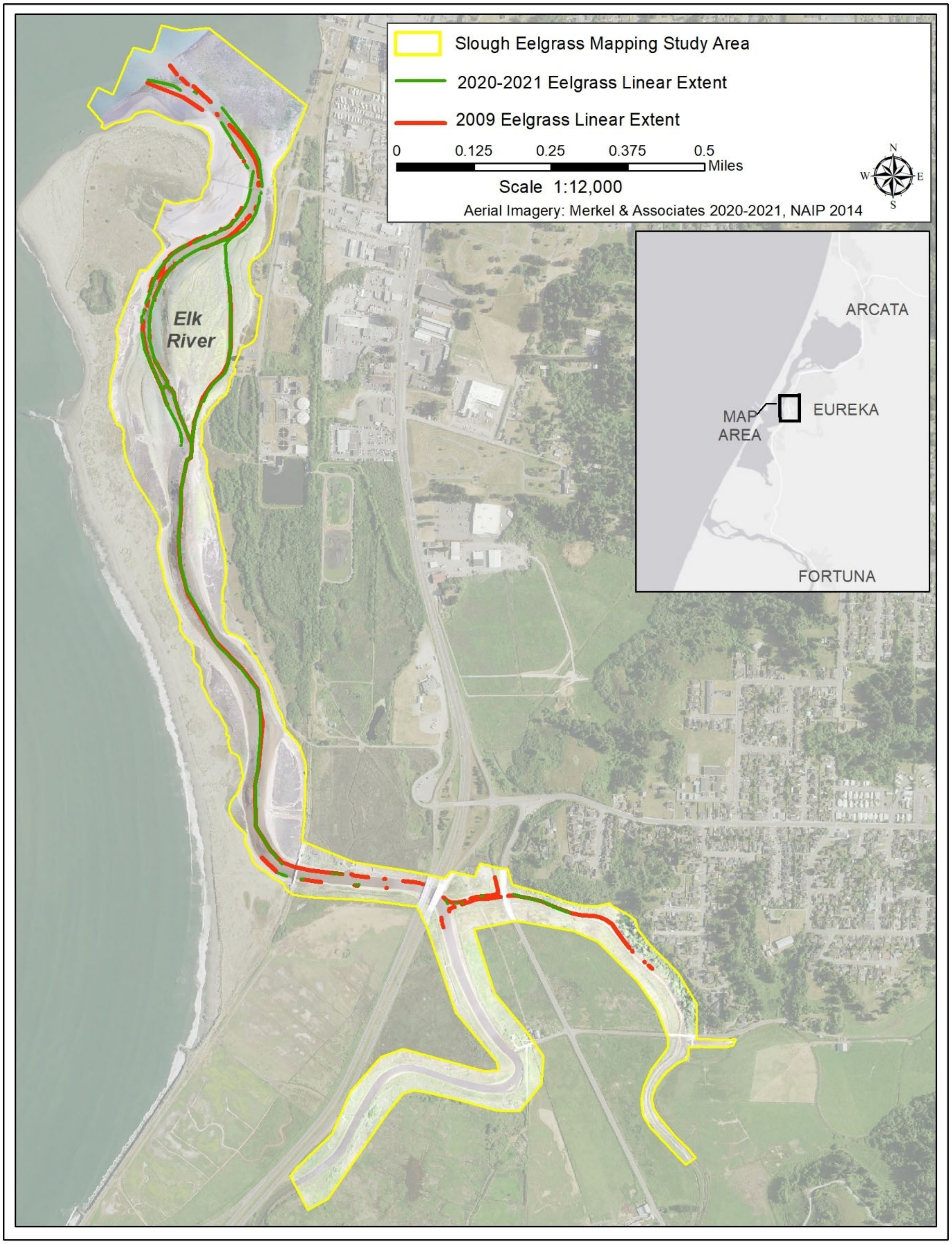


Figure 8. Elk River Eelgrass Linear Extent Change Analysis, 2020-2021 versus 2009.

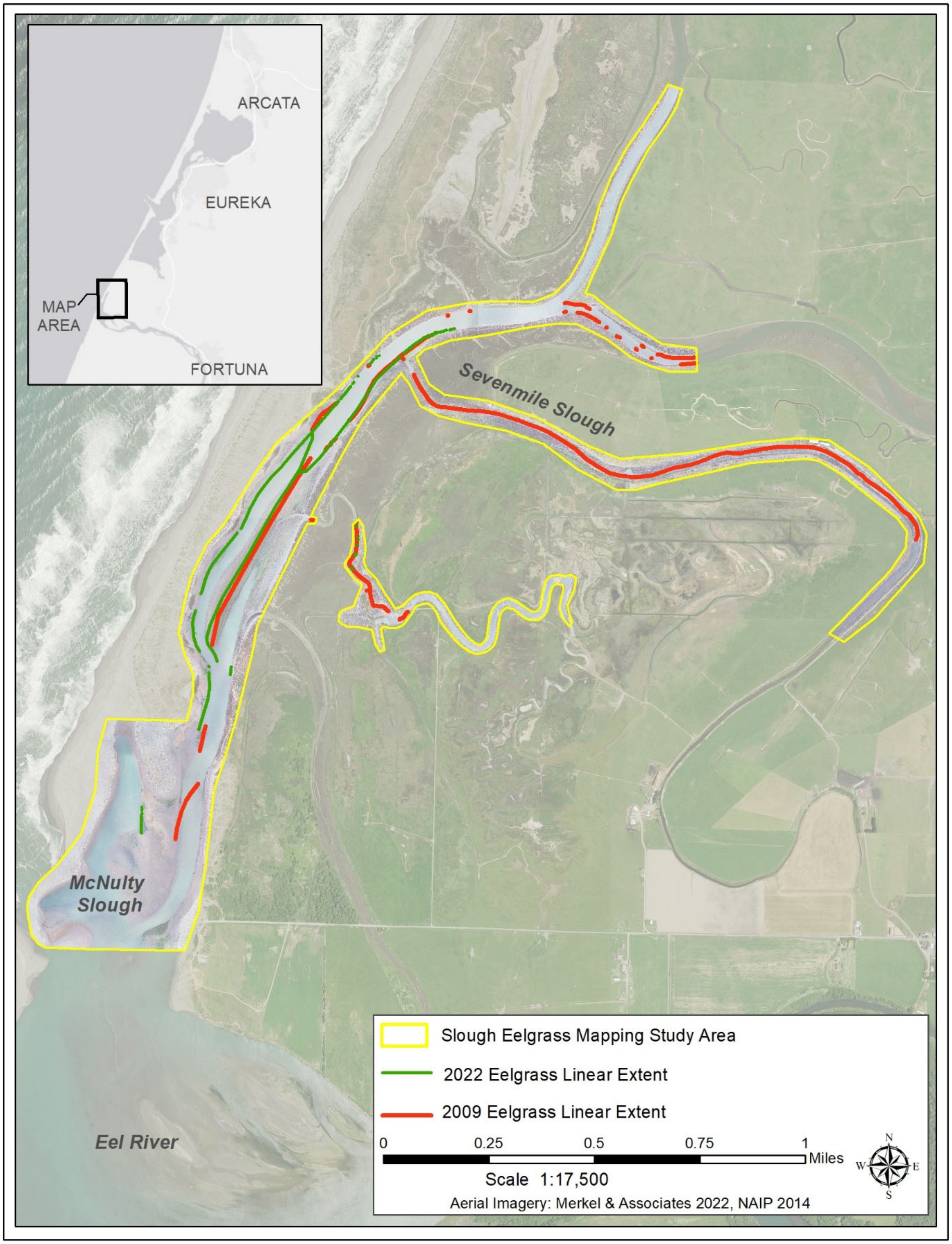


Figure 9. Eel River Estuary (North) Eelgrass Linear Extent Change Analysis, 2022 versus 2009.

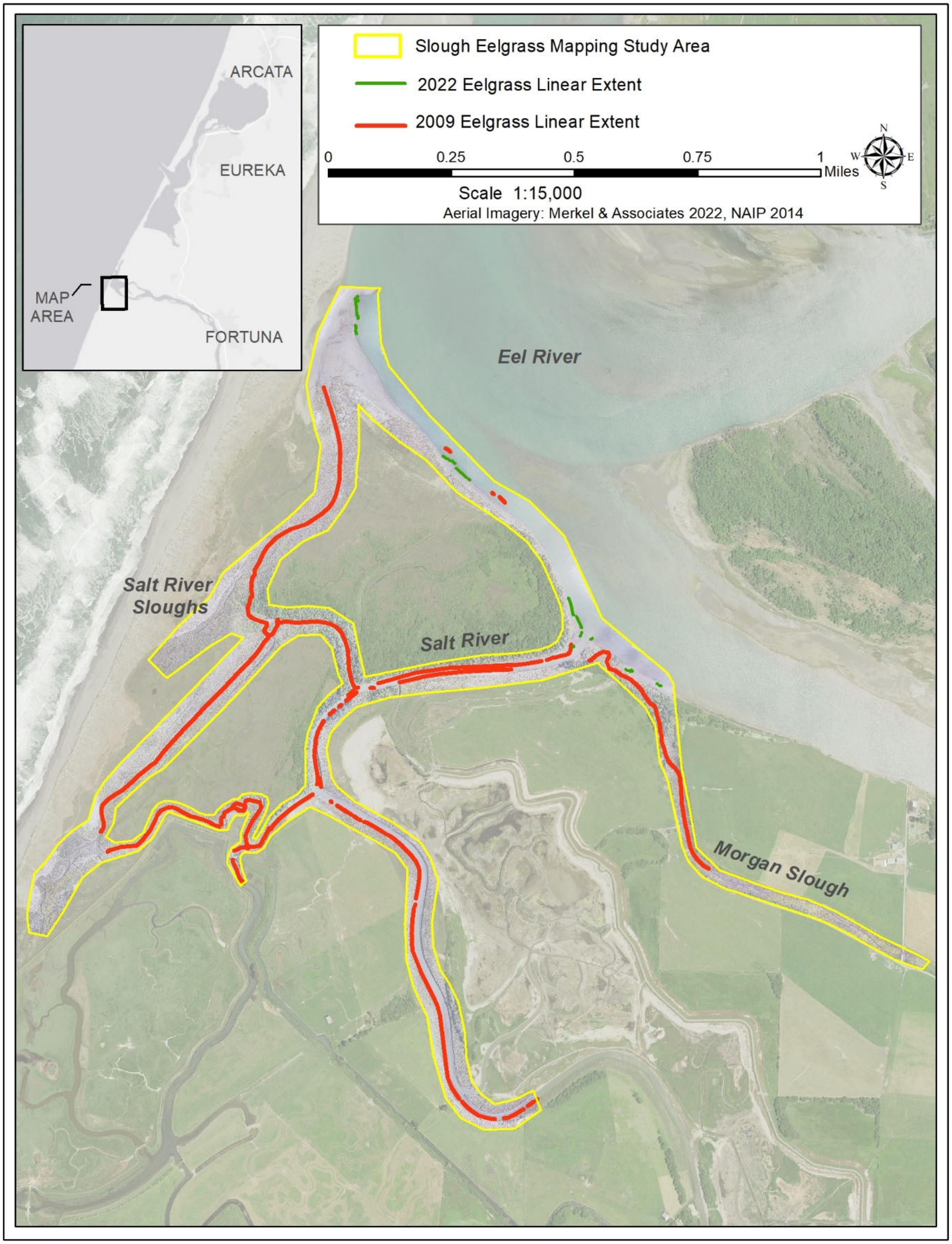


Figure 10. Eel River Estuary (South) Eelgrass Linear Extent Change Analysis, 2022 Versus 2009.

Task 3. Eelgrass Loss and Erosion Pilot Studies in South Bay and Mad River Slough

Figure 11 presents the topobathy DSM of the South Bay pilot study area derived from UAV-based aerial photogrammetric surveys and supplemental depth measurements collected during the 2021 field season. Figure 12 presents a detailed view of the most active area of headward channel expansion and associated intertidal flat erosion observed within the South Bay pilot study area and shows the results of the sediment stake erosion investigation in the context of the 2021 DSM. The 2021 topobathy DSM accuracy was assessed against the RTK-surveyed ground control monuments used to support georeferencing and found to have a root-mean-squared (RMS) error of 2.7 cm. Results of the sediment stake monitoring investigation indicated that elevation losses within the most active areas of headward channel migration and intertidal flat ranged from approximately -1 to -16 cm of vertical sediment elevation loss between 2020 and 2021.

A side-by-side comparison of the 2021 topobathy DSM and 2009-2011 California Coastal Conservancy Lidar Project DEM are shown in Figure 13. Figure 14 presents the results of differencing the 2021 DSM and the 2009-2011 Lidar DEM over the 61-acre South Bay pilot study area. Areas colored in shades of yellow to red are indicative of erosion and sediment loss, whereas areas with colors ranging from light to dark blue indicate minor sediment accretion, mostly associated with lateral channel migration and deposition over portions of the intertidal flats. In terms of elevation change within the pilot study area, the maximum accretion observed resulted in a positive increase of 0.43 meters in surface elevation, while the greatest loss of elevation associated with channel incision was -1.68 meters. Within the study area, a total of 5,580 cubic meters (7,298 cubic yards) of net erosion was documented over the past decade, with greater than 95 percent of the observed sediment loss occurring within approximately 15 acres of the South Bay study area.

Figure 15 presents a 5-year time-series of UAV-aerial imagery of the area of active erosion within the South Bay pilot study area beginning in July 2018 and continuing through June 2023. Monitoring of the headward migration rate of the advancing erosional front comprised of the expanding channel network and eroding intertidal meadow platform along 10 randomly placed synthetic longitudinal transects indicated that erosion rates were generally consistent between 2018 and 2021, with an average annual migration rate of 23.4 feet (2018-2020) and 24.6 feet (2020-2021). Between 2021 and 2022, the average migration rate slowed to 17.8 feet before slowing further to 8.3 feet between 2022 and 2023 as the erosional fronts approached the shoreward margin of the meadow (Figure 15).

A conceptual model of the bio-geomorphic coupling of intertidal eelgrass habitat and the surface expression of the estuarine intertidal flat and channel network configuration is presented in Figure 16. This model depicts a process of eelgrass sediment trapping and elevation building during favorable conditions for eelgrass, followed by unfavorable conditions resulting in eelgrass losses within the accreted upper margins of eelgrass beds. When this happens, the loss of stabilizing eelgrass that holds sediment, dampens wave energy, and slows tidal drainage off the flats, allows for cascading erosion of the over-built intertidal flats. This erosional process ultimately results in further eelgrass losses until such time as the gradients flatten adequately to allow for recolonization by eelgrass. Evidence suggests that this is a natural and recurrent process based on observable geomorphic features in the bay. However, the process may reasonably be expected to become more frequent under changing climatic conditions.

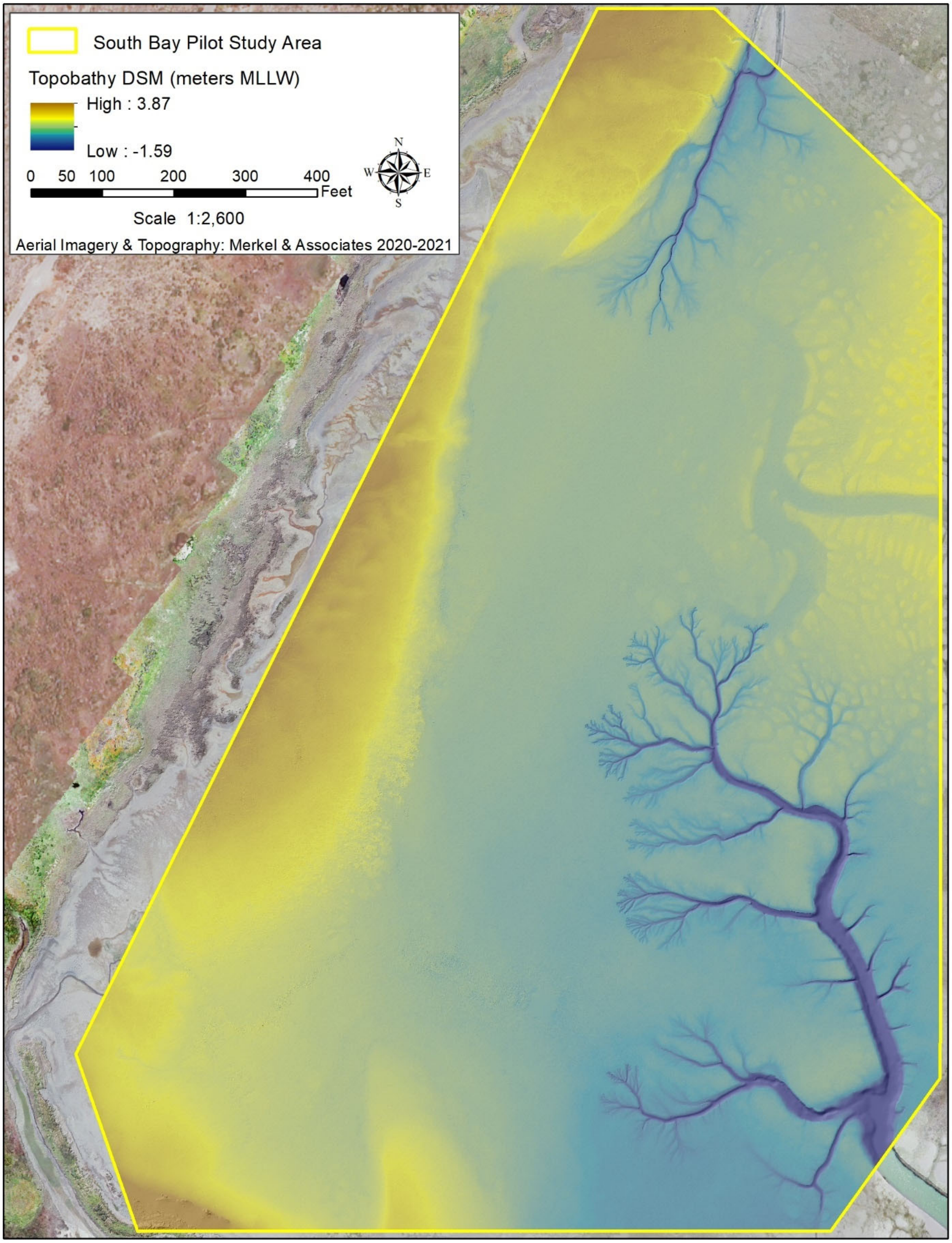


Figure 11. Structure-from-Motion (SfM) Photogrammetric Topobathy Digital Surface Model (DSM) of the South Bay Pilot Study Area Developed During May-July 2021.

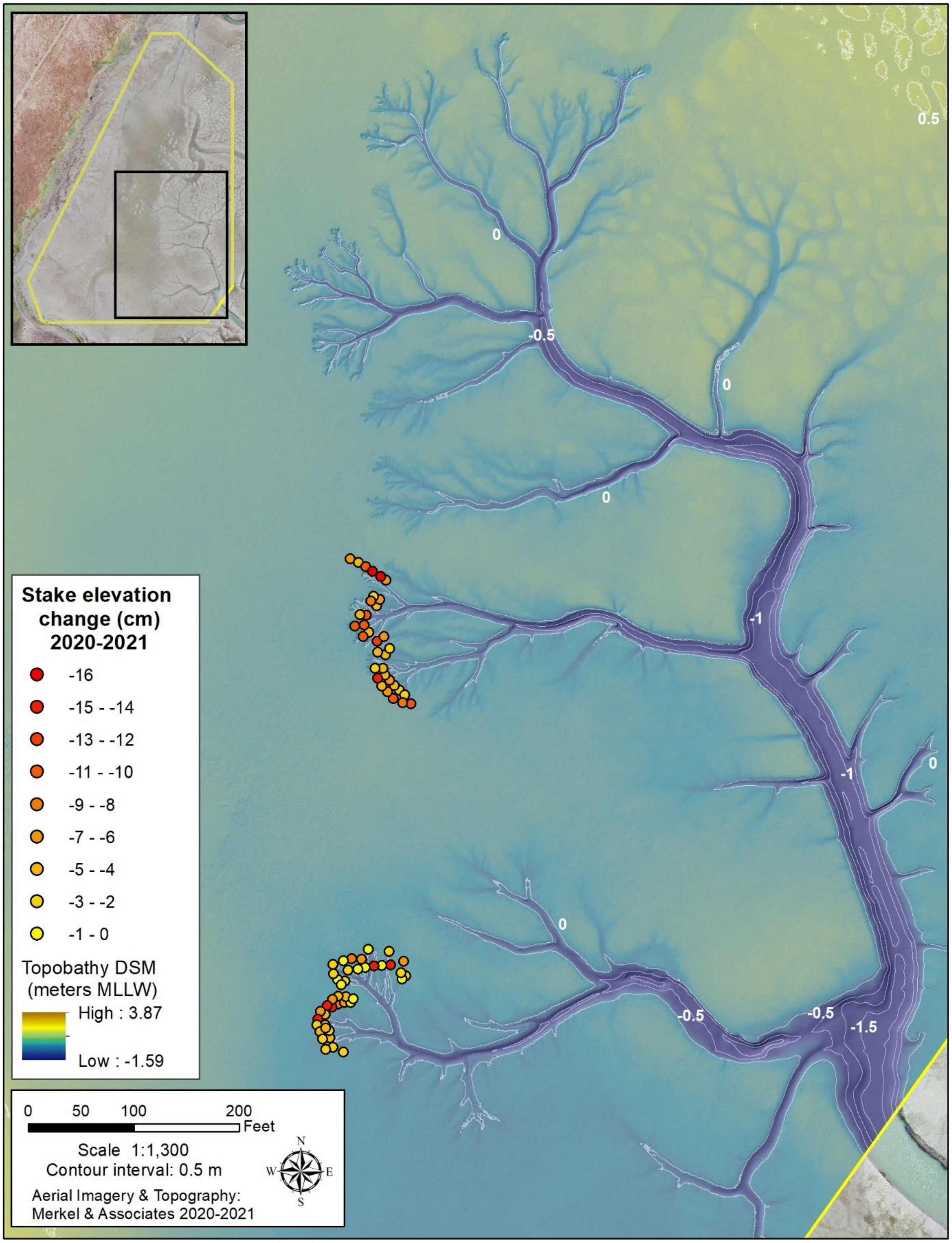


Figure 12. DSM Detail of the South Bay Pilot Study Area and Results of the Sediment Stake Erosion Monitoring Investigation Completed in June 2021.

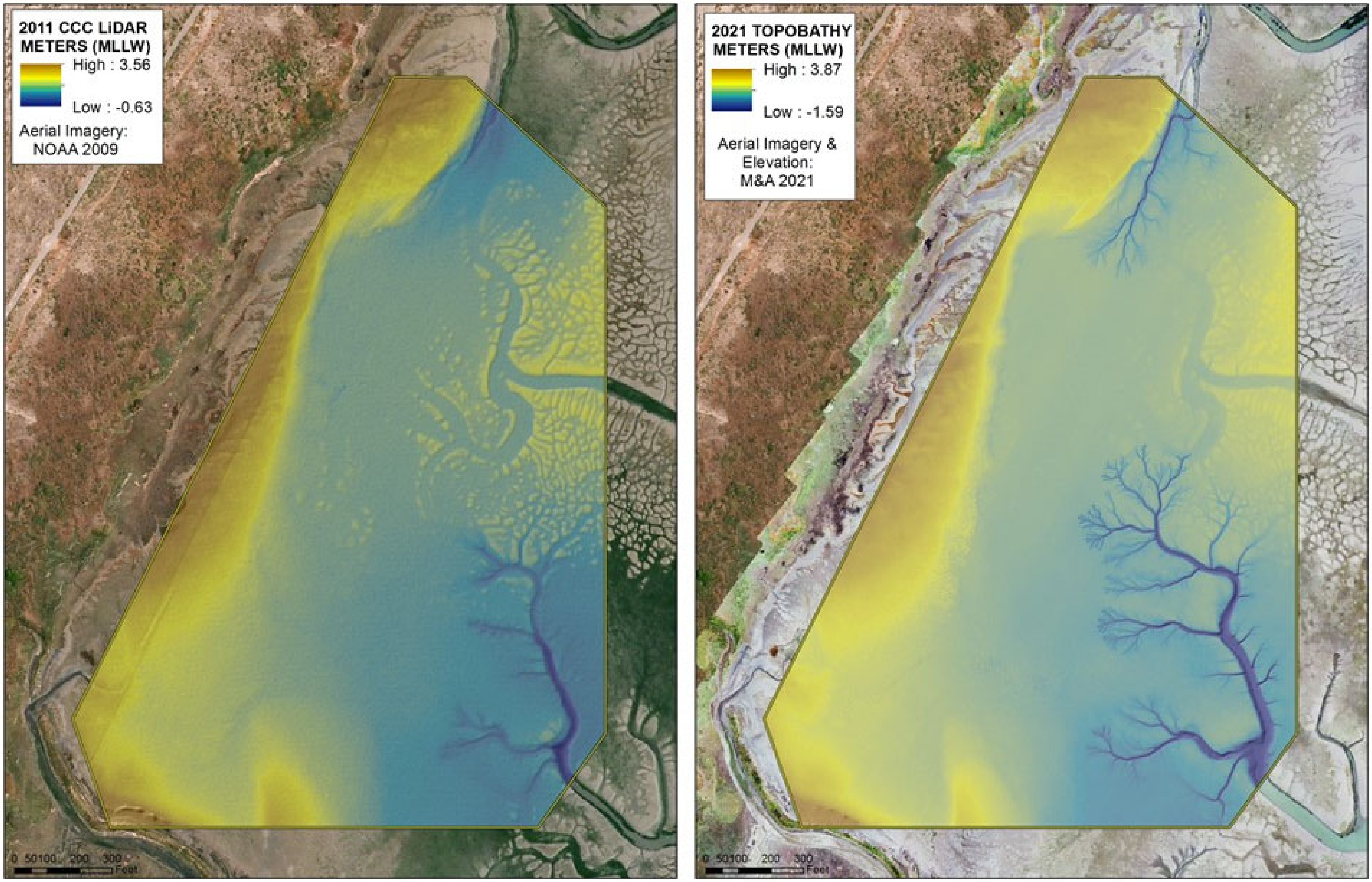


Figure 13. Side by Side Comparison of the 2009-2011 Coastal Conservancy LiDAR DEM (Left) and 2021 Topobathy DSM of the South Bay Pilot Study Area Developed During May-July 2021.

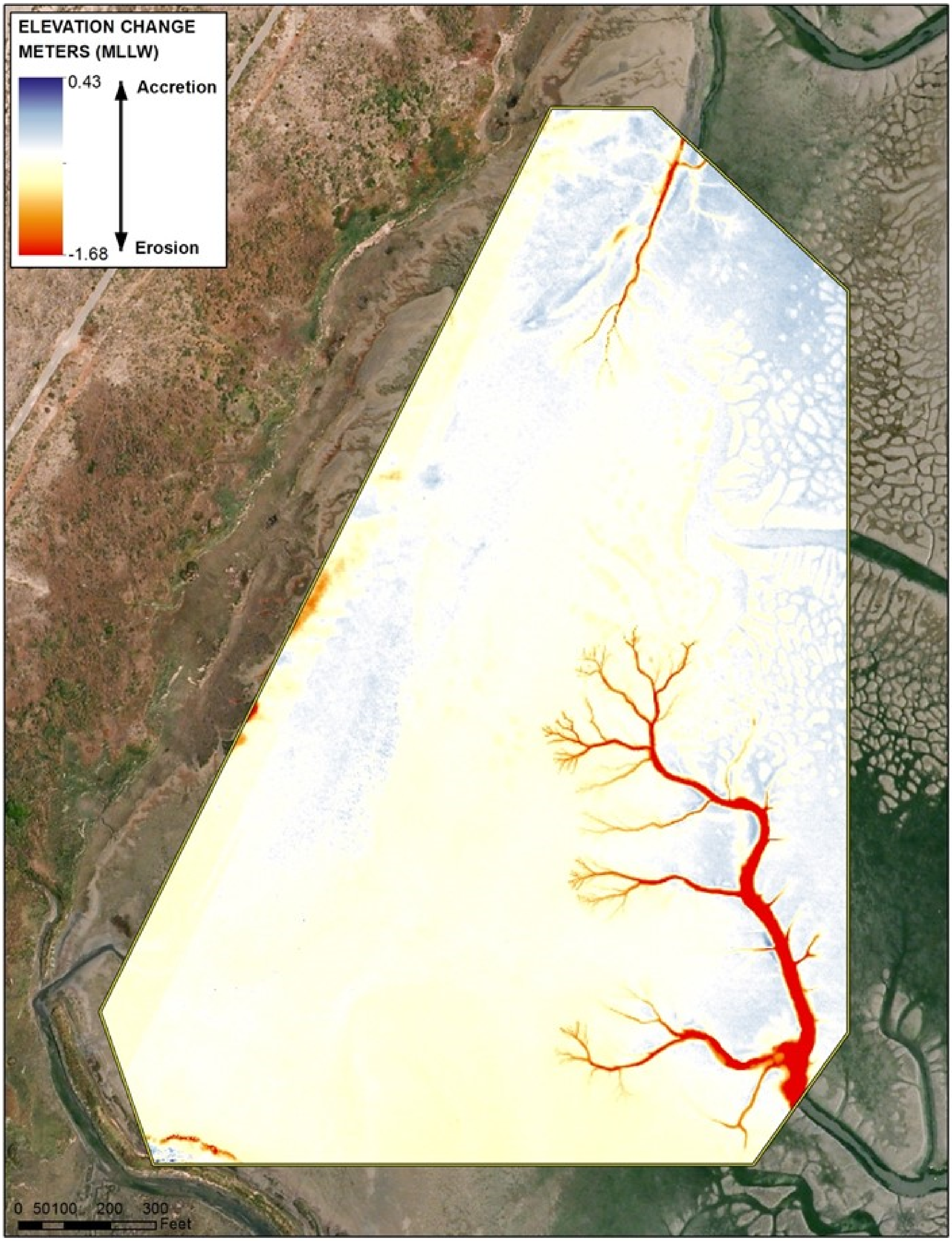


Figure 14. Elevation Change Quantified Through Differencing of the 2021 Topobathy DSM of the South Bay Pilot Study Area Developed During May-July 2021 Against the 2009-2011 California Coastal Conservancy Lidar DEM.

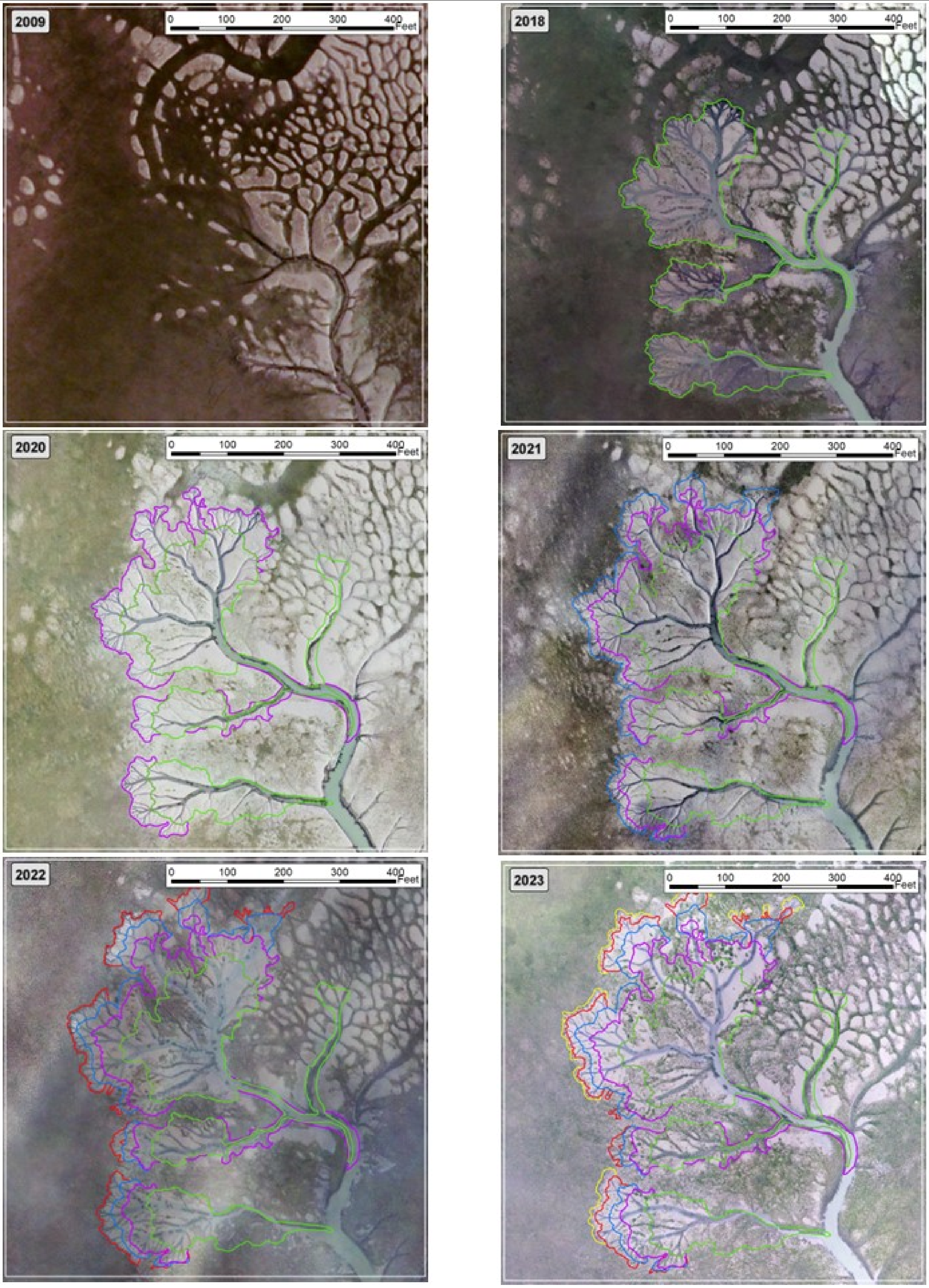


Figure 15. Time Series Depiction of the Largest Advancing Erosional Front in the South Bay Study Area Captured between July 2018 and June 2023, with the 2009 Humboldt Bay and Eel River Benthic Habitat Project Aerial Imagery Provided for Context.

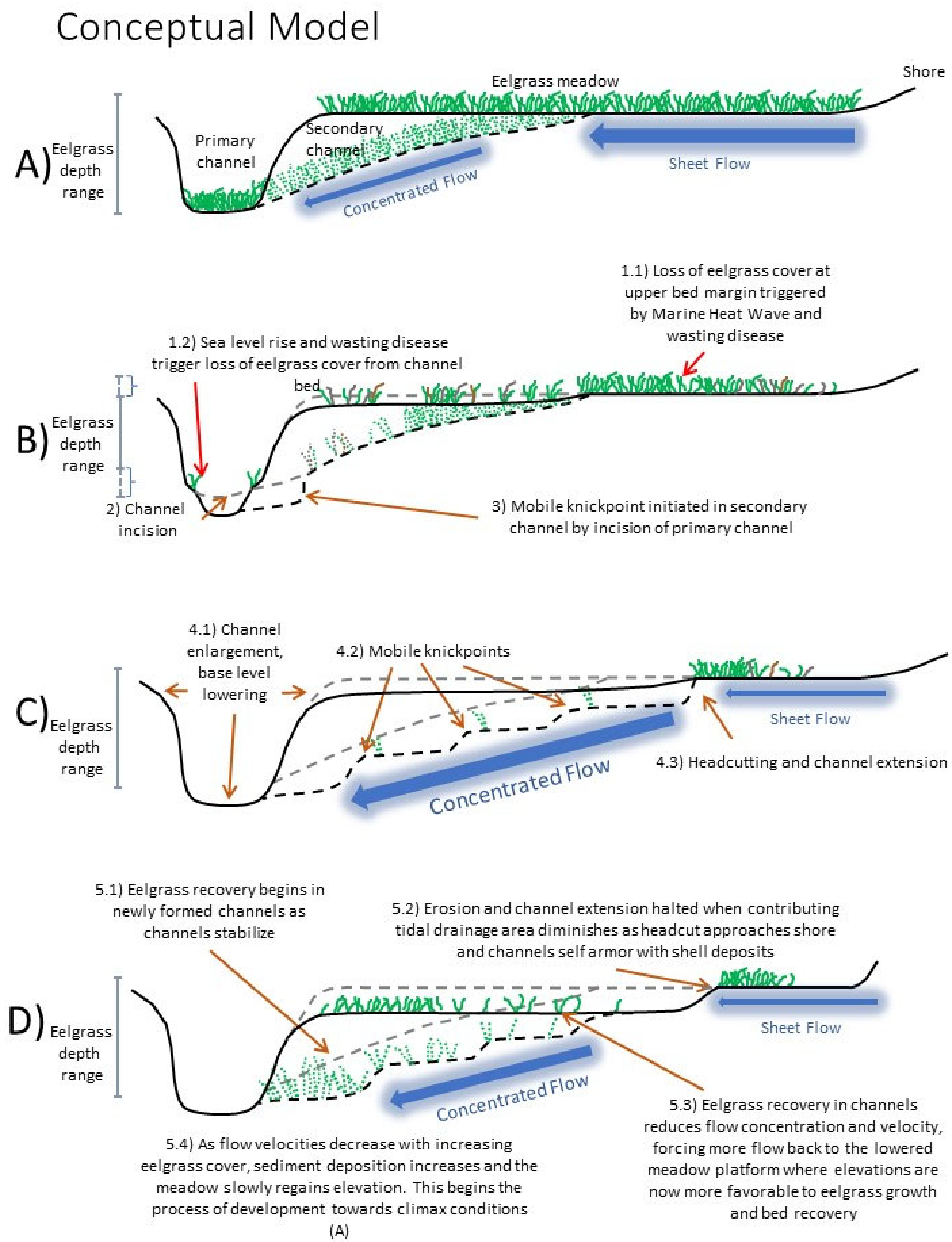


Figure 16. Conceptual Biogeomorphic Feedback Model Depicting Coupling Between Intertidal Eelgrass and Estuarine Tidal Flat and Channel Geomorphology in South Bay.

Table 3 presents the results of eelgrass turion density sampling completed in 2021 and 2022 to provide additional context regarding eelgrass plant conditions observed in association with areas in the South Bay and Mad River Slough study areas experiencing erosion and eelgrass bed retreat and fragmentation during the study. Turion density was assessed, and qualitative observations were made in July 2021 and July 2022 in the South Bay study area and during August 2022 in the Mad River Slough study area. In the South Bay Study Area in 2021, mean turion density was approximately 60 percent lower within residual patches of eelgrass that persisted following passage of the erosional front relative to the upstream meadow, where erosion had not yet appeared to be directly influencing eelgrass growing conditions. In 2022, conditions within the eroded flats and expanding channels further diverged from what was observed in the upstream eelgrass meadow, with mean turion density in the erosion-affected areas being approximately 80 percent lower than in the upstream meadow area located shoreward of the advancing erosional front. During both 2021 and 2022, the observed incidence of eelgrass flowering was substantially greater in areas affected by erosion relative to the unaffected meadow. With respect to eelgrass wasting disease, indicative necrotic lesions and leaf shed were observed at low to moderate levels within the eelgrass meadow but were most prevalent in plants located at the advancing scarp that formed at the leading edge of the erosional front, resulting in aerial exposure and fragmentation of eelgrass rhizomes. Biogenic activity associated with burrowing organisms in the substrate was noted along the active erosional fronts and appears to have contributed to the rapid rate of erosion observed through the formation of cavities and subsurface conduits for tidal water draining out of the meadow during outgoing tides. Silt loading on eelgrass was also observed to be most prevalent on plants within or in close proximity to the area of active erosion, likely in response to ongoing sediment mobilization. In some cases, rates and patterns of erosion have been influenced by differences in sediment density, and piping effects of invertebrate burrows.

Eelgrass plants exhibiting evidence of physiological stress and wasting disease along the scarp associated with the advancing erosional front in the South Bay study area in July 2021. Cavities in the exposed substrate resulting from infaunal biogenic activity are also visible along the scarp. Photo credit: Joe Tyburczy

Relatively high rates of erosion are also suggested by abundant piles of live bivalves in the channels below the eroding mudflats.

In the Mad River Slough pilot study area, early indications of eelgrass recovery were first observed in August 2022 within the area where bank erosion was most pronounced and eelgrass bed loss was observed in 2020. Virtually no eelgrass was detected within the area of bed loss in either 2020 or 2021 at this study site, but multiple yearling eelgrass plants were observed and appeared to be in good condition during the August 2022 site visit. Turion density within the newly recruited patches was approximately 50 percent lower than what was observed within the intact eelgrass bed occurring within the northern portion of the pilot study area. Eelgrass plant health otherwise appeared largely consistent between the newly recruited plants in the loss area and the bed immediately to the north, with minimal evidence of eelgrass wasting disease, low incidence of flowering, and low to moderate silt loading observed throughout the area.

Table 3. Pilot Study Eelgrass Turion Density Sampling Results 2021-2022.

Study Site	Date	Number of quadrat samples	Location	Mean Density (Turions/m^2)	Standard Deviation
South Bay	**7/26/2021**	**20**	**Erosion/Eelgrass loss area**	**116.8**	**59.2**
		20	**Reference Area**	**286.4**	**111.1**
South Bay	**7/16/2022**	**20**	**Erosion/Eelgrass loss area**	**66.4**	**49.9**
		20	**Reference Area**	**325.6**	**105.8**
Mad River Slough	**8/29/2022**	**20**	**Erosion/Eelgrass loss area**	**44.0**	**22.0**
		20	**Reference Area**	**86.4**	**37.2**

Figure 17 presents the results of the 2020-2021 sediment stake erosion investigation completed at the Mad River Slough pilot study site in conjunction with the DSM developed during the 2021 field season. Sediment surface elevation changes along the sediment stake array ranged from +2 cm to -8 cm during the approximate 1-year study interval. Erosion was most pronounced along the lower elevation, along-shore transect and within the lower elevation portion of the cross-shore transect, while accretion was most pronounced along the higher portion of the cross-shore transect and within the intact eelgrass bed at the northern end of the pilot study site. It was further noted that areas along the upper portion of the cross-shore transect, where accretion was most pronounced, were characterized by relatively dense mats of *Rhizoclonium*, a turf-forming green algae that was found to expand in coverage along the upper portion of the slough bank near the upper margin of eelgrass habitat.

The 2021 Mad River Slough pilot study DSM was differenced against the 2009-2011 California Coastal Conservancy Lidar DEM to quantify changes since the site was last surveyed. Elevation changes ranged from an increase of 0.08 meters to a loss of 0.52 meters of elevation relative to the 2009-2011 DEM. Observed patterns of elevation change indicated that the area subject to eelgrass loss within the southern portion of the pilot study site exhibited substantial erosion in areas generally below 0.5 m MLLW, with areas of intermediate and higher elevation tending to have eroded less. In the northern portion of the pilot study area where the eelgrass bed has remained mostly intact, long-term erosion was somewhat less pronounced, with a narrow band along the lower elevation portion of the bed appearing to exhibit minor accretion. In evaluating sediment flux over the 1.2-acre portion of the pilot study site analyzed, a total of 1,045 cubic meters (1,367 cubic yards) of net sediment loss was observed between surveys.

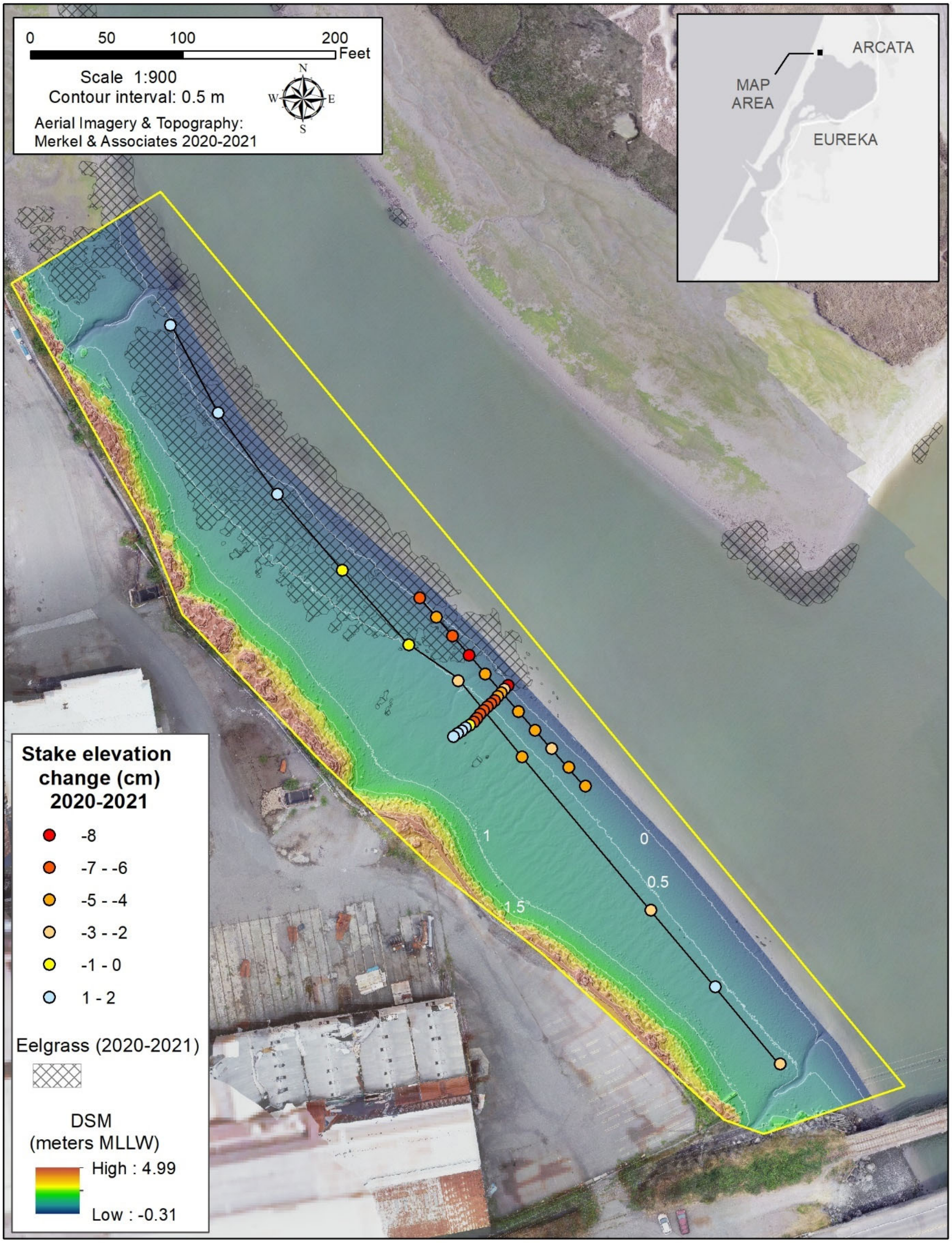


Figure 17. Eel River Estuary (South) Eelgrass Change Analysis, 2009 versus 2022 Study Period.

Figure 18. Elevation Change Quantified Through Differencing of the 2021 Topobathy DSM of the Mad River Slough Pilot Study Area Developed During May-July 2021 against the 2009-2011 California Coastal Conservancy Lidar DEM.

Discussion

Substantial changes have occurred within portions of the Humboldt Bay and Eel River estuaries since 2009, when benthic habitat was last assessed synoptically across these systems. These changes are not believed to be directly associated with local anthropogenic activities or management actions, rather they appear to be driven by a combination of inter-related factors including climate change, sea level rise, drought, marine heat waves, and the exacerbation of eelgrass wasting disease. In some areas (e.g., northeastern South Bay and lower McNulty Slough), these changes have resulted in localized gains in eelgrass habitat; however, across the majority of the areas captured in this study, eelgrass has declined relative to 2009. The time period in which this study was completed follows the most intense marine heat wave observed to date in the northeast Pacific. The unprecedented large-scale warm-water anomaly emerged in the Northeast Pacific within the Bering Sea in late 2013 with sustained biological influence extending through 2016 (Belkin and Short 2023). This event was followed closely by and overlapped with a multi-year drought in northern California. Both of these climatic stressors are believed to have played an important role in the recent changes observed in eelgrass distribution and abundance within these systems. The effects of this heat wave were seen within eelgrass beds up and down the coastline with eelgrass losses due to a combination of thermal stress and outbreaks of wasting disease, the second likely stimulated by the first (K. Merkel, pers. obs.). Notably, following the cessation of the marine heat wave, atmospheric conditions within the Humboldt Bay region continued to exhibit reduced precipitation and elevated temperatures relative to long-term averages during 2020 and 2021 (National Weather Service, Eureka, CA). This likely played an important role in expanding desiccation and thermal stress in upper elevations of the eelgrass beds.

Beginning in 2022, the region experienced a return to cooler and wetter weather conditions (National Weather Service, Eureka, CA.), which is believed to have influenced observations made during the latter portion of the study, which have included some signs of eelgrass recovery occurring within areas of South Humboldt Bay and lower Mad River Slough. Beyond these positive indicators of localized eelgrass recovery and expansion, eelgrass habitat has become more fragmented overall, particularly along the upper intertidal margins and lower intertidal and subtidal channels within South Bay. Within the sloughs and tributaries of Humboldt Bay and the Lower Eel River estuary, eelgrass habitat has generally contracted since 2009, with the greatest losses occurring within the upper tidal reaches of these channel systems where estuarine circulation and water exchange volume diminishes.

The observed changes in eelgrass distribution and abundance documented in this study suggest that eelgrass baseline conditions are shifting in response to changes in the climatic environment, and these shifts are leading to resultant geomorphic changes in the bay, that have further effects on the eelgrass habitat. The pilot study investigations completed in South Bay and to a lesser degree, Mad River Slough, also suggest that the physical environment and estuarine geomorphology are tightly coupled with eelgrass distribution through bio-geomorphic feedback. Developing a better understanding of these linkages between eelgrass ecology and the bay's geomorphology, as well as the larger scale patterns of eelgrass retreat within the upper reaches of the bay's sloughs and tributaries provide key insights into this changing resource, which can be used to inform future management actions, including eelgrass restoration.

Within the reconnaissance mapping study area in the South Bay, patterns of eelgrass distributional changes observed relative to 2009, suggest that eelgrass habitat has become generally more fragmented within the southern portion of the bay and at higher intertidal elevations in the eelgrass meadows. Further north within South Bay, eelgrass has expanded in areas that are more proximate to the bay entrance where tidal circulation and estuarine water temperatures are presumed to be lower. Some of these areas where eelgrass has expanded appear to have also experienced erosion, which may have resulted in a more favorable inundation/exposure regime by lowering of the intertidal flats within the tidal frame. While the changes observed are fairly dramatic at a local scale, it is important to note that the overall balance between eelgrass gains and losses documented in this study amount to a net loss of 22 acres of eelgrass habitat in an area that supported a total of approximately 1,078 acres of eelgrass habitat in 2009. This represents a net decline of approximately 2 percent in the 11-13 years over which the changes were evaluated. Figure 19 provides a side-by-side comparison of the eastern portion of the South Bay reconnaissance mapping area in June 2009 and August 2021, and illustrates the general nature of the changes observed throughout the southern portion of South Bay. These changes include lateral and longitudinal expansion of the channel network, fragmentation of eelgrass habitat along the upper intertidal bed margin and within the channel network, and the apparent transition of unvegetated intertidal flats adjacent to eelgrass beds to extensive mats of green macroalgae (*Rhizoclonium* spp.).

In contemplating the changes observed in eelgrass distribution within the sloughs and tributaries of Humboldt Bay and the Eel River Estuary, landscape context appears to play an important role in structuring eelgrass habitat during a period of shifting baseline conditions. In Mad River Slough and to a lesser degree, Eureka Slough, a combination of relatively broad intertidal flats and narrow subtidal channels are believed to exacerbate thermal stress, which would be anticipated to affect the upper portions of these systems where tidal circulation is less robust. This issue is believed to be more pronounced in Mad River Slough as a result of its location being further from the bay's entrance and as a result of lacking direct fluvial inputs of cold, fresh water to help offset increasing bay water temperature, whereas Eureka Slough receives discharge from the Ryan Creek/Freshwater Creek watershed. In contrast with Mad River Slough and Eureka Slough, which exhibited declines in eelgrass linear extent of 77 and 41 percent, respectively, eelgrass linear extent in Elk River declined only 5 percent during the study period. Elk River differs from Mad

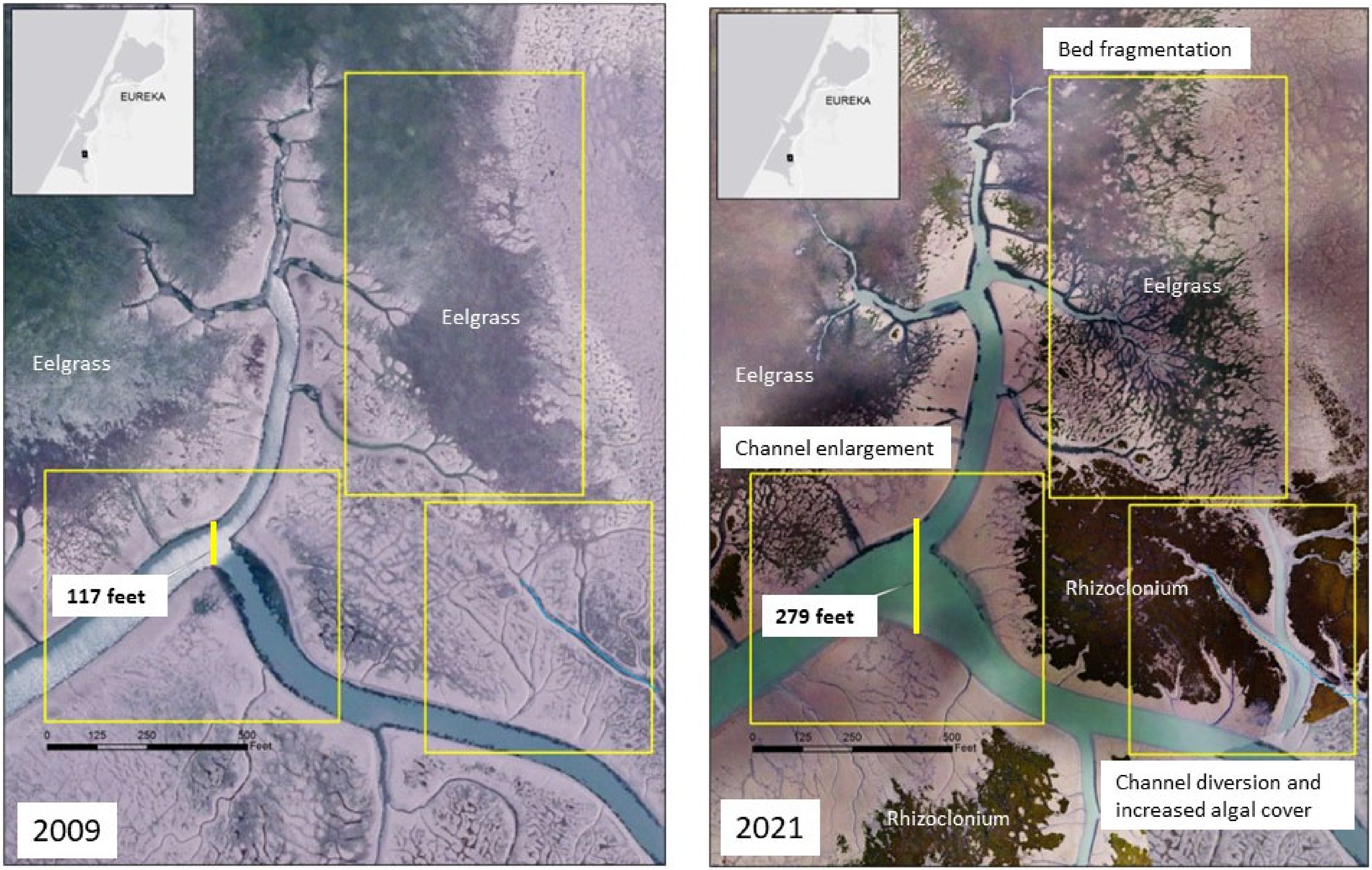


Figure 19. Side by Side Comparison of Eelgrass Fragmentation, Channel Enlargement and Diversion, and Increased Algal Cover Observed in the Eastern Lobe of the South Bay Study Area, 2021 Versus 2009.

River and Eureka Slough in that in addition to receiving relatively cold, freshwater discharge from its watershed, the lower, tidally-influenced portion of the river is relatively confined and narrow, with less intertidal flat area relative to the subtidal portion of the river channel. Elk River also enters the bay in close proximity to the bay mouth, where colder water from the nearshore ocean exerts a strong influence on water temperature. Recent, large-scale estuary restoration efforts completed within the lower Elk River watershed are likely to improve the resilience of eelgrass habitat within this tributary and could lead to an expansion of eelgrass within this portion of the bay that may be intrinsically better able to adapt to changing climatic conditions.

In the Eel River Estuary, changes in eelgrass distribution followed a similar but generally more extreme overall pattern relative to Humboldt Bay's sloughs and tributaries. Eelgrass retreated from the upper portions of McNulty Slough but expanded somewhat at a local scale in the lower portion of the slough (+ 20%), close to the river mouth. The majority of the observed expansion occurred in association with the recruitment of eelgrass along the right bank of the lower channel and lateral expansion of the largest eelgrass bed within the lower portion of the slough. The right bank of the channel is situated along the northern barrier spit separating the ocean from the estuary and appears to be a dynamic feature affected by aeolian sand transport and lack of a fixed breakwater, allowing the channel to migrate somewhat over time. It is plausible that the channel may have become somewhat more stable in this area of the slough, facilitating eelgrass colonization and increasing the linear extent of eelgrass within the lower portion of the slough. Despite the overall increase in linear eelgrass extent, eelgrass was noted to have retreated from upper reaches of the slough by approximately 6,200 feet relative to the upper extent of eelgrass distribution in 2009.

In contrast to the expansion of eelgrass linear extent that was observed in lower McNulty Slough, eelgrass retreated almost entirely from the southern portion of the estuary, and was only found to occur in fragmented, small patches along the left bank of the mainstem river channel. These areas were likely colonized by eelgrass during the 2018-2020 drought, when river flows were diminished and where water quality conditions likely remained more suitable than they were within the slough network. The principal factor believed to be responsible for the dramatic decline in eelgrass linear extent from the southern Eel River sloughs is thermal stress. These slough channels are extremely shallow, making them vulnerable to relatively small changes in the thermal or hydrologic regime. Differences in image resolution between the 2009 and 2020-2022 study imagery affect our capacity to assess changes in intertidal eelgrass areal extent. This is particularly noteworthy within the larger sloughs captured in this study due to the presence of mixed assemblages of eelgrass and macroalgae within exposed areas of the intertidal flats. Because of an inability to draw necessary spatial resolution of the beds from the 2009 survey, areal comparisons were not made in most cases and changes in linear distribution along the sloughs was employed as the metric of change. However, the narrow and confined sloughs of the southern Eel River estuary supported dense eelgrass with minimal macroalgae, making it possible to spatially quantify the loss of eelgrass area in this part of the estuary with greater confidence. In this case, the relatively dramatic decline in eelgrass linear extent in the southern Eel River Estuary represented a loss of 9.46 acres of eelgrass relative to 2009. The overall extent of eelgrass loss would be within the range of interannual variability within Humboldt Bay, however, it may be of outsized importance within the Eel River Estuary. First, the Eel River Estuary suffered an estimated 28.6% decline in eelgrass between 2009 and 2020-2022. This is substantive in its own right; however, perhaps more important has been the extirpation of eelgrass from large segments of the estuary slough system. This reduction in eelgrass distribution has substantively altered the habitat characteristics of major portions of the estuary by removing structuring vegetation that had provided value through sustaining water quality, reducing temperature fluxes, and contributing foraging and sheltering habitat along miles of the slough channel network. This loss of submerged aquatic vegetation may be of further concern in that it has occurred at a time of drought when considerable overhanging woody riparian vegetation has also been in a state of decline due to seawater intrusion associated with declining fluvial discharges.

One element of the observed decline in eelgrass growing conditions within the Eel River sloughs that may hold a silver lining, is that ground truthing efforts completed to confirm whether *Zostera japonica* remained present within the former infestation area in northern McNulty Slough resulted in no detections of this exotic seagrass that has been found to be invasive in the Pacific Northwest. While the ground truthing efforts were not exhaustive throughout the sloughs of the lower Eel River study area, the lack of detection of *Z. japonica* in the area it was previously found in greatest abundance suggests it may have succumbed to a combination of facilitated eradication efforts conducted by California Sea Grant and CDFW staff, and the effects of climate change and drought in recent years.

The slough mapping and change analysis completed under Task 2 was initially envisioned to provide insight into the effect of tidal prism expansion associated with estuary restoration projects that were being planned and implemented within former tidelands of the lower Eel River and Humboldt Bay on the distribution of eelgrass within the slough systems where restoration was being advanced. Prior to the acquisition of new aerial imagery used to support eelgrass mapping within the sloughs studied, it was postulated that the expansion of tidal prism associated with the implementation of large-scale estuary restoration projects would improve tidal circulation and facilitate expansion of eelgrass habitat as the increased volume of tidal exchange supports conditions suitable for eelgrass. The results of the present mapping study provide an updated baseline on eelgrass distribution within these systems; however, it appears that the near-term effects of climate change and drought have, at least in the short term, overwhelmed any gains that might have occurred if these systems were in a state of equilibrium relative to what was observed in 2009.

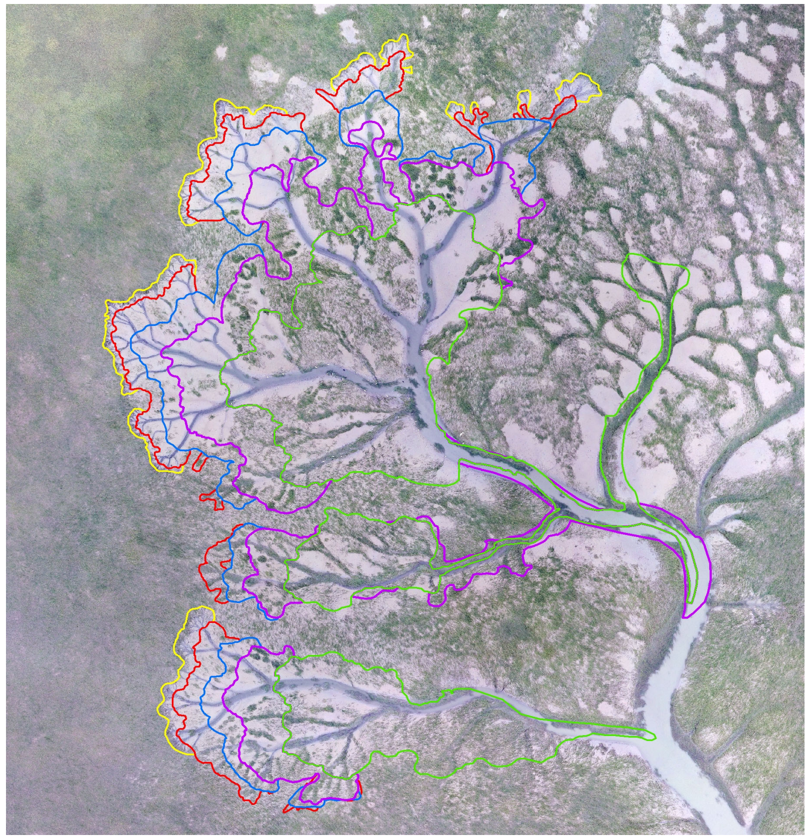
As climate change progresses in coastal Humboldt County, it may be useful to draw comparisons with other estuarine slough systems from the San Francisco Bay where overall climatic conditions are similar but slightly warmer and clear sky conditions are more prevalent. In both the Napa River and Petaluma River, extensive tidal wetlands occur within the tidally influenced portions of these rivers; however, these areas of the northern San Francisco Bay experience relatively high water temperature conditions during the summer months that preclude the capacity for eelgrass to occur within these portions of the estuary. Future monitoring of eelgrass distribution trends within the sloughs and tributaries captured in this study, may be an important precursor to contemplating facilitated restoration of eelgrass within these portions of the Humboldt Bay and Eel River estuary. If recent changes in eelgrass distribution are indicative of a directional shift in habitat suitability as opposed to a shorter-term perturbation to ambient climatic conditions, this could have major ramifications in directed restoration actions. However, it is premature to determine if the conditions that have led to eelgrass declines are anomalies or trends.

Investigations completed at the pilot study sites in South Bay and Mad River Slough under Task 3 provide greater insight into the patterns of eelgrass loss, expansion of the channel network, and erosion of intertidal flats that was observed to occur more broadly throughout the South Bay during the reconnaissance-level spatial analysis completed under Task 1. In the South Bay pilot study area, where dramatic, localized erosion of the tidal flats and associated loss of eelgrass cover was first identified and initially evaluated in 2018, continued aerial mapping and ground-based observations completed over the course of this study have illuminated the contribution of multiple factors to the observed physical and biological changes occurring within the study area.

While eelgrass wasting disease is believed to be a contributing factor to the observed erosion and fragmentation of the intertidal eelgrass meadow in the South Bay study area, other drivers are strongly believed to influence virulence of *Labyrinthula* and wasting disease outbreaks. In addition, other factors may have even more direct linkages to the observed erosion and loss of eelgrass cover within the bay. These additional factors include the region's rapid rate of relative sea level rise (Anderson 2018) and the ongoing expansion of the tidal prism and associated increase in the volume of tidal exchange; thermal stress associated with marine heat waves (Di Lorenzo and Mantua, 2016) and increased solar irradiance in coastal northern California relative to historic conditions (Johnstone and Dawson, 2010). In addition, the long-term decline in suspended sediment discharge from local watersheds since the 1964 flood (Warrick et al. 2013) coupled with the ecosystem-engineering capacity of eelgrass to facilitate deposition and accretion of fine sediment resulting in the long-term increase in intertidal meadow elevation (Poppe and Rybczyk, 2022) are important factors driving conditions leading to and ultimately being observed in the processes presently in play. These inter-related factors are believed to drive bio-geomorphic feedbacks between eelgrass and the intertidal flats and channels that comprise the estuarine ecosystem of Humboldt Bay. The conceptual model presented in Figure 16 is explained in a stepwise manner in greater detail below:

Conceptual Bio-geomorphic Feedback Model of Eelgrass Loss in South Humboldt Bay

- *Under climax conditions, eelgrass extends upward into middle intertidal elevations through the process of sediment accretion that builds intertidal elevations. Dense eelgrass beds slow drainage during falling tides and resist losses due to desiccation and thermal stress by water trapping and “sacrificial” leaf loss wherein the majority of the bed benefits by evaporative cooling as top leaves desiccate at low tide. Channels narrow due to reduced drainage rates and are stabilized by eelgrass growth in channel beds.*
- *Significant environmental perturbations such as marine heat waves or outbreaks of wasting disease led to reduced plant density over the elevated flats. This exacerbates drain-out rates during ebb tides causing scour within the channel systems and further loss of eelgrass. Similar results occur as a result of relative sea level rise due to rapidly expanding tidal prism. As the primary channels incise the secondary channel gradients increase and head-cutting migrates up the channels towards the flats.*
- *Mobile knickpoints develop along the channels and migrate upstream at differential rates. These knickpoints are generated by accumulation of bivalves washed out of the flats that armor the channel, harder clay strata, and resistant eelgrass rhizome mats. These features are transitory, ultimately giving way allowing the channels to elongate towards the head (shore) of the watershed. As the channel drainage velocities increase, channel facing flats also erode and deliver sediment into the channels.*
- *As channels elongate and approach the head waters of the local watersheds, the reduction in channel gradient, coupled with reduction in contributing drainage area results in increasing stability of the sediments. This allows for recolonization by eelgrass within the channels and on the lowered flats.*
- *As the eelgrass beds in the recolonization areas begin to densify, they start to trap sediment and resist sediment loss. This restarts the process of building the tidal flats and eelgrass elevation towards the climax conditions described in “a” if suspended sediment supplies remain adequate.*



The observed rate of headward erosion and eelgrass loss at the South Bay pilot study area began to decrease in 2022 (red line) and continued to decrease further in 2023 (yellow line). During this time, partial eelgrass recovery was observed to initiate from the trailing edge of the eroded flats and lowered channels.

In observing the headward extension and lateral expansion of channels, and erosion and loss of intertidal flat elevation documented in the South Bay pilot study area over multiple years beginning in 2018, it appears that the loss of eelgrass cover resulting from this ongoing erosion is at least partially transient. Beginning in 2022 and continuing in 2023, partial recovery of eelgrass cover initiating from the trailing edge of the eroded meadow platform and lowered channels became evident in the UAV aerial imagery. During the same time period, the observed rate of headward expansion of the erosional fronts at the South Bay study area also decreased. While erosion was still active along portions of the leading margin of the fronts, some areas of the front ceased eroding in 2022 and 2023, particularly in areas where the fronts were approaching the upper shoreward margin of the eelgrass meadow. This reduction in the rate of erosion appears to be largely driven by the effective reduction of hydraulic head as the growing channel network and decreasing contributing drainage area upstream of the channel system approach a new equilibrium. However, a return to cooler and more overcast weather conditions during the Spring of 2022 and continuing through the Spring of 2023 may have alleviated thermal stress within the intertidal and reduced the extent of eelgrass wasting disease, which may have contributed to improved growing conditions and enhanced eelgrass recovery.

In the Mad River Slough pilot study area, the erosion and subsequent loss of intertidal eelgrass cover within the southern portion of the study area occurred along an outside bend in the Mad River Slough Channel. It was noted during completion of the slough mapping that eelgrass losses along the slough and associated bank erosion occurring along channel margins were often most pronounced in areas with greater sinuosity, which would be expected to result in higher current velocities relative to opposing channel banks. With ongoing sea level rise and a loss of the majority of the slough's eelgrass cover occurring relative to what was mapped in 2009, it appears that the southern portion of the Mad River Slough study area have been more susceptible to erosion and subsequent loss of eelgrass cover relative to areas further north along this reach of the channel.

Early indications of eelgrass recovery observed at the Mad River Slough pilot study site in June 2023, with several expanding eelgrass patches visible as darker areas along the lower portion of channel bank and in the water along the channel margin.

Similar to what was observed in South Bay, the first signs of eelgrass recovery at the Mad River Slough pilot site were observed in August 2022, with the persistence and growth of several isolated eelgrass yearling plants occurring primarily within the lower portion of the eelgrass loss area along the right bank of the channel. Based on the size of the plants observed, it is believed that they persisted from seedlings that recruited during 2021. During a site visit in June 2023, photos of the Mad River Slough pilot study site were captured from the abandoned railroad bridge located immediately south of the pilot site during a predicted -1.1-foot low tide. The plants observed in 2022 appeared to have generally survived and expanded relative to the previous year, suggesting that erosion at the site has largely abated. This is an encouraging sign given the overall pattern of eelgrass decline observed throughout the slough during the 2020-2021 study period.

In considering the broader context of these observed changes in eelgrass habitat and estuarine geomorphology, it is plausible that eelgrass habitat in Humboldt Bay is responding to several ongoing changes in the physical environment that affect watershed processes and suspended sediment supply, the thermal regime within the intertidal zone, light availability at depth, current velocity, and the relative extent of eelgrass wasting disease.

It is likely that eelgrass has facilitated substantial sediment accretion and a building of intertidal flat elevation throughout much of the vegetated extent of Humboldt Bay during the 20th century, when watershed disturbance associated with commercial logging peaked near the middle of the century, followed by the flood of record occurring in several north coast rivers including most notably the Eel River, in 1964 (Warrick et al. 2013). As the intertidal flats built in elevation in response to the increased supply of watershed-derived sediment, eelgrass habitat extended higher in the tidal frame as a consequence of its capacity to trap this sediment.

Prior to the initiation of the marine heat wave in 2014, which was previously unprecedented in the modern record of the northeast Pacific Ocean (DiLorenzo and Mantua, 2016), the persistent overcast conditions, cool maritime climate, and relatively low water temperature regime within the bay relative to many other eelgrass systems allowed eelgrass to thrive at high intertidal elevations compared to most other regions supporting eelgrass. In South Bay, dense, meadow-form eelgrass beds have been found to extend to slightly above 0.5 meters MLLW in elevation, which would leave them vulnerable to increasing desiccation and thermal stress under changing climatic conditions.

It is believed that in parallel to the building elevations of the intertidal flats, regional suspended sediment supplies from local watersheds began to decline following a peak in the mid 1960's. As thermal stress associated with the marine heat wave (2014-2016) and subsequent drought conditions have persisted with variable severity over much of the last decade, eelgrass meadows situated above MLLW became increasingly stressed and more susceptible to presumably elevated wasting disease and thermal stress. At the same time, the high rate of relative sea level rise observed within the pilot study areas of Humboldt Bay (3.39 to 5.84 mm/year; Anderson 2018), has resulted in an ongoing increase in the tidal prism that must be exchanged. This would be expected to result in increased current velocities within the bay at the same time that the loss of eelgrass cover diminished the bay roughness, thereby reducing sediment stabilization and storage capacity over the bay flats. These factors are believed to have increased tidal current velocities and scour and led to a feedback loop, where decreasing roughness and increased volume of tidal exchange amplified ongoing erosion. The process of channel extension and expansion into the intertidal meadow platform in South Bay results in an observable increase in concentrated, rapid drainage of tidal water during ebb tides that contrasts starkly with the slow, sheet-flow dominated drainage of the intact, unchanneled eelgrass meadow.

From a management perspective, the study has illuminated that a shift in baseline eelgrass growing conditions has occurred during the past decade. Developing greater awareness of a potentially shifting baseline within the resource and regulatory community is an important first step in improving our capacity to manage eelgrass. With respect to the quantity of erosion observed in association with two pilot sites evaluated in this study, the net loss of 6,625 cubic meters (8,665 cubic yards) of fine-sediment, most of which was generated within approximately 16 acres of the combined 62 acre study areas, suggests the total volume of sediment flux that has occurred in association with the loss of eelgrass cover, channel expansion/enlargement, and intertidal flat erosion at a baywide scale is substantial. As a thought exercise, assuming the areas captured in this study are representative of changes occurring more broadly throughout the bay within the elevation range represented in the study plots, this volume of sediment loss would conservatively total approximately 700,000 cubic meters (900,000 cubic yards). As recent investigations beyond the focus of the present study have revealed many locations of similar erosional features, the scaling up of erosion baywide may be a reasonable assumption. This would then beg many subsequent questions related to the effects of such pervasive sediment flux. These include questions regarding what affects chronic and protracted elevated turbidity levels have on subtidal environments, and where is all of this sediment settling. Because sediment from the flats is principally finer material, it would be expected to transport easily within high velocity flows in the channels and migrate long-distances from the point of origin. Drawing from principals of sediment movement, it is likely that a good portion of the sediment is being exported from the bay, some amount of the sediment is likely moving into marsh habitats and eelgrass vegetated flats, while other sediment is most likely settling in more quiescent subtidal environments. This would principally be off-channel areas such as dredged marina basins. Considering that the rapid sediment erosion is believed to have commenced during the marine heat wave and with the first observations of wasting disease there should have been a significant mobilization of sediment over the past decade that would accelerate marina basin infills and sediment accretion rates within terminal channel marsh environments over what has been the case in the prior decade.

As the bio-geomorphic processes have unfolded and been tracked in detail over multiple years, it now appears to illuminate the capacity and mechanisms whereby intertidal eelgrass habitat responds to and partially recovers from having engineered its way to vulnerability to a warming climatic regime. Further, with the observations of the present erosional processes in mind, a geomorphic tour of the bay using baywide LiDAR, finds similar subtle evidence that these processes have occurred before in not-too-distant history. As such, while alarming in the moment, the dynamic processes may be a natural resetting of over-built eelgrass flats that are triggered by infrequent episodic events. Perhaps these infrequent resets of the upper margins of eelgrass beds that trap and hold sediment may be akin to forest rejuvenation by episodic fires. However, the observations are more alarming where such changes occur at a rate where they may have broader ecological consequences due to proportional scale and distribution, such as within the Eel River Estuary, or where such changes result due to prolonged climatic trends versus punctuated events, as may be the case.

Another point to consider relates to the developing interest in carbon sequestering within eelgrass beds. The concept of carbon storage within sediments that are built up beneath eelgrass has great appeal and, in some cases, has been demonstrated to be significant. However, the long-term value of this sediment carbon storage is based on permanence. The erosion of over-built mudflats results in the release of both mineral and organic sediment supplies. This would result in a transitory character of at least some of the storage capacity within intertidal beds. As a result, it may be more appropriate to focus efforts on eelgrass for carbon sequestering benefits within subtidal accretional beds over intertidal accretional beds.

Moving forward, further monitoring of indicator sites within Humboldt Bay is recommended to develop a better understanding of eelgrass dynamics and to better understand the future trajectory of erosion and eelgrass recovery within the bay. This was previously recommended within the Humboldt Bay Eelgrass Management Plan (Merkel & Associates 2017). This may be particularly important in light of the observed and anticipated ongoing acceleration of relative sea level rise in conjunction with uncertainty regarding future suspended sediment availability and climate change within the region. The interplay of these factors are expected to exert a strong influence on eelgrass' capacity to keep pace with relative sea level rise, adapt to changing light availability at depth, and transgress shoreward in response to changing conditions within the bay.

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