San Francisco Estuary Wetland Regional Monitoring Program: Standard Operating Procedures for Vegetation Monitoring

SF ESTUARY
Wetlands Regional Monitoring Program

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Executive Summary:
This document recommends standard operating procedures (SOPs) for the monitoring of vegetation in brackish and saline tidal wetlands (emergent marshes and scrub-shrub wetlands) of the San Francisco Estuary (SFE) to the Steering Committee (SC) of the Wetland Regional Monitoring Program (WRMP). The monitoring recommendations herein were developed by the Vegetation Workgroup of the WRMP's Technical Advisory Committee (TAC).

Vegetation monitoring is crucial for understanding and tracking changes in coastal wetland habitats, particularly emergent wetlands in the San Francisco Estuary (SFE). The vegetation in tidal wetlands is influenced by various factors such as substrate and soil type, inundation, and salinity regime. Monitoring vegetation at a regional scale is essential for comprehending the physical and biological characteristics of the SFE.

The WRMP recognizes the significance of vegetation monitoring and aims to address key questions related to the distribution, abundance, diversity, and condition of tidal wetland ecosystems. The WRMP Program Plan outlines specific monitoring questions and indicators for vegetation monitoring and is particularly focused on tracking change over time due to restoration of tidal habitat and shifts in response to changing climate conditions.

To achieve comprehensive vegetation monitoring, a combination of remote sensing, field surveys, photo-points, and special studies is proposed. Remote sensing techniques enable the tracking of large-scale vegetation patterns and changes over time, while field surveys provide detailed information on species composition, percent cover, and diversity. Photo-points serve as a more cost-effective method to monitor specific areas and detect change and are particularly useful for monitoring vegetation establishment at tidal wetland restoration project sites. Lastly, special studies are suggested when funding allows that aim to monitor plant communities at ecotone boundaries, where vegetation response to climate change may first be detected.

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WRMP Background

The Wetland Regional Monitoring Program (WRMP, www.wrmp.org) is a multi-agency effort to coordinate the monitoring of estuarine wetland habitats within the San Francisco Estuary (SFE) and inform wetland restoration, conservation, and adaptive management as reflected in the mission statement:

The WRMP delivers coordinated regional monitoring of the San Francisco Estuary's wetlands to (1) inform science-based decision-making for wetland restoration and adaptive management and (2) increase the cost-effectiveness of permit-driven monitoring associated with wetland restoration projects.

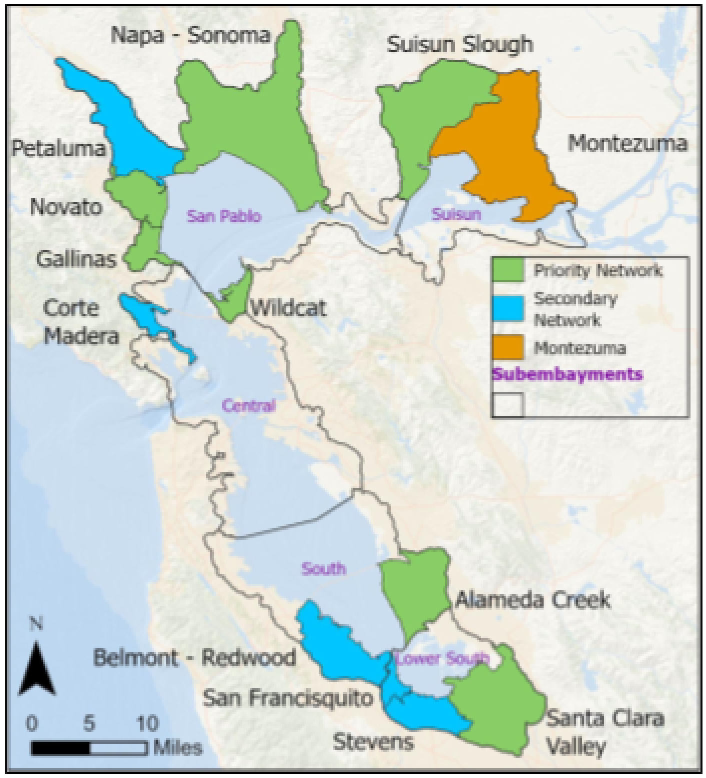

Figure 1. Map of the Operational Landscape Units, Subembayments and WRMP priority networks.

The SFE is the largest enclosed estuary in the western United States, ranging from the upper estuary (Suisun Marsh, Suisun Bay, and the Delta) that receives freshwater inputs from the watershed of the Sacramento River and San Joaquin River, to the lower estuary, which experiences relatively greater marine influence. The overarching goals of the WRMP are to (1) understand how landscape-scale drivers such as climate change are affecting these ecosystems across space and time, (2) support decision-making informed by the best available science, and (3) facilitate improved coordination of the monitoring required by environmental regulatory (permitting and habitat/species recovery) processes. The WRMP focuses on the monitoring of brackish and saline wetland habitats throughout the SFE, including those in five regions delineated within the WRMP: Suisun Bay, San Pablo Bay, and Central, South, and Lower South San Francisco Bay (Figure 1).

The Technical Advisory Committee (TAC) of the SFE WRMP provides scientific and technological advice to the Steering Committee (SC) of the WRMP. The purpose of this document is to recommend Standard Operating Procedures (SOPs) for monitoring the status and trends of tidal wetland vegetation over time through remote sensing of dominant plant alliances, site-specific vegetation cover, and photo-points. These approaches have been selected by the TAC and its Vegetation Workgroup based on historical experience, conceptual and empirical models, peer-reviewed literature, and/or consensus-based professional judgment regarding their importance for capturing relevant vegetation dynamics and for answering the WRMP Management Questions outlined in the WRMP Program Plan (WRMP, 2020). These SOPs will be referenced by the WRMP in its plan for initial WRMP monitoring implementation (expected in December 2023) that will propose which Level 1, 2, and 3 indicators[1] should be monitored (and, in the case of historical data, synthesized).

While different monitoring elements of the WRMP are outlined individually in separate SOPs, they are interrelated and will be integrated in the WRMP Monitoring Plan. For instance, field-based monitoring of vegetation should be co-located with hydrogeomorphic monitoring for indicators such as elevation, salinity, and tidal inundation. In this way, the trends and patterns seen in vegetative cover and species composition over time can be correlated with important abiotic factors to improve understanding of and in some cases model the regional factors driving vegetation change. Similarly, field-based monitoring can be coordinated with regional vegetation and habitat mapping efforts in order to validate remote-sensed products.

1. Vegetation Monitoring Background

Vegetation is a foundational element in coastal wetland habitats including emergent marshes (the dominant vegetated tidal wetland type in the estuary) and scrub-shrub tidal wetlands. Tidal marshes are biogenic habitats, formed by the plant species that are able to colonize the harsh physical conditions of intertidal mudflats and that have cascading effects and feedbacks on the physical and biological environment around them. Vegetation in emergent marshes is affected by substrate type and species responses to inundation and salinity regime (Moffett et al., 2010; Pennings et al., 2005; Silvestri et al., 2005). Understanding and tracking change in plant communities is therefore critical to understanding the physical and biological characteristics of tidal wetlands at a regional scale. Furthermore, the vegetation within these habitats links crucial physical processes with dependent wildlife, playing a pivotal role in conserving many sensitive and protected wildlife species.

Measuring and tracking vegetation is a key component of wetlands monitoring programs nationally; a local example is the San Francisco Bay National Estuarine Research Reserve (SF Bay NERR). Until recently, vegetation has been most commonly monitored in the field at the site scale, but recent advances in remote sensing techniques enable us to track changing vegetation alliance distributions at large spatial scales. This approach is particularly relevant to region-wide monitoring programs such as the WRMP. Remote sensing enables tracking large patterns in dominant vegetation distribution and changes over time. Pairing this regional coverage of vegetation classes with site-level monitoring of vegetation cover allows additional tracking of species composition and diversity within vegetation classes while validating and calibrating remotely sensed data.

[1] The WRMP science framework is based on the Wetland and Riparian Area Monitoring Plan (WRAMP) framework established by the California Water Quality Monitoring Council, which describes how to integrate Level 1 (remote sensing), Level 2 (qualitative field assessment), and Level 3 (quantitative field assessment) data.

1.1. Vegetation Monitoring for the WRMP

The SFE spans a vast region and is one of the largest estuaries on the west coast of North America (Mount & Kimmerer, 2022). Within the initial geographic focus of the WRMP (Fig. 1), which encompasses five sub-embayments downriver of the Sacramento-San Joaquin Delta, an estimated 53,000 acres of tidal marsh exist, including 7,700 acres of wetlands restored since 2009 (Goals Project, 2015). Numerous additional restoration projects are planned for the region in the coming years. Vegetation monitoring of restoration projects is almost always conducted at a site-scale; however, this monitoring rarely follows projects long-term nor is it necessarily indicative of regional trends in vegetation parameters (Taddeo & Dronova, 2019). One notable exception is the South Bay Salt Pond Restoration Project that employed a landscape-scale approach to vegetation monitoring, using remote sensing to map vegetation alliances and change over time within the Lower South Bay and part of the South Bay (Fulfrost, 2021). As climate change affects drivers such as sea-level rise (SLR), ocean warming, storm events, and weather patterns in estuaries, it is important to track changes in vegetation patterns as well as in restoration projects to improve understanding and management of wetlands at this larger, regional scale.

The WRMP science framework is built around a sequence of Guiding Questions and associated Management Questions, which have been approved by the Steering Committee and are described at length in the WRMP Program Plan (WRMP, 2020). Vegetation monitoring for the WRMP aims to address the Program's Guiding Question 1: "Where are the region's tidal marsh ecosystems, including tidal marsh restoration projects, and what net changes in ecosystem area and condition are occurring?" and the resulting Management Question 1A: "What is the distribution, abundance, diversity, and condition of tidal marsh ecosystems, and how are they changing over time?" To answer the Management and Guiding Questions, there are more specific Monitoring Questions and indicators found within the Master Matrix (WRMP, 2020, app. A2). The Vegetation Workgroup of the WRMP refined the Monitoring Questions related to vegetation and the resulting indicators (in bold) leading to the following five Monitoring Questions:

- What is the current distribution, extent, and diversity of dominant vegetation in the estuary's tidal wetlands?
  - **Map of wetland vegetation alliances**
- How is the spatial extent and distribution of dominant vegetation communities changing over time, particularly along the primary and secondary salinity gradients of the estuary?
  - **Vegetation alliance distribution over time**
- How does vegetation cover and composition at restoration Project Sites develop and compare to Benchmark and Reference sites along key hydrogeomorphic gradients such as inundation/elevation and salinity?
  - **Percent cover of vegetation across elevational gradients in Project, Reference and Benchmark sites**
- How does site-specific vegetation cover and composition at Benchmark and Reference Sites relate to environmental shifts due to climate change such as sea-level rise and changes in salinity?

    - **Percent cover and composition of vegetation across transition zones in Benchmark and Reference sites**
- What is the percent cover of non-native plant species within specific sites and regionally and how is it changing over time?
    - **Change in percent cover and distribution of invasive plant species**

The objective of this SOP is to monitor changes in tidal marsh vegetation across a wide region, encompassing diverse marsh types. This SOP proposes a set of methods to document large-scale vegetation patterns using remote sensing, field-based surveys, photo-points, and special studies to establish a comprehensive understanding of the drivers influencing wetland vegetation and to identify finer-scale trends.

This SOP is designed to complement other WRMP SOPs for hydrogeomorphic (HGM) monitoring, habitat mapping, and the California Rapid Assessment Method (CRAM) for perennial estuarine wetlands. All of these SOPs are designed to leverage data from legacy/existing monitoring efforts as well as new data collected through the WRMP. The HGM SOPs (WRMP, in-progress, expected by December 2023) address monitoring of inundation, elevation, salinity, suspended sediment concentrations, and related indicators that serve as primary physical drivers of the distribution and composition of tidal wetland vegetation communities. This SOP is designed such that HGM and vegetation indicators can be co-located (e.g. elevation and vegetation transects) and/or correlated and synthesized across multiple scales of space and time based on prior and current observations, conceptual and empirical models, and best professional judgment. The habitat mapping SOP (also known as the Geospatial SOP for Indicators 1 and 3, WRMP, 2022) and Level 1 components of this Vegetation SOP are designed to utilize the same remote sensing inputs, to reduce costs and support concurrent analyses of habitat and vegetation change over time. CRAM has a clearly defined protocol that includes rapid vegetation assessment, focusing on ecological conditions of relevant wetland characteristics relative to an internal reference standard, and can be used to identify areas where more in-depth vegetation monitoring may be beneficial. This SOP also maintains consistency with methods from other long-term monitoring programs such as those of the National Estuarine Research Reserve System (NERRS) and the National Parks and Long Term Ecological Research network. The WRMP Monitoring Plan (WRMP, in-progress, expected December 2023) will provide additional detail about how legacy/existing and new data describing different WRMP vegetation, hydrogeomorphic, and habitat indicators will be collected, synthesized, interpreted, and communicated.

While understanding non-native plant species dynamics is of interest to the WRMP and can be captured in site-scale monitoring or detection of species such as *Lepidium latifolium* via remote sensing, the Workgroup determined that targeted non-native plant surveys are best monitored by existing efforts such as the Invasive Spartina Project (ISP). The WRMP will coordinate with these efforts.

In summary, the vegetation workgroup of the WRMP recommends an approach to monitoring tidal wetland vegetation across the region that includes:

- Photo-point monitoring at permanent locations to locally track changes in vegetation and landscape features and as part of remote sensing field validation,
- Remote sensing imagery analysis to map the number and distribution of vegetation alliances,
- Field surveys of vegetation that quantify percent cover, species richness, and frequency of plant species at the site level (and provides additional calibration data for remote sensing imagery), and
- A field-based special study to evaluate changes in plant communities at marsh ecotone boundaries of Benchmark Sites as a leading indicator for regional change due to climate change.

1.2. SOP Development:

A working group of regional vegetation experts and stakeholders met to develop criteria to evaluate potential vegetation metrics and monitoring methods needed to address monitoring questions of interest to the WRMP, as detailed in the Program Plan (WRMP, 2020). They emphasized the need to apply methods at different spatial scales across the SFE to track regional and site-specific changes in marshes of varying salinity, age, provenance, and management history (Benchmark, Reference, and Project Sites). The working group prioritized photo-points, remote sensing for mapping vegetation alliances, and field monitoring for vegetation percent cover at priority WRMP Network sites. They emphasized tracking leading indicators of change and identified secondary metrics for potential use. Methods should be applied at various spatial scales, coordinating with other WRMP efforts and leveraging historical data. Alignment with regulatory requirements in restoration projects for comparison and integration was also highlighted. The development of the Vegetation Monitoring SOP benefited from extensive written contributions from the workgroup members, and comments from the TAC.

1.3. Geographic Focus and Scope

This SOP is designed to be implemented across a regional scale and within sites that vary in their history of human impact and restoration. The WRMP Priority Monitoring Site Memo (WRMP, 2023) identifies six priority site networks that span the 5 sub-embayments of the SFE (Suisun, North Bay, Central Bay, South Bay and Lower South Bay) where historical monitoring data can be synthesized and where new monitoring can be focused (Figure 1). Within each network, marshes that vary in their age and human intervention are identified including Benchmark Sites (relict, ancient marshes), Reference Sites (older restoration projects and centennial wetlands, fringing marshes that accreted sediment since the 19th Century), and Project Sites (recent restoration projects that reflect a variety of restoration approaches). This SOP outlines vegetation monitoring protocols that can be applied to sites both within and outside of the Priority Monitoring Site Network.

1.4. Coastal Marsh Vegetation Ecology to Inform Monitoring

Coastal marshes are defined by annual and perennial emergent vascular plant species typically less than a few meters in height (Cowardin et al., 1979). Tidal wetland plants are adapted to tolerating the abiotic stresses of intertidal environments, including salinity stress, waterlogging stress and toxic compounds such as hydrogen sulfides that accumulate in anoxic soils. Species distribution is determined by plant tolerance to abiotic stressors and biotic interactions with other vegetation (Bertness & Hacker, 1994). Zonation often occurs along elevation gradients due to changes in tidal inundation regime and other physical factors (Bertness, 1991; Janousek et al., 2019; Moffett et al., 2010). More diffuse zonation patterns occur across estuarine salinity gradients (Crain et al., 2004; Graham-Bruno et al., 2023; Vasey et al., 2012) and less saline tidal wetlands are generally more diverse (Janousek & Folger, 2014; Vasey et al., 2012; Watson & Byrne, 2009). To fully quantify estuarine vegetation at the regional scale, species distribution patterns across intertidal elevational gradients within a wetland and across estuarine salinity gradients that occur from salt to brackish and tidal fresh-water must be considered. Field-based sampling at the site scale should incorporate gradient-directed transects (gradsects) to sample all dominant plant zones and diversity across these gradients (Parker et al., 2011).

Shifts in dominant marsh communities have been documented due to a number of natural and anthropogenic stressors such as changes to tidal hydrology (Thorne et al., 2018), consumer outbreaks (Handa et al., 2002), eutrophication (Valiela et al., 2023), and warming (Gedan & Bertness, 2009). Anticipated shifts in dominant plant communities in the SFE due to drivers of interest to the WRMP (e.g., SLR, changes in sedimentation, and extreme weather) will likely occur along the dominant environmental gradients described above and therefore, long-term vegetation sampling should be designed with these potential changes in mind (Raposa et al., 2017). For example, relative SLR will result in longer inundation periods for intertidal plant communities at a specific location, and species may migrate up the intertidal gradient, decline in productivity, or decrease in abundance, unless marsh elevation keeps pace with SLR (Janousek et al., 2016; Parker & Boyer, 2019; Schile et al., 2017). Within sites, boundaries between distinct vegetation zones (such as the boundary between *Salicornia* and *Spartina*-dominated areas in more saline marshes) and the high marsh-terrestrial boundary may be places with major vegetation shifts (Mahall & Park 1976, Callaway et al. 2007, Grewell et al. 2014). Similarly, SLR is expected to result in salinity intrusion farther inland in the SFE (Cloern et al., 2011), so monitoring wetland vegetation in brackish and low-salinity marshes can indicate if shifts upriver (e.g. from brackish to salt) are occurring.

Monitoring design can target anticipated vegetation change in the estuary in the coming decades due to climate change, human stressors, and restoration efforts. These anticipated changes include:

- Vegetation drowning or migration inland as SLR and reduced sedimentation increase tidal inundation
- Vegetation stress or dieoff due to prolonged drought or flooding
- Vegetation migration up-river as drought and SLR lead to increased salinity or salt water intrusion of existing brackish and tidal freshwater marshes
- Vegetation expansion locally due to marsh restoration or enhancement efforts
- Shifts in marsh dominants due to invasive species
- Changes in vegetation dominance due to shifts involving extreme weather
- Loss of vegetation seaward due to marsh edge erosion

1.5. Invasive Species Ecology

Invasive plant species of concern in the SFE include invasive *Spartina* (*Spartina alterniflora* and its hybrids) (Daehler & Strong, 1997). These invasives can occupy lower tidal elevations, transforming mudflats into marshes and displacing the native *Spartina foliosa*. Extensive effort has been made to eradicate these invasives by the Invasive Spartina Project (ISP). Spectral imagery does not allow differentiation of *Spartina* species, so tracking of invasive *Spartina* must be field-based and is currently tracked throughout the SFE by the ISP.

Additional invasive species of concern include perennial pepperweed (*Lepidium latifolium*) and several species of non-native sea lavender (*Limonium spp)*. Perennial pepperweed is a concern particularly in brackish wetlands where it forms dense patches and can be easily recognized through aerial imagery (Andrew & Ustin, 2006; Fulfrost, 2021). Algerian sea lavender (*Limonium ramosissimum*) and European sea lavender (*L. duriscul*um) are problematic in hypersaline habitats near the upland/wetland ecotone and should be mapped when the opportunity arises in the field (Archbald & Boyer, 2014). Oppositeleaf Russian thistle (*Salsola soda*) native to southern Europe is of concern in brackish to saline wetlands, particularly diked marshes and higher-elevation fringes of tidal habitats (Grewell et al., 2007; Grossinger et al., 1998). Brass buttons (*Cotula coronopifolia*) and spearscale (*Atriplex prostrata*) are examples of non-native species that have naturalized in the SF Estuary and are not of concern as “invasive.”

1.6. Rare Species

There are a number of rare species within the SFE, especially in the Suisun Subregion (Graham-Bruno et al., 2023; Vasey et al., 2012) and rare species have been found to play vital roles in ecological processes that are not reproduced by common species (Leitão et al., 2016; Zedler et al., 2001). These rare species are often found within specialized habitats that host other unusual species that are not formally listed but nonetheless represent important ecotypes found within tidal wetland mosaics (Vasey & Baye, 2018). Special status species (rare species) identified in the California Natural Diversity Database (CNDDB) should be recorded and noted when encountered in field-based percent cover surveys. Additionally, as these rare ecotypes are identified, these field observations should be noted for future analysis. Further assessment may occur as resources permit.

2. Monitoring Vegetation Across Multiple Scales

2.1. Rationale and key considerations

Monitoring wetland vegetation at the regional scale differs from site-scale monitoring in many ways including breadth, resolution, and outcomes. The goals of a regional monitoring protocol are to track vegetation patterns and trends that may be the result of large-scale drivers. Regional monitoring must balance time and resources needed with the value of data acquired. For this reason, the WRMP Vegetation Workgroup advises a multiple component approach to monitoring that focuses first on indicators deemed essential to a regional monitoring program, and outlines additional indicators that would be important to track should resources allow. The different components can feed into each other. For example, the photo documentation and/or field-based sampling can calibrate remote sensing monitoring and the remote sensing monitoring can provide information on estuary-wide trends in vegetation and provide information on where future special study should occur. Furthermore, the field monitoring is useful in identifying early indicators of impacts of climate change and to evaluate finer-scale development of vegetation at Project sites that can be compared with vegetation patterns at Benchmark and Reference sites.

2.2. Important Monitoring Considerations

Key WRMP questions relevant to vegetation monitoring concern current distribution, extent, and diversity of dominant alliances and associations in the SFE, and the rates of change in such plant assemblages over time along the estuary's salinity gradients and more specifically at Benchmark, Reference and Project sites. Changes in tidal inundation, salinity, and marsh elevation, as well as plant invasions are expected to affect sizes, locations, and species composition of landscape patches, i.e., distinct spatial aggregations of such alliances that can be mapped with remote sensing. Robust detection of such changes while minimizing the risk of mapping error and false change inference relies on several conditions that need to be considered by monitoring strategies:

- **Monitoring vegetation change should involve both field surveys and remote sensing at each iteration as a "portfolio".** Remote sensing imagery is key for contiguous, spatially explicit mapping of vegetation patches and identification of dominant communities. However, a minimum number of vegetation field plots are essential for training and validation of such mapping efforts particularly when remote sensing data are not consistent among observation periods due to changes in image source and specification, wetland conditions and weather during observations, and other factors. Additional field surveys (transects and/or photo-points) not used as training/validation may also provide crucial information on specific ecological indicators of change that are not easily detectable with remote sensing, such as presence and percent cover of subdominant species. As such, field surveys may indicate shifts in percent cover of some major species that may become directional over time (e.g., in response to changes in salinity or inundation) while not yet substantially changing the mapped identity of the corresponding community (association) or spatial boundaries of the latter.

- **A baseline assessment of current dominant vegetation is necessary to understand the magnitude, nature, and direction of detected vegetation changes.** The key goal of the baseline assessment is to provide a record of current conditions against which the next or previous iterations can be compared. This can be done through field based surveys, such as photo-points and transects, or remote sensing.

- **Detecting change in a meaningful way (i.e., change in response to major drivers such as climate change) requires strategies to separate signals of change from short-term natural variation.** The dynamic and heterogeneous nature of tidal wetlands creates **a particular risk of detecting "false" changes** (e.g., mistaking short-term interannual variability in vegetation distribution of percent cover for long-term change). From a remote sensing perspective, image differences in resolution and timing of acquisition , characteristics of the wetland surface itself, will add variability to mapping results even when there is no substantial "true" change on the ground. Planning of the mapping and data analysis should incorporate strategies to minimize such data analysis risks when making conclusions about wetland change. Statistical techniques should also be employed to help detect changes and how they relate to variables such as climate, weather and hydrology. Field validation will improve confidence in detecting meaningful change.

- **Vegetation monitoring at a regional scale may be constrained by cost and resources so attention must be given to acquiring the best monitoring data that is also feasible and manageable**. With this objective in mind, the integration of field data across multiple sites should be considered to enhance monitoring outcomes using remote sensing while optimizing the extent and cost of field surveys. This can be achieved by:
    - Keeping the set of field-assessed variables to the necessary minimum
    - Reducing the scope of sampling at individual sites for the purpose of remote sensing validation
    - Choosing a less costly field sampling method (e.g. photo-points and or use of Unoccupied Aerial Vehicles (UAV/drones) over transects) that should allow for an easier replication in time and space

3. <u>Methodology</u>

This SOP includes four key monitoring components: photo-points, remote sensing monitoring, site-based field monitoring, and a special study targeting vegetation change in transition zones as a leading indicator of rapid climate change. Additional vegetation parameters that can be valuable to monitor (e.g. above and belowground biomass, plant heights, and phenology) could be added or included as special studies in the future if resources allow.

3.1. Photo-Points

Photo-point monitoring is an easy and cost effective way to track changes in tidal wetland vegetation, morphology, and overall ecosystem health over time. It is an especially useful approach in newly restored wetlands, where it can often help satisfy regulatory (permit) requirements for post-project monitoring and performance assessment. One of the key benefits of photo-point monitoring is its non-invasive nature, as it does not require extensive transects throughout a site, and can often be implemented from relatively more accessible locations such as upland edges and levee crests. Photo-point monitoring can be used at Project, Reference, and Benchmark sites but is particularly useful for documenting early stages of morphological and vegetative development at Project sites. While remote sensing provides a landscape-scale perspective, photo-points offer the advantage of detecting finer-scale changes that may not be discernible through remote sensing alone. In addition, field-based monitoring such as transects can be time consuming, costly, and not appropriate if the site is recently restored with no or little vegetation.

3.2. Recommended Photo-Point Monitoring Approach

We recommend using photo-point monitoring at all Project sites as the primary site-based monitoring tool until vegetation reaches a cover threshold of 25% (determined through methods such as remote sensing, see section 3.4) and transect monitoring (see section 3.6) can begin. In the absence of sufficient funding to support transect monitoring at sites with greater than 25% cover, we recommend photo-point monitoring at all sites to track vegetation and geomorphic change over time and validate remote sensing images. When photo-point monitoring is first initiated and/or as vegetation develops at a Project site, dominant, subdominant, invasive and rare species should be individually photographed, identified in the field and included in photo archives for reference as voucher specimens.

3.2.1. Location

Photo-point station locations should be distributed throughout a site at key areas of interest, including but not limited to: breach locations, expected locations of accretion maxima, estuarine-terrestrial transition zones, the edges of tidal creeks, locations where upstream watersheds and/or other freshwater features discharge into a site, and related locations of expected geomorphic and vegetation change. A sufficient number of stations should be established to track changes across a site over time. Stations should clearly be marked on a map so they can easily be found on the ground. Location can either be marked with a permanent marker (such as a PVC pipe or stake), or navigated to using a GPS with high accuracy (centimeter accuracy). Photo stations should be permanent, and the direction of each photo taken at a given photo-point should be constant and determined with compass bearings. Some photo-points may lend themselves to the collection of photos in multiple directions, and/or each cardinal direction, at each sampling episode. If significant and noteworthy changes occur in new locations, additional permanent photo stations can be established to capture these developments.

3.2.2. Photography Technique

This SOP incorporates by reference the detailed photography techniques described in the US Forest Service Photo Point Monitoring Handbook (Hall, 2002) and an SOP for Photo-Documentation approved by the California State Water Resources Control Board's Surface Water Ambient Monitoring Program (CARCD, 2001). In summary, photographs should be taken with a digital camera using the same settings for each re-image. Photographers should ensure the chosen camera settings provide a deep depth of field to keep both foreground and background in sharp focus (small aperture or high f-stop), and set camera resolution to at least 20 megapixels (Cox et al., 2021). Photographers should utilize the Landscape mode (full frame on a 35 mm camera or 26 mm focal length on a cellphone), and hold the camera at eye level (5 feet above the ground surface). Photographers must use a compass to ensure that the orientation and angle of the photo is the same each time. They should select the most suitable shooting conditions for capturing accurate and high-quality images, and whenever possible, consider incorporating distinctive reference points, such as rocks, trees, fencelines, or prominent hills, to facilitate accurate replication of photos or scenes in future monitoring efforts. Photos should also minimize the amount of sky and place the horizon towards the top of the frame. It is beneficial to review previous photos in the field to ensure that sequential images cover the same area consistently.

In the future, photo-point monitoring could benefit from drone technology. Drones offer the advantage of capturing photos quickly while minimizing environmental disturbance, as they eliminate the need for manual site access. These unmanned aerial vehicles can be programmed to revisit specific locations, providing valuable data over time. However, it's worth noting that drone use is currently restricted from certain areas, such as within the National Estuarine Research Reserve sites like China Camp and Rush Ranch, and requires licensed operators. Drone use is not a recommended method for photo-point monitoring but this can change in the future with technology advancements, change in access restrictions, and more people having a license to fly a drone.

3.2.3. Timing and Frequency

To accurately capture changes in vegetation and geomorphology over time, and minimize the influence of tide stage on photo interpretation, photographs at photo-points should be taken during the same tide stage, preferably at low tide. Photographers should utilize predicted and observed tides from the National Oceanic and Atmospheric Administration (NOAA) to time their photographs as accurately as practicable. The time of each photograph should be recorded, and its tide level determined from the nearest tide gauge.

Wherever possible, photographs at photo-points should be captured immediately before and after a site is restored to tidal action, to establish a baseline for assessing change over time. Since Project sites often experience rapid change, photographs should be taken at photo-points least twice annually. Photographs should be taken during the peak growing season or in the fall, as close to the growing season as possible given access limitations. The second set of photographs should occur in the early spring so as to capture any geomorphic changes to the system due to winter rain events.

3.2.4. Photo management

Photos should be properly documented and organized to allow for easy access and analysis. Photo numbers must be recorded to indicate which photo corresponds to which photo-point, at which orientation. Photos should be organized in a structured folder system on a computer or related digital storage system, with clear and descriptive names for each folder. Files should have a standard naming convention and should include relevant details such as site name, date, photopoint ID, and cardinal direction of the photo. Photographers/data managers should utilize metadata tagging to embed essential information directly into the photo files. This can include details like camera settings, location coordinates, date, and even keywords describing the content of the photo. Metadata makes it easier to search and sort through the photo collection. Ideally, photos will be uploaded into a WRMP data visualization platform (yet to be developed) that will allow a user to click on a photopoint and observe an annotated time series of the photographs taken at a given location. Photo annotations should include key observations, the date/times of any management actions that may be relevant to conditions observed in the photos (e.g. after a breach, after vegetation management actions, etc.), and the bearing (in degrees) of the photograph

3.2.5. Analysis

Photos should be visually analyzed each year to assess geomorphic and vegetation change throughout each site. Spatial patterns of vegetation establishment and change should be noted, and should include which species are present in which locations (e.g. along tidal channels/berms, tidal flats, upland/terrestrial edges, etc.). Analysts should note significant changes such as the accretion of mudflats, the emergence of channels, other shifts in geomorphology, and the presence of any invasive species (e.g., plants with a “high” rating in the California Invasive Plant Council Inventory). Ultimately, the primary objective of this photo-point monitoring is to diligently document any new landscape changes, providing valuable insights into the evolving dynamics of the wetland ecosystem.

Figure 2. Map the WRMP geographic focus area and Operational Landscape Units.

(Data source:SFEI, Map Author: A. Thomsen)

3.3. Remote-Sensing and Mapping of Vegetation Alliances

Remotely sensed aerial or high-resolution satellite imagery can be used to map vegetation distribution at large spatial scales such as the WRMP geographic focus area (Figure 2). Remote-sensing can be efficient and less costly than field sampling a large area. Remote sensing can also be useful for creating a baseline map of vegetation alliances and associations at a regional scale and allow for repeat mapping to detect change over time. A regional map of vegetation distribution can also be used to look at changes at smaller scales such as sub-embayments and sites. Furthermore, remote sensing allows for quantification of trends at all sites regardless of accessibility.

3.3.1. Data Sources and Spatial resolution

Satellites with a long history such as the Landsat program provide important historical information, however they lack the spatial resolution (30 m) to see smaller changes. Newer satellite imagery such as the European Space Agency’s Sentinel 2a and 2b have higher spatial resolution (10 m) and their 5-day temporal resolution increases the chance of image collection at low tide. Commercially available satellite imagery provides higher spatial resolution, such as MAXAR (0.31 m) and Planet (3.1 m) but may substantially increase project costs. Aerial imagery from National Agriculture Imagery Program (NAIP) has high resolution (0.6 m in recent years and 1 m pre 2016) and is freely distributed. However, NAIP is flown once every 2-3 years and tides are not taken into consideration. This can lead to imagery being acquired during higher tide when wetlands are submerged. Future efforts may correspond with lower tides if flight operators are required by funders, but this has not previously happened.

Drones are another option for high spatial resolution imagery, particularly beneficial for sites that are hard to access or sensitive to disturbance. Drones can be flown on demand and the operator can ensure the flight is at low tide. The spatial resolution can also be high and is determined by the altitude of the drone flight. However, drones must be flown by a licensed operator, have restrictions on where and when they are allowed to fly, and can be expensive to acquire and maintain. Accurate spatial referencing of drone images requires having a set of fixed ground control points spread over the study area, the establishment and maintenance of which can be highly challenging in tidal wetland settings. The drone imagery also requires more image processing than NAIP or satellite images, and this burden increases for larger observation areas. Lastly, drones are not ideal for covering large areas since they have limited battery life and have regulatory restrictions beyond the line of sight.

3.3.2. Elevation

Many edaphic and hydrologic factors influence the distribution and abundance of plants along the elevational gradient of a tidal marsh. For this reason, a digital elevation model (DEM) is an important variable for vegetation classification. LiDAR remote sensing in particular provides high resolution elevation maps and can also help indicate vegetation structure. If possible, DEMs should be vegetation corrected using methods such as LEAN (Buffington et al., 2016, 2019). LiDAR derived elevation (last return data) can be artificially high in regions with dense vegetation since laser pulses cannot penetrate the dense canopy. In the future LiDAR sensors may improve, making it easier to get more accurate elevation estimates. Until then, one must consider making corrections to elevation models to account for dense vegetation. This is especially important in subregions such as the Suisun, where vegetation can be both dense and tall. For LEAN elevation corrections, plant greenness and in situ elevation survey data (e.g., by RTK-GNSS) are used as input variables to correct elevation and the correction model is site specific. In addition, depending on the LiDAR data, a normalized digital surface model (nDSM) can be created. The nDSM can provide vegetation height and is calculated by looking at the difference in the first return (in this case the top of plants) minus the wetland sediment surface (Weidner & Förstner, 1995).

3.3.3. Vegetation Alliance Categories

Mapping to vegetation alliances versus species or association specific maps within wetlands usually helps boost the accuracy of the maps. Vegetation does not generally grow in monocultures; rather there is often one dominant species present with a mix of subdominant vegetation. Such mixes can form unique spectral signatures at a given spatial scale (resolution) of remote sensing observations, which can make them easier to distinguish from the imagery products than individual species. The Manual of California Vegetation (MCV) defines vegetation alliances and associations within California and is used by vegetation mapping efforts such as HEMP and Pacific Veg Map (CNPS, 2023; Fulfrost, 2021). Vegetation alliances are higher-level classifications that group vegetation communities with similar dominant species and overall composition. An association is a more specific classification within an alliance, and represents a vegetation community that is distinguishable by its dominant plant species, growth form, and habitat characteristics. In most cases, it is preferable to map the vegetation to the alliance level. However, in limited cases mapping to association level may be necessary. The proposed approach involves mapping to the vegetation alliance (or key association) levels outlined in the MVC. A list of these is included in Appendix C. If necessary, additional alliances can be included or key associations can be added.

3.4. Recommended Remote Sensing Vegetation Mapping Approach

3.4.1. Data collection

Ideal data

Consistent with the Baylands Change Base Map, mapping vegetation alliances should ideally occur every five years. For sites that may experience rapid changes in vegetation, more frequent vegetation mapping accompanied by field surveys may be necessary. Using the same imagery as the Habitat Map for vegetation alliance mapping can reduce project costs, while also keeping data sources consistent across different types of mapping efforts.

The ideal remote sensing imagery (see the Data Sources and Spatial resolution section above) consists of high resolution (15 cm to 30 cm) aerial imagery with red, blue, green and near-infrared bands (4-band imagery). Flights are typically timed during low tide and around peak biomass in the summer to capture the growing season. Aerial imagery can also be collected to maximize the difference in vegetation signatures. This is useful in cases where vegetation of interest occurs less frequently such as *Grindelia stricta* along tidal channels. LiDar data used for vegetation alliance mapping should be consistent with LiDAR data used in the Baylands Change Basemap and should be timed near the time of aerial imagery flights. A digital elevation model (DEM) can be generated using the bare earth LiDAR product. Ideally, the DEM should be vegetation corrected using methods such as Buffington et al. (2016, 2019). This method consists of elevation corrections using field-based RTK-GPS and Normalized Difference Vegetation Index (NDVI). However, other methods such as minimum bin gridding and machine learning to correct the elevation can be considered (Schmid et al., 2011; Rosso et al., 2006).

Less costly methods

If funding to collect multispectral data is not available, then NAIP, which is collected every 2-3 years, has 30-60 cm spatial resolution, and is freely available is an option. Despite NAIP's limitations, as highlighted above (Section 3.1.1), it has higher resolution than other freely available satellite imagery making it more desirable for mapping finer-scale vegetation patterns. Use of other multispectral datasets in conjunction with NAIP might also prove beneficial. Satellite imagery such as Planet or Sentinel has high temporal resolution, therefore imagery collected during low tides and peak growing season can be targeted and can also be used to estimate phenology (i.e., seasonal variation in vegetation type-specific spectral signatures), which may help distinguish vegetation classes.

In addition, if new LiDAR data can not be acquired then either using the most recently available LiDAR DEMs or creating site specific DEMs using Real-time Kinematic-Global Navigation

Satellite System (RTK-GNSS) surveys can be used to interpolate into DEMs and do point to point comparisons. RTK-GNSS survey methods should follow methods proposed by the USGS (US Geological Survey, 2012). RTK-GNSS surveys would be far too time consuming to conduct intensively across the entire region, but this method can be used at smaller local scales, and can serve to validate and calibrate DEMs derived after correcting LiDAR data for vegetation (Buffington et al., 2016).

Ancillary data
Additional datasets can also be used to help with image classification. The Baylands Change Basemap can be beneficial in constraining vegetation classes, and should be considered as an input dataset. Furthermore, a time series of satellite images such as through Planet or Sentinel can help provide phenological information to support vegetation recognition from either such satellite imagery, or from single-date aerial data such as NAIP. Different vegetation alliances can have distinct phenological curves throughout a growing season, which can help better distinguish vegetation classes. Derivatives of the high resolution aerial or satellite images can also help with image classification. These can include: slope, aspect, Enhanced Vegetation Index, Normalized Water Index, and others.

Calibration data
These data are essential in providing training data for machine learning methods, encompassing field-collected information relevant to the desired vegetation classes intended for mapping using remote sensing. Calibration samples should be taken within each vegetation class and across the entire region being mapped. The field samples should also be collected around a similar time as the remote sensing data. Field crew should focus on collecting the following:

- Species present (richness)
- Percent Cover
- Cardinal photos
- Plot shape
- Plot size

Samples should be collected based on a modified relevé method (see Appendix A,CNPS, 2022), and use the associated Combined Vegetation Rapid Assessment and Relevé Field Form (Appendix B). Using the remote sensing data, the image can be segmented into polygons and the samples should be collected based on stratified random sampling of these polygons. Sample locations should be spatially distributed and have a sufficient sample size for each vegetation class. Pairing a sub-meter resolution GPS with ESRI's Collector App, field crews can navigate to sample locations and record vegetation information directly into the App. To determine the appropriate sample size, refer to (Congalton & Green, 2019). One should consider the practicality and accessibility of selecting sampling locations. Vegetation information from the Field Monitoring of Vegetation Percent Cover section can be used in calibration if there is no spatial autocorrelation. Vegetation plots along transects collected through the Field Monitoring of Vegetation Communities (described in section 3.3) can also be used as additional calibration points. To determine the appropriate sample size refer to Congalton and Green (2019).

Validation data
This is necessary for accuracy assessment of the vegetation alliance maps. Validation data should be collected using the Rapid Assessment/Relevé Protocol (CNPS, 2022). See Appendix A for the Relevé Protocol and Appendix B for the Combined Vegetation Rapid Assessment and Relevé Field Form. These methods have been used for the HEMP and Pacific VegMap mapping efforts. Validation locations should be chosen using a stratified random sampling approach. Sufficient samples within each alliance/association should be collected (30-50 samples per class is typical), and validation samples should be taken throughout the study area. Refer to Congalton and Green (2019) for more information on determining sample size and location.

3.4.2. Image Classification

There are many ways remote sensing data can be processed to generate classified vegetation alliance maps. The most common approaches include heads-up digitizing or semi-automatic image classification.

Heads-up digitizing involves manual tracing of vegetation classes using available multispectral imagery, and aerial photographs. Although used in some previous efforts (e.g., VegCamp), this approach is extremely labor-intensive, time-consuming, and difficult to generalize for repeated mapping protocols. Therefore, it should be ideally considered only as a last resort measure to refine automatically or semi-automatically developed maps in regions with notoriously low accuracy or high mapping uncertainty.
.
Semi-automated supervised classification involves collecting training data (field vegetation surveys) and using machine learning to establish relationships between the field collected vegetation types and remote sensing data, followed by an accuracy assessment. This approach is less labor intensive and more consistent than the heads-up digitizing approach, but can be combined with the latter if necessary, such as, for example, in HEMP and Pacific VegMap efforts.

Recommendations
- In this SOP, we recommend using a semi-automatic classification method with manual editing, if required. This approach is advantageous as it reduces labor intensity, allows for the production of highly accurate maps, and ensures long-term efficiency and replicability. Additionally, this method minimizes reliance on human expertise for class assignment and aligns with similar mapping efforts in the area (HEMP and Pacific VegMap).
- An object-based approach is recommended over a pixel-based classification method.

Justification
This recommendation is made based on the following considerations:
- As the name suggests, pixel classification uses remote sensing data to classify vegetation on a pixel by pixel basis. This method can lead to significant speckling, or

noise, within the classification or single pixels being classified differently than the majority of surrounding pixels. Speckling can be limited with filtering, however, it is difficult to know if the speckling is representative of the actual vegetation condition (e.g., spectral heterogeneity due to sparse coverage or flowering at the time of observation) or if it is an artifact (such as shadows or uneven flooding).

- The object-based classification method uses image segmentation to break areas up into regions with similar remote sensing signatures (aka segments, or “objects”) and classifies the segment into the most likely vegetation alliance based on the input training data.
- Image segmentation results in less speckling than the pixel based approach because spectral values of individual pixels become statistically integrated at the scale of the minimum mapping units, i.e. segmentation-generated objects.
- The object-based approach is used by Pacific VegMap and the Habitats Map, as well as multiple previous peer-review wetland mapping studies (e.g., reviewed by Dronova, 2015).
- Note: a benefit of the pixel based classification is that it allows for mapping of mixed pixels through fuzzy logic. This means that a pixel can be mapped with the probability of being within one vegetation alliance and the probability of it being within another alliance. However, fuzzy logic can also be used in the object-based approach (Jabari & Zhang, 2013).

With image segmentation, one must specify a minimum mapping unit. VegCamp, Habitats Map, and most of the Pacific VegMap, use 0.25 acres as minimum mapping units, meaning that segments or polygons will be no smaller than 0.25 acres. For wetland vegetation classification, Pacific VegMap uses areas as small as 600 ft^2. To maintain consistency, it is recommended to establish an initial minimum mapping unit of 0.25 acres. However, adjustments can be made if required to achieve higher accuracy levels. The shape of the minimum mapping unit just needs to be continuous, so theoretically it can be long and thin to follow channel margins, or it can oblong. If necessary, the minimum mapping unit can be set smaller, particularly if the aim is to map vegetation growing in smaller patches such as the *Grindelia stricta* Provisional Association.

Machine Learning

After the image is segmented, it is then fed into a supervised machine learning algorithm to classify the image. It should be noted that primitive segments produced by initial segmentation do not have to precisely trace the full outlines of vegetation patches. Rather, they are used as minimum mapping units to which machine learning classification assigns class identities in the next step. Once classification is finished, primitive objects can be merged in the final map according to their assigned vegetation categories (classes).

Supervised classification requires training samples, i.e., examples of known locations of the classes of interest, which can be used to generate their training signatures and attributes. Field collected data of known vegetation types is used to train the classification models (see section 3.4.1). While a variety of classification approaches have been proposed by remote sensing literature, earlier maximum likelihood-based approaches have shown persistent challenges due to reliance on specific statistical assumptions and/or requiring large sample sizes for robust performance. Supervised machine learning algorithms can overcome some of these challenges because they assign class labels to mapping units based on iterative learning from training samples which aims to minimize the error between classes assigned by the algorithm and true class identity of such samples. Some of the machine-learning algorithms also relax statistical assumptions that can be challenging to meet in wetland settings. For example, Support Vector Machine algorithms do not require large training sample sizes because they focus on the boundaries between classes in the data space rather than similarity to training sample class means as in traditional maximum-likelihood methods.

Recommendation

In this SOP we do not recommend relying on a specific single machine learning approach. Instead, employing a few different approaches and assessing their accuracies is advised to determine the one that achieves the highest level of accuracy. For example, Random Forest, Support Vector Machines, and Convolution Neural Networks are commonly used for vegetation classification and have shown success in previous vegetation mapping studies, including in wetland landscapes. Random Forest is a commonly used approach. Random Forest uses an ensemble learning method approach, where each tree in the forest trains a random subset of the input data. Within each tree, a class prediction is made. The final classification comes when you put all the trees together (creating a forest) and the dominant class within the forest is picked (Breiman, 2001). Support Vector Machines works by creating a hyperplane which separates the datasets into a defined number of classes. The machine learning process iterates through classifiers to maximize the distance between the classes (Meyer et al., 2018). Convolution Neural Networks consist of the user specifying vegetation classes at known areas (the input layer). Middle layers are generated to reach an output layer with minimum errors (Campos-Taberner et al., 2020). Because each of these methods requires specifying its own parameters and performing assessments of sensitivity of classification accuracy to those, methods should be written down in detail so they can be repeated in the future.

After classification using machine learning, manual edits can be made if necessary. Keeping manual edits to a minimum is recommended, although it may become necessary to utilize them to enhance image accuracy.

3.4.3. Accuracy Assessment

After the area is classified with vegetation alliance, accuracy assessment needs to be done. A subset of the field collected vegetation data can be used as validation data (see section 3.4).

Recommendation

It is advisable to aim for an overall mapping accuracy of 85% or higher, with a user's and producer's accuracy of at least 80% for each alliance. Accuracy assessment can be conducted based on the recommendation of Congalton and Green (2019). If accuracy assessment targets are prohibitively expensive, the target and methods used can be reassessed.

3.4.4. Other Remote Sensing-derived Metrics

One output from the machine learning process is a raster of uncertainty, this can be used to spatially assess **vegetation alliance uncertainty**. The uncertainty output can also be used to create a fuzzy logic field within the vegetation alliance layer. The fuzzy logic field would include the second most likely vegetation alliance modeled by the machine learning process.

Using the classified map of vegetation alliances and the remote sensing layers (such as a vegetation index layer) as input variables, other questions can be answered. **Vegetation alliance acreage** can be calculated to better understand the relative abundance of major vegetation types throughout the region and within each site, and their change over time. The occurrence or distribution of specific vegetation classes can be mapped, such as gumplant (*Grindelia stricta*) cover, which is a critical habitat for marsh birds and typically occurs in long, linear stands adjacent to channels or uplands. **Elevation distribution within vegetation alliances** can be calculated accurately by utilizing a vegetation-corrected DEM and tidal amplitude information. Using the map of classified vegetation alliances, the elevation ranges can be extracted within each of the alliance classes and give a better idea of how these alliances are distributed within the tidal frame.

Another metric is **unvegetated to vegetated area ratio** for a given spatial unit, which is often thought of as an indicator of marsh health in microtidal marshes (Ganju et al., 2017; Wasson et al., 2019). This will be more beneficial for benchmark sites or sites that are better established. Project sites, and other recently restored sites may be highly unvegetated but the sites are still establishing and vegetation cover is increasing. **Patch cover type heterogeneity** refers to a measure of diversity of mapped categories (e.g., vegetation alliances) in a given spatial unit (e.g., site parcel), and is often computed via metrics that take into account both the number of unique cover types and their relative area, such as Shannon-Wiener diversity index.

Finally, satellite imagery bands can be used to generate maps of a given **spectral vegetation index**, such as Enhanced Vegetation Index or Normalized Difference Vegetation Index. Some of these indices already exist as open-access satellite products (for example, from Landsat satellites). Such datasets can provide a snapshot of vegetation greenness within the region, and is a proxy for aboveground biomass, as well as a time series of greenness change over different months and years. For Project Sites, the change of a vegetation index over time can help distinguish colonization rates within the site and give a better estimate of how long it takes for vegetation to become established. It can also help show how long it takes for the rate of colonization to slow down, which indicates the site is starting to be more fully established. By contrast, it can also show when vegetation declines over time as can be the case when mature marshes experience rapid SLR, reduced sediment supply, or tectonic subsidence leading to marsh “drowning”.

3.4.5. Options for creating initial vegetation map

There is currently no comprehensive vegetation alliance map for the entire estuary. Partial maps exist thanks to HEMP, VegCamp and Pacific VegMap efforts. Each of these efforts have different methods and accuracy assessment (if any) within the tidal wetland areas, but they all provide an idea of the vegetation alliances found within the region. Combining these various vegetation maps can provide an idea of vegetation alliances throughout most of the Bay. The drawback to using the patchwork of available maps is the inconsistent time periods represented by the data, the fact that not all of the tidal wetland vegetation alliance maps have accuracy assessments, that some efforts are pixel based while others are object based classifications, and that some areas within the estuary are missing. However, this approach is the least costly, least time consuming and still provides a general idea of vegetation alliances within a large portion of the Bay.

Considerable field data were collected with each mapping effort, and additional vegetation surveys were conducted by groups such as CDFW. These data can potentially be obtained and used as calibration and validation to create a new Bay-wide vegetation alliance map using 2020 NAIP imageries and the methods recommended in this SOP. The field data needs to be collected around the same time as the remote sensing imagery. Doing a retrospective analysis can provide a comprehensive vegetation alliance map within the Bay and use similar methods that future mapping efforts can follow. However, the number of available field samples need to be sufficient and available for use. Some of the datasets may not be available outside of that mapping effort and the dates of field collection may not correspond well to the 2020 NAIP imagery. Furthermore, this effort will take more time and effort than stitching together already available vegetation alliance mapping efforts.

3.4.6. Remote Sensing Product Analysis

Recommended initial remote sensing derived products include an estuary-wide map of tidal wetland vegetation alliances. Over time, alliance maps should be reproduced (ideally every five years), at which point change in distribution and acreage of dominant vegetation alliances can be detected along key estuarine subgradients and calculated at OLU or estuary-wide scales.

3.5. Field Monitoring of Vegetation Communities

Field-based monitoring is essential to capture plant composition (percent species cover) and species richness within an individual wetland. Methods proposed here are consistent with other wetland monitoring programs, such as NERR Sentinel Site Monitoring. A consistent approach allows for comparison with other estuarine systems on the Pacific Coast and across the country. Field monitoring also can detect finer-scale changes than through remote sensing. Field-based monitoring may capture boundary shifts, rare species occurrence, vegetation stress, detection of subdominant and invasive species occurrence, and compositional changes.

The field-based methods described below are designed to yield a suite of primary and derived vegetation metrics that help address the two field-based questions and that support the remote sensing section of this SOP. Transect-based sampling is intended to be conducted at all appropriate Project, Reference, and Benchmark sites. It addresses both field-based questions by providing data that are representative at the site level. Special study sampling is more focused and addresses the second monitoring question by providing additional data on changes at transition zones.

Field monitoring questions:

How does vegetation cover and composition at restoration Project Sites develop and compare to Benchmark and Reference sites along key hydrogeomorphic gradients such as inundation/elevation and salinity?

How does site-specific vegetation cover and composition at Benchmark and Reference Sites relate to environmental shifts due to climate change such as sea-level rise and salinity?

3.6. Recommended Transect-Based Field Monitoring Approach

When restoration projects are newly constructed and in early stages of marsh development, Project Sites require unique monitoring approaches. These sites are sparsely vegetated, sensitive to disturbance and difficult to access. Once Project Sites have developed past a 25% vegetation cover threshold, they can be monitored using the transect-based field monitoring protocol outlined below. During this period, it is advised to utilize photo-point stations for monitoring purposes (described above).

The primary field-based approach for vegetation monitoring is the transect-based method, designed to address two key questions related to the field monitoring of vegetation. It should be conducted similarly at all Project, Reference, and Benchmark sites. It yields data that are representative at the site level which is important for comparing Project sites with Reference and Benchmark sites and for tracking change at the site level over time. The sampling approach is congruent with determining relationships between vegetation and abiotic drivers (and change in those drivers over time). The transect-based approach enables analyses to be conducted at the plot, transect, site and sub-regional scales as well.

The primary vegetation metric collected in each sampling plot is percent cover for each individual species present in the plot (or the lowest taxonomic resolution possible such as genus or family when a plant cannot be identified to the species level). If funding allows, we also recommend measuring the maximum canopy height within each quadrat. From the primary metric data collected in the field, the following derived metrics can be computed at the following scales for a single sampling period (and see Table 1):

- Mean (±SD) percent cover by species at the transect and site scale
- Total plant cover (±SD) of all species per site at the plot, transect, and site scale (total cover is a measure of canopy complexity)
- Mean (±SD) species richness at the plot and transect scale
- Frequency of occurrence of each species at the site scale
- Species composition
- Estimates of total plant species richness at the site scale (by species accumulation curves or Chao metrics)

Additionally, the following derived metrics can be computed at the following scales when data are combined for two or more sampling periods:

- Change in percent cover at the transect, site, or sub-region scale for all plant species

- Change in frequency of occurrence at the site or sub-region scale for all species
- Change in species richness at the plot, transect, site, or sub-region scale

3.6.1. Data Collection

Initial layout of transects

The layout of transects within each study site is based on the NERR (National Estuarine Research Reserve) SWMP (Systemwide Wetland Monitoring Procedure) protocol (Moore et al., 2023). Field-based monitoring should consist of a set of 3-9 (depending on the geometric shape of the site) roughly parallel permanent transects per site, oriented perpendicular to the upland edge of a site. Transects should extend from the upland edge (at least 20 cm above the elevation of expected highest annual tide at the site) to the bay-ward edge of a site and should be marked at each end by permanent markers (e.g. PVC post) as well as precise geographic location and elevation by RTK-GNSS measurements. This layout helps capture samples across the elevation gradient present at a site. At the time of transect establishment, each site should be divided into three approximately equal areas as illustrated in Figure 3. The length of the upland edge of each of the three areas is mapped and determined in GIS and 1-3 random points are chosen within each segment as the starting location of each transect. Longer sites may be suitable for three transects (1 per segment), while narrow sites such as fringing bay marshes may be better sampled with 6 or 9 transects (2 or 3 per segment). Transects are numbered from left to right from an upland perspective. Transects should be spaced at least 20 m apart from each other to obtain adequate interspersion of transects across a site (Neckles et al., 2002). If a random point is too close to a transect previously established, a new point should be chosen with the next random number.

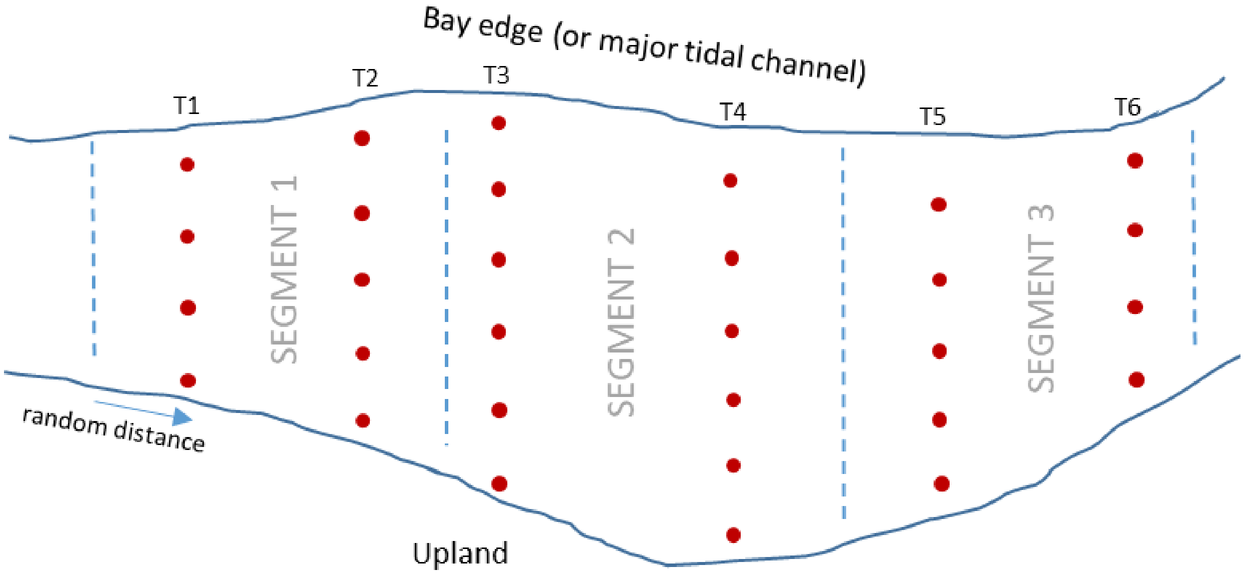

Figure 3. Layout of vegetation permanent transects and plots at a typical monitoring site, divided into three equidistant segments. Transect starting points are randomly selected at the upland

edge (1-3 per segment depending on how narrow or wide the site is) and extend perpendicular to the upland and bay (or tidal channel edge). Plots are evenly spaced along the transects.

Initial layout and establishment of plots

A minimum of 30 plots should be sampled per site. Plots are evenly spaced along each transect (Neckles et al., 2002), starting 10 m bayward of the upland marker post. To determine the spacing interval (which is unique to each site based on site area), the total length of all 3-9 transects is computed in GIS and divided by 35 (a minimum of 30 plots per site is desired, but 35 is used in case some points fall on channels and are skipped.

Plots are 1.0 m^2 in size. Along each transect, each plot should be permanently marked at each of its four corners with PVC stakes that extend about 10-20 cm above the maximum canopy height (e.g., for succulent-dominated wetlands), or are at least 0.5 m tall in areas with tall vegetation (e.g., tules). One or more corners of each plot may additionally be marked with bright flagging tape in areas of tall vegetation where plots would be difficult to see. The horizontal and vertical position of the center of each plot is recorded at the time of establishment with RTK-GNSS. Plots should only be located on relatively level wetland areas (e.g., the “marsh plain”) and tidal channels are avoided. Due to the planned even spacing of plots, if a plot would otherwise fall in a tidal channel, it is moved to the nearest spot of level vegetated wetland but at least 1 m from the channel edge.

Timing of plot sampling

Plots should be sampled near the height of the growing season (peak biomass) if possible (June-September). Some sites may only be available for sampling starting September 1st due to access restrictions for protected wetland species.. Data should be collected at all sites every 3-5 years using the permanent transects and the same methods. Project sites may be sampled more frequently (every 1-2 years), especially in the first 5-8 years after restoration when vegetation communities may be changing rapidly. At project sites, there may be a minimum threshold of vegetation cover at the site level, before sampling begins. For example, field-based vegetation sampling at Hamilton Wetlands was not required until vegetation reached 5%.

Collecting data at each plot

At the time of sampling, the quadrat is placed on the vegetation canopy and a photograph of the plot is taken from above (orthogonal to the ground surface) for archival and QA purposes. Photos should be properly documented and organized to allow for easy access and analysis. Within each 1.0 m^2 plot, field teams determine visual estimates of percent cover of all species located in the plot (whether or not the species is actually rooted inside the plot). Values can be recorded to the nearest 5-10% for cover ranging from 10-100% and the nearest 1-2% for cover ranging from 0-10%. Very minimal, trace occurrence of a species should be recorded as 0.5%. Estimating cover when a species is present in the 35-65% range, or if it is scattered throughout the plot in mixture with other species, can be a little challenging. However, estimates can be improved by mentally dividing the square quadrats into halves or quarters or tenths. Lines on the quadrat allow workers to mentally divide the quadrat space into helpful fractions. Additionally, field workers can take pictorial guides into the field to help them determine cover estimates. Recording data as coarse cover classes is not recommended, because they are not

as precise as continuous scale data and in analyses they either need to be treated as categorical data, or their midpoint used as continuous data.
All species within each plot should be recorded, including understory species and species that may be rooted outside the plot but that have stems or leaves within the area encompassed plot. This is important for determining species richness. First, a field worker records the percent cover of bare ground (ground visible from above that has no plant cover). Next the percent cover of each plant species is determined and recorded independently; vegetation canopies may need to be gently moved by hand to find all species since some grow as smaller understory species. If two workers are present, they should each independently record percent cover of all species present. These two observation sets can then be averaged for each plot and this will reduce some error in cover due to person-to-person variability. Due to canopy layering, the total cover of all plant species will often exceed 100%. If a plant cannot be identified to the species level, the worker should record its cover at the lowest taxonomic group possible (e.g., genus or family), and collect photographs or physical voucher specimens for later identification by a colleague.

All plant matter that is attached should be counted in the percent cover of a species, including yellowing or browning material. The degree of senescence should be noted on the datasheet. Any unattached plant matter, including wood, should be counted as a separate category (wrack) since it may or may not have originated in the plot and may only be temporarily present within the plot until it is moved by the tides. Macroalgal cover can also be noted as a separate category, either all taxa lumped, or split by major algal group including green algae such as *Ulva* spp. (Chlorophyta), brown macroalgae (Phaeophyceae), red algae (Rhodophyta), and the yellow-green alga, *Vaucheria* (Tribophyceae). Macroalgae may be unattached or attached to plant stems, shell fragments, or small pebbles.

If funding allows, maximum vegetation height of the dominant plant per plot should also be measured. Within each quadrat, the 4 individual plants or plant parts with the tallest biomass should be recorded. Height should be measured at the tallest portion of the plant when stretched out.

At the same time that plots are surveyed for vegetation, workers may also remeasure the elevation of the center of the plot by RTK-GNSS, assess groundwater or soil conditions, and measure pore water salinity or other environmental drivers consistent with other SOPs under the WRMP.

3.6.2. Data management after the field

Physical (or digital) field sheets should be scanned by field workers after data collection to make sure they are complete, that values are legible, and that there are no outstanding questions about the data. Soon after field work, photographs and/or specimens of unknown plants should be sent to colleagues for identification. Physical field-sheets should be entered into digital spreadsheets or tables (e.g., Excel, Access, or other). Digital data should be QA/QC checked and archived. We recommend data validation limits (e.g., in digital spreadsheets or databases) to minimize entry errors and out-of-bound values. We also recommend the plotting of all raw data to identify and correct outliers (with data validation limits in place) and examination of known relationships to control for data integrity and accuracy. All QA/QC procedures, outcomes, and adjustments should be documented in a metadata file and respective tables associated with the project. Final, clean data sets, including metadata and QAQC history, should be uploaded to the WRMP Data Submission Portal annually for long-term monitoring or at the completion of a short-term project window, or as is otherwise specified by WRMP guidelines.

Photo numbers must be recorded to indicate which photo corresponds to each quadrat and should be organized in a structured folder system on a computer or related digital storage system, with clear and descriptive names for each folder. Files should have a standard naming convention and should include relevant details such as site name, date, and quadrat ID. Photographers/data managers should utilize metadata tagging to embed essential information directly into the photo files. This can include details like camera settings, location coordinates, date, and even keywords describing the content of the photo. Metadata makes it easier to search and sort through the photo collection.

3.6.3. Transect-Based Data Analysis

From the primary metric (percent cover), secondary metrics can be computed as outlined in the table below. Using elevation data that accompanies the plots, the ~30 plots at a site can be stratified into discrete elevation zones after data collection if desired for more detailed analyses (e.g., differences in species composition between sites or sampling periods for a particular elevation zone can be analyzed).

Table 1. List of secondary metrics that can be determined from percent cover data in vegetation plots. The Chao class of site-level diversity metrics are described in Chiu et al. (2014).

Secondary metric	**Computed as**	**Scale(s)**
Mean (±SD) cover by species	Average cover of all species along a transect or at a site or sub-region	Transect, site, subregion
Total plant cover	Total cover of all species per plot	Plot, transect, site, subregion
Mean (±SD) species richness	Count of all species present per plot, averaged for larger than plot scales	Plot, transect, site, subregion
Site level species richness	Species accumulation curves using occurrence (<0% cover) data; Chao class of metrics	Plot, subregion
Frequency of occurrence by species	Number of plots with the species present divided by all plots	Transect, site, subregion
Species composition	Ordination or other multivariate models	Site, subregion

3.7. Recommended Special Studies Field Monitoring Approach

Special studies of monitoring vegetation in the field complement routine monitoring by photo-points, remote sensing, and standard vegetation transects described previously. In this section we describe a special study designed to track vegetation shifts due to rapid climate change at Benchmark and Reference sites that specifically asks, **can shifts in the boundary between two different vegetation assemblages in transition zones provide a leading indicator of the trajectory of change due to sea-level rise and other factors?**

Rationale for Special Study

According to recent studies, the rate of relative SLR is likely to outpace previous predictions (Parker & Boyer, 2019; Siegert et al., 2020). The primary causes of increased SLR are melting land ice sheets and ocean water thermal expansion. A recent global study has indicated that the rate of ice sheet melting between 1992 – 2020 increased nearly four times (Otosaka et al., 2023). Increasing rates of SLR have already caused dramatic shifts in tidal marsh dominants in marshes along Long Island Sound (Raposa et al., 2017; Watson et al., 2016). Consequently, it is prudent to assume that rates of SLR in the SFE are likely to dramatically increase in coming decades.

It has long been recognized that small changes in duration of inundation and pore water salinity can have dramatic effects on the distribution of tidal marsh plants (Mahall & Park, 1976) creating a narrow boundary between, for example, low marsh plants such as *Spartina foliosa* and high marsh plants such as *Salicornia pacifica*. Wasson et al. (2013) took advantage of this fine-scale relationship to document a significant shift of tidal marsh vegetation at the upland boundary at the Elkhorn Slough tidal wetland over ten years. They essentially utilized a “gradsect” approach (Gillison & Brewer, 1985) to track this relatively rapid change over time. Scaling down gradsects to the boundary between channel margin vegetation and the marsh plain, Parker et al. (2011) demonstrated that short transects across this boundary dramatically increased the efficiency of assessing plant diversity in the marsh since the channel margin vegetation hosts a distinctive flora not well represented on the marsh plain; i.e., random sampling of the marsh as a whole typically misses the prominence of these specialized species. Recognizing that changes in the location of boundaries between different vegetation assemblages could provide important insights into the response of vegetation to climate change, Caddy-Retalic et al., (2017) initiated a “bioclimatic transect network” to focus on tracking vegetation shifts as a leading indicator of the effects of climate change.

For special studies sampling, a series of short transects will be established along the boundaries of distinct tidal marsh plant assemblages. This approach serves two main purposes: (1) it has the potential to offer early indications of the impact of factors like sea-level rise, extreme weather events, and rapid accretion or elevation loss on marsh species assemblages, and (2) it contributes to a more comprehensive quantification of tidal marsh plant diversity. These narrow and linear marginal plant assemblages play a significant role in the overall species richness of estuarine tidal wetlands. Further, these more restricted plant assemblages are also known to provide important wildlife habitat values in tidal wetlands (e.g., *Grindelia* provides habitat for breeding song sparrows). By obtaining early warning as to vegetation response to rapid climate change effects, this will enable the management community to initiate proactive steps to protect restoration projects and to evaluate their progress in the context of these more regional environmental drivers.

3.7.1. Focal monitoring areas

The special studies analysis is focused on providing a leading indicator of marsh change by detecting fine-scale shifts in transition zone vegetation and boundaries. Specifically, this includes change in cover/diversity at the transition zones and change in the location of the transition zone. Sampling assumes continuation of SLR over the next several decades and its potential acceleration to a level that exceeds current sedimentation and accretion rates (Thorne et al., 2018). This sampling is proposed only for benchmark/reference sites because they have established vegetation and will be sensitive to climate change in a way that can be monitored. This type of data is intended as an early warning system for managers, so that they have appropriate information to act in a timely manner at project sites. Monitoring three transition zones (low marsh and high marsh, Upland and high marsh, and channel margins and marsh plain transition zone) is proposed, with each zone offering potential indicators of wetland change (Thorne et al., 2018).

Low marsh and high marsh transition zone

The first location is the transition between low marsh and the marsh plain in more saline marshes, occurring approximately at local mean high water (MHW). Changes at this transition zone may indicate how tidal wetlands are adjusting to predicted sea-level increases. Using a salt marsh like China Camp as an example, a transect crossing the boundary between *Spartina foliosa* in the low marsh and *Salicornia pacifica* in the marsh plain will inform managers of the potential impact of increasing rates of SLR. If no substantial statistical change is found in the vegetation after reported increases in mean sea level from other sources, the initial interpretation would be that sedimentation is keeping up with SLR. If, for the transects, the cover of *Spartina foliosa* increases and the transition boundary shifts landward, then an interpretation is that sedimentation rates are insufficient to keep up with SLR. Another interpretation is there is land-ward erosion of the wetlands edge. This highlights the importance of monitoring wetland elevation in conjunction with vegetation which is covered in the Hydrogeomorphic SOP. Managers then have the opportunity to take management action at project sites as well as at reference or benchmark sites.

Upland habitats and high marsh transition zone

The second transition zone of monitoring interest is the transition between high marsh and non-tidal upland. With SLR, this boundary is expected to move upslope into the terrestrial zone, if possible. Or upland vegetation may disappear completely if upslope transition areas are not available. Changes will inform managers of the rate of SLR, or the possibility of changes in high marsh soil salinity and inundation. The vegetation at many transition zones is generally of higher diversity and species are patchily distributed. However, at various sites in the SFE, the upper transition zone can be vegetated by non-natives with lower diversity. Analyses may include combining percent cover of terrestrial species together and comparing this with the combined percent cover of wetland species together, thereby observing any movement of the transition zone boundary upslope as shifts in percent terrestrial vs percent wetland species. Shifts in the composition of wetland species also provides an additional insight, because the transition zone wetland species differ in sensitivity to salinity. Declines or increases in the more sensitive species may be linked to changes in salinity, elevation, or other marsh processes.

Channel margins and marsh plain transition zone
The third transition zone of interest is the plant communities along the margins of intertidal channels. In SFE salt marshes there is generally only one type of plant community along channel margins which has several species; in brackish tidal marshes there can be two or more distinct plant assemblages along channel margins adjacent to each other depending on the peak salinity and length of tidal inundation. These brackish marsh transitions generally fall along a salinity gradient, with lower salinity adjacent to the channel and salinity increasing with distance perpendicular to the channel. Similarly, there is also an inundation and drainage gradient with distance from channels. Changes in composition will further indicate shifts in salinity or inundation. For example, if the width of the zone remains constant (suggesting sufficient sedimentation), but the composition shifts, that could indicate increases or decreases in salinity or inundation sensitivity depending on the shifts in percent cover of species composition of the channel-side vegetation. Thus, this transition zone indicates the net impact of SLR and rates of sedimentation along channels, along with the impacts of salinity, increasing or decreasing, on this salinity/inundation sensitive vegetation.

3.7.2. Data Collection

Sampling should be conducted at a minimum of three Benchmark or Reference sites representing the Suisun Bay, the San Pablo Bay, and the South Bay; ideally these should be the same sites as the transect-based sample sites.

Five replicate belt transects will be established across the boundaries at each of the three transition zone types (15 total transects per marsh). Locations will randomly be chosen in GIS and modified in the field if there are access issues. For each transition zone location, identify the boundary transition area. Next, establish a beginning point for each belt transect within the zone expected to migrate or expand with SLR: in the low marsh for the low marsh/marsh plain transition zone, within the high marsh at the high marsh/upland transition zone, and adjacent to the channel, for the channel margin transition zone. The end point of the belt transect should extend into the neighboring zone to a location with an elevation 15-20 cm greater than the zone boundary. (At current rates of SLR the transect would have an approximate 20-25 year horizon.) Mark the beginning and ending points with a PVC pipe (Fig. 4). Use an RTK-GNSS rover to locate the geospatial coordinates of each marker and its elevation.

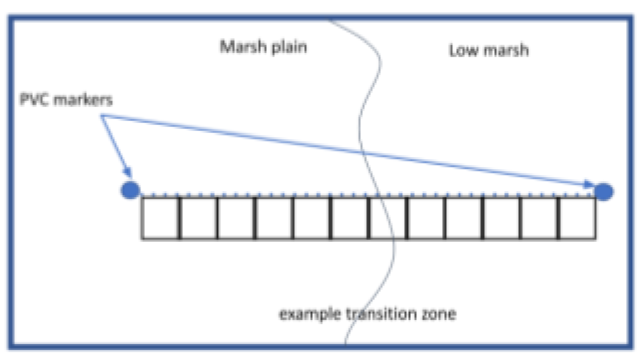

Figure 4. Example belt transect across the low marsh-marsh plain transition zone.

Using elevation as a metric for establishing points is essential as locations will not necessarily have the same morphology, and elevation knowledge will aid in establishing replicate transects at similar elevations. At both ends of the transect, elevation, salinity and inundation should be measured according to monitoring protocols outlined in the WRMP Hydrogeomorphic SOP.

Sampling is accomplished by a belt transect, using sequential $1m^2$ quadrats along the transect from the beginning point to the end (Fig. 4). For each quadrat, list all species present and estimate percent cover for each to the nearest 5%. Using the same approach as in section 3.6.1 and 3.6.2 photographs and archive plant cover in each belt transects should be taken for future reference. At some agreed upon frequency, repeat this protocol over time to detect fine-scale changes in vegetation distribution and elevation. Ideally, compare changes to remote sensing data of plant assemblages at the site scale.

After field work is complete data sheets should be digitized and QA/QC'd as outlined in section 3.6.2 (Data management after the field).

3.7.3. Special Studies Data Analysis

Within each transect, species richness and total percent cover of each species will be calculated. Average species richness and percent cover of each species can then be calculated for each transition zone. Changes in percent cover within the belt transect indicate distribution shifts of transition zone vegetation and changes in dominance can indicate a migration of the zonal boundary location. In addition, changes in plant composition within the transition zone can be driven in species-level changes that can be indicative of specific drivers. For instance, species particularly sensitive to salinity versus waterlogging stress will indicate shifts in those drivers. In addition, percent cover in a subset of transition zone plots (e.g., every other plot along the belt transect) could be used to supplement the understanding of vegetative cover obtained in above described transect-based sampling that disproportionately samples the marsh plain. Augmenting the understanding of vegetative cover and composition in these marginal communities can also assist in improving mapping accuracy.

4. Conclusion

Tidal marsh vegetation provides a critical link between estuarine wildlife habitat and hydrogeomorphic processes that shape its vegetation patterns. Viewed from a regional perspective, the vegetation of the San Francisco Bay Estuary reflects the many different changes that have accompanied different biogenic and anthropogenic influences that occurred over time. Because of vegetation sensitivity to changes in salinity and duration of inundation, among other factors, recognizing how vegetation patterns are changing, where and how fast they are changing, and the likely ecological drivers of these changes provides Bay Area scientists, managers, and the public with important insights into how and what management actions might be taken to address threats to its community well-being. The procedures detailed in the Vegetation Monitoring SOP for the WRMP aim to deliver timely insights to assist the region in effectively adapting to the anticipated challenges in the near future.

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6. Appendices

Appendix A

CDFW-CNPS Protocol for the Combined Vegetation Rapid Assessment and Relevé Field Form

Appendix B

Combined Vegetation Rapid Assessment and Relevé Field Form

Appendix C

Suggested vegetation alliances (or key association) levels

The listed associations are ones used in tidal marsh vegetation mapping efforts in the region.

- *Atriplex prostrata – Cotula coronopifolia* Semi-Natural Alliance
- Bare earth
- *Baccharis pilularis* Alliance
- *Bolboschoenus maritimus* Alliance
- *Carex barbarae* Alliance
- *Distichlis spicata* Alliance
- *Festuca perennis* Alliance
- *Frankenia salina* Alliance
- *Grindelia stricta* Provisional Association
- *Juncus* (*oxymeris*, *xiphioides*) Provisional Alliance
- *Juncus arcticus* (var. *balticus*, *mexicanus*) Alliance
- *Lepidium latifolium* - (*Lactuca serriola*) Semi-Natural Alliance
- *Leymus triticoides* Alliance
- Mudflat/Dry Pond Bottom Mapping Unit
- *Persicaria lapathifolia – Xanthium strumarium* Alliance
- *Phragmites australis* - *Arundo donax* Semi-Natural Alliance
- *Sarcocornia pacifica* (*Salicornia depressa*) Alliance
- *Schoenoplectus americanus* Alliance
- Schoenoplectus (acutus, californicus) Alliance
- *Spartina foliosa* Association
- *Triglochin maritima* Association
- *Typha* (*angustifolia*, *domingensis*, *latifolia*) Alliance
- *Zostera* (*marina*, *pacifica*) Pacific Aquatic Alliance