ELKHORN SLOUGH
TECHNICAL REPORT SERIES 2012: 1

Sponsored by the Elkhorn Slough National Estuarine Research Reserve and the Elkhorn Slough Foundation

A novel approach combining rapid paleoecological assessments with geospatial modeling and visualization to help coastal managers design salt marsh conservation strategies in the face of environmental change

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February 2012

Elkhorn Slough National Estuarine Research Reserve

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The appropriate citation for this document is:
Wasson K, Watson EB, Van Dyke E, Hayes G, Aiello A. 2012 . A novel approach combining rapid paleoecological assessments with geospatial modeling and visualization to help coastal managers design salt marsh conservation strategies in the face of environmental change. Elkhorn Slough Technical Report Series 2012:1.

This document can be downloaded from the Technical Report Website of the Elkhorn Slough Reserve: http://www.elkhornslough.org/research/bibliography_tr.htm

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FUNDING

CICEET

This technical report is a version of the final report prepared for the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), which funded the project from 2009-2012. Additional support was also provided by the Estuarine Reserve Division of NOAA.

ABOUT THE ELKHORN SLOUGH TECHNICAL REPORT SERIES

The mission of the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve is conservation of estuarine ecosystems and watersheds, with particular emphasis on Elkhorn Slough, a small estuary in central California. Both organizations practice science-based management, and strongly support applied conservation research as a tool for improving coastal decision-making and management. The Elkhorn Slough Technical Report Series is a means for archiving and disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature.

EXECUTIVE SUMMARY

We developed, refined and implemented tools to help coastal managers understand and manage for salt marsh sustainability in the face of threats from anthropogenic changes to sediment inputs and water quality resulting from land use changes, and sea level rise associated with global climate change. Salt marsh sustainability is an intricate balance between relative sea level rise and marsh platform elevation. Given ample sediment supply and marsh elevations supra-optimal for maximum productivity, increases in inundation result in enhanced sediment deposition and increased production. However, where tidal marshes lack elevation capital, existing marsh plains are only able to keep pace with sea level rise given sufficient sediment supply. In past centuries, human activities at multiple scales have dramatically influenced this balance in North American estuaries.

The project was developed in response to needs from end-users engaged in the Tidal Wetland Project (TWP), a collaborative ecosystem-based management initiative launched and directed by staff at Elkhorn Slough National Estuarine Research Reserve (ESNERR). The TWP stakeholders comprised the primary audience for the marsh sustainability visualization tools resulting from this project. More broadly, this project also serves as a demonstration of the benefits to coastal management of using the NERRs as "sentinel sites" for global climate change. ESNERR has pioneered the collection of monitoring data relevant to investigations of marsh sustainability, and with this CICEET project has demonstrated how such data can be successfully incorporated into a collaborative framework for understanding marsh sustainability and migration to support development of improved salt marsh conservation strategies.

We used rapid, shallow subsurface stratigraphic assessments at an unprecedentedly high scale of spatial resolution to map the ancient, natural extent of marshes at Elkhorn Slough. We found that marsh extent was somewhat dynamic over time, with at least two previous episodes of marsh deterioration documented by the sediment record during pre-historic times. Although our analysis was restricted to the portion of the estuary that has never been reclaimed, results strongly suggest that the current aerial extent of marsh is lower than it was during early European-American settlement, but somewhat greater than the extent supported by the estuary over the past 200-3,000 years. We shared these reconstructions of past habitat extent through maps presented to TWP stakeholders. The results were surprising to this audience, and represent a paradigm shift. Aiming for marsh extent documented in the earliest maps or aerial photos might not be within the most typical natural range for the estuary, and may be neither feasible nor sustainable given the watershed sediment supply and low turbidity of the estuary. TWP stakeholders will be developing a new strategic plan for estuary-wide priorities in coming years, and this new information on ancient marsh extent will be used as one component of setting restoration goals for the estuary.

We collected data on sediment accumulation and erosion, and marsh platform elevation processes within differing geomorphic contexts by conducting radiometric dating and analysis of sediment composition for 10+ shallow sediment cores, completing terrestrial laser scanning, acoustic profiling, monitoring sediment elevation tables and feldspar marker horizons and deploying litterbags to measure decomposition rates. These data were synthesized to obtain a better understanding of the processes that generate marsh stability at Elkhorn Slough, and were also used to parameterize and evaluate predictive models. The results of these analyses, in concert with monitoring and modeling efforts suggest that extensive marsh drowning observed at Elkhorn Slough over the past sixty years has complex causes. The creation of an artificial mouth to the estuary to accommodate Moss Landing Harbor is one major contributing factor, leading to

dramatic initial die-back in the 1950s and decreasing long-term resilience of the marshes to sea level rise, by lowering their position in the tidal frame. However, this factor alone does not appear to explain the on-going marsh loss observed in past decades. Rather, subsidence of the marsh plain appears to be a major contributor to current marsh drowning. This subsidence may be driven, at least in part, by decreased root biomass or increased below-ground decomposition rates resulting from poor water quality related to high nutrient loading and eutrophic conditions. The identification of subsidence and the development of hypotheses involving eutrophication also represent a major paradigm shift, which will generate more science and inform marsh restoration strategies in coming years. There has been some resistance to the new ideas, and additional data and experiments are still needed. So management actions will not change overnight. However, it appears likely that consideration of issues related to subsidence will be part of future marsh restoration planning for the estuary, as a result of this project.

We implemented a geospatial decision support platform and developed numerical models to investigate marsh sustainability, parameterizing these models with newly collected data on sediment accumulation as well as our existing data on marsh elevation, tidal inundation, and vegetation cover. We explored and adapted a range of marsh sustainability and migration scenarios with TWP stakeholders using visualization tools. Our modeling results confirm that Elkhorn Slough's marshes are very sensitive to environmental changes. Under a scenario of 1 m of sea level rise during the coming century, 90% of the estuary's marshes would disappear. This result underlines the need for targeted restoration projects where marsh elevation can be sustained and enhanced, and also highlights the challenge of larger scale marsh conservation in the estuary. Predictive modeling will be critical as TWP stakeholders move forward with strategic planning of restoration projects in general, and with the recently initiated sediment addition project in particular – elevations of the new marshes must be sufficient to account for the observed subsidence and likely sea level rise rates. Predictive modeling also was used to explore with stakeholders the potential for marsh migration. Due to the steep topography adjacent to current marshes, there is very limited potential for such migration. Stakeholders expected that the head of the estuary, at the Carneros Creek floodplain, might prove a valuable marsh migration corridor, but the modeling revealed limited scope for future marsh habitat there. The greatest extent of marsh migration is theoretically possible in the southern estuary, along the old Salinas channel and Tembladero floodplains. However, since these are highly productive and valuable farmlands, and since they are beyond the current focus area of the land trusts active in the Elkhorn Slough area, enabling marsh migration to the south may be very challenging. Nevertheless, some workshop participants expressed interest in exploring potential incentive programs for landowners.

Our geospatial visualization tools were also shared with two different groups of end-users through Coastal Training Program (CTP) workshops. We presented climate change predictions and sea level rise scenarios to a group of landowners around Elkhorn Slough and regional conservation interests to gauge the needs of this community. We determined that their needs – including analyses focusing on human infrastructure and economic analyses – were more appropriate to other regional climate change initiatives than to this CICEET project. We also presented our SLAMM models and some of the underlying data at a workshop for managers and scientists from the San Francisco Bay region. The ESNERR CTP program conducted a needs assessment of coastal managers and found a need to better link those doing monitoring, modeling, and management of salt marshes in the Bay region. In partnership with San Francisco Bay NERR and USGS, we hosted a workshop to identify management needs and compare approaches for monitoring and modeling marsh sustainability in the face of sea level rise. Our Elkhorn Slough case study was highlighted to this broader audience of stakeholders, and will continue to shape the development of a regional approach to marsh sustainability science and management.

INTRODUCTION

***Problem statement*: Coastal managers lack the tools needed to design effective strategies for conserving and enhancing salt marshes in the face of altered land uses in the watershed, sediment supplies, and sea level rise.**

Salt marsh sustainability is an intricate balance between relative sea level rise and marsh platform elevation (Figure 1, Wasson 2011). Given ample sediment supply and marsh elevations supra-optimal for maximum productivity, increases in inundation result in enhanced sediment deposition and increased production. However, where tidal marshes lack elevation capital, existing marsh plains are only able to keep pace with sea level rise given sufficient sediment supply. In past centuries, human activities at multiple scales have dramatically influenced this balance in North American estuaries. In some locations, land use changes, including forest clearing, and the introduction of grazing and agriculture, increased soil erosion, which led to immediate and rapid expansions in salt marsh acreage following European colonization (Brush 2001; Hilgartner and Brush 2006). Conversely, sediment retention by upstream dams is currently reducing sediment supply in many coastal areas (Vörösmarty et al. 2003; Patch and Griggs 2006). Meanwhile, a recent increase in the rate of sea level rise has been documented globally using historic tidal gauge records and satellite altimetry (e.g., Meehl et al. 2007). Consequently, by the 2080s, sea-level rise could cause the loss of as much as 30% of the world's coastal wetlands (Nicholls et al. 1999; Bindoff et al. 2007).

To design wise and effective coastal management strategies, managers need to understand baselines of natural salt marsh area for the system prior to increased sediment inputs from land use changes associated with European colonization. In some cases current extensive salt marshes may be historical artifacts resulting from temporarily increased sediment loads over the past centuries. Sustaining these marshes without these sediment loads may not be feasible, nor may it even be desirable, since they are not part of the longer-term (pre-colonization) natural baseline. Moreover, salt marsh managers also need to understand which existing marshes would benefit most from conservation and enhancement strategies (vs. which don't need help to be sustainable, or which are going to be lost regardless of enhancement efforts). Additionally, managers need to identify areas where new salt marshes can colonize and migrate as sea level rises, so appropriate lands can be acquired and constraints to migration can be decreased. Finally, recent studies implicate feedbacks between land use and nitrogen loading as a potentially important stressor for salt marsh sustainability: ideally, by better defining marsh sustainability for highly impacted coastal estuaries, such as Elkhorn Slough, we will contribute to a broader understanding of sustainable land management options for coastal areas.

Developing tools for helping coastal managers understand and manage for marsh sustainability in the face of land use and sediment changes and sea level rise is recognized as a priority in the coastal management community nationally (e.g., Day et al. 2008; Tribbia and Moser 2008), by the NERR system (Climate Change White paper, Sentinel Sites Strategic

Proposal), and at Elkhorn Slough in particular (Elkhorn Slough Tidal Wetland Project Team 2007). Although at various locations around the country, there are long-term studies underway monitoring ongoing rates of marsh deterioration (Erwin et al. 2004; Nielsen et al. 2008), and using stratigraphic tools to understand past processes of marsh formation and submergence (White and Tremblay 1995; Jennings et al. 1995; Ward et al. 2008), there are no good models available for integrating the science of marsh sustainability with coastal decision-making because recognition of this problem is very recent. On the Pacific coast in particular, science-based coastal management for marsh sustainability in the face of sea level rise has not yet been pioneered, and there is an urgent need for better information about coastal climate change scenarios and better development of the relationship between information producers and users (Tribbia and Moser 2008). What distinguished our project is the development of a varied toolbox of field methods that can be conducted rapidly and a decision support platform designed *a priori* to inform place-based management by the end-users, coastal decision-makers engaged in salt marsh conservation.

OBJECTIVES

Our ultimate goal was to help coastal managers design realistic salt marsh conservation and enhancement strategies in the face of watershed land use changes, altered sediment budgets, and sea level rise (Figure 2). We set out to accomplish this by developing and implementing a variety of geomorphologic characterization methods and shallow-subsurface stratigraphic assessments and incorporated these data into geospatial modeling, visualization, and decision support tools. The broad objectives were:

1) Assess ancient marsh extent to inform the setting of restoration targets

For many estuaries, the baseline for marsh restoration consists of earliest maps and aerial photographs (Striplen and DeWeerdt 2002; Stein et al. 2007). However, some evidence suggests that, at least in California, much tidal marsh formed only over the last two hundred years. In many cases, the earliest maps establish the recent inception of tidal marsh (Nelson 2008; Grossinger et al 2003), or alternatively radiocarbon dating has established that "basal peat" dates only to the last 1-200 years (Brown and Pasternack 2005; Watson 2006). Maintaining recent marshes generated by human land uses may not be desirable, nor even feasible with the cessation of these sediment loads.

The traditional approach for addressing such questions consists of comprehensive, detailed, long-term paleoecological investigations. We instead implemented and refined a new, relatively rapid assessment methodology for mapping the ancient extent of salt marshes. This reconstruction was presented as a visualization tool for coastal managers through the ecosystem-based management initiative, providing a more accurate and potentially realistic baseline for sustainable marsh conservation targets than provided by assessment of current or historic marsh extent.

2) Characterize past and current processes supporting marsh sustainability to understand future trajectories

Knowledge of the extent of historic habitats is a gateway to understanding the processes that created them, and which may be harnessed to better manage them today. The stratigraphic analyses used to map ancient marsh extent also yielded critical information on past sediment supplies and tidal regimes that supported the marshes. Examination of the very top of sediment cores as well as of current monitoring data on sedimentation, elevation, and tidal elevation shed light on the current conditions that may be contributing to observed marsh drowning.

In order to proceed with predictive modeling, we needed to first expand our understanding of spatial variability in the rates of recent sediment accumulation and erosion. It was critical to better understand sediment dynamics in order to (1) establish variability in rates of sediment accumulation and erosion, (2) to link sediment accumulation rates with measurable environmental variables (such as elevation, turbidity, and position within tidal channel network) and (3) to parameterize spatially explicit modeling efforts.

3) Model future marsh sustainability and migration and develop visualization tools

We implemented a geospatial decision support platform and developed numerical models to assist coastal managers and stakeholders in developing salt marsh conservation strategies through interactive exploration and visualization of long-term marsh evolution and migration scenarios. The platform was based on a well-established, decision tree-driven conceptual model of marsh vegetation response to relative sea level changes and sediment dynamics (SLAMM). We incorporated enhancements to the model though its open source, modular architecture. The conceptual model was built upon an accurate, high spatial resolution, LiDAR-derived topographic surface and included customizable, place-specific elements corresponding to Elkhorn Slough's hydrologic, geographic, and anthropogenic features.

4) Inform strategic planning for salt marsh conservation and restoration by jointly exploring future scenarios using visualization tools with key stakeholders

We conducted four coastal decision-making workshops to engage key stakeholders in development and application of decision support tools for marsh sustainability management. We used a collaborative approach to share and refine visualizations. Two workshops involved coastal managers and decision makers as part of the Tidal Wetland Project, an ongoing ecosystem-based management initiative to conserve and restore tidal wetlands in Elkhorn Slough. The output from these investigations will be integrated into the Tidal Wetland Project adaptive management process by clarifying our conceptual model of marsh dieback and sustainability and, in turn, indicating the most promising management options. The third workshop explored a sea level rise visualization tool with land owners adjacent to the Elkhorn Slough. Land owners suggested key elements needed to improve visualizations, a foundational step to engaging the stakeholder group most important to sustaining salt marsh with sea level rise. The fourth workshop was aimed at comparing visualization tools developed through this grant with other visualization tools developed otherwise and facilitating a dialogue amongst scientists and managers to determine how to improve tools aimed at informing salt marsh conservation and restoration. This grew out of a needs assessment we conducted, interviewing coastal managers regarding their needs with regard to marsh sustainability science and management.

METHODS

Technical methods

1) Assess ancient marsh extent to inform the setting of restoration targets

Marsh extent was reconstructed by collecting and analyzing approximately 85 three-meter sediment cores collected at the vertices of a 200m x 200m grid from undiked locations around the estuary (Watson 2011). This represented an unprecedented spatial scale of coverage for this estuary, and indeed for most estuaries. Chronological control was provided by radiometric dating techniques appropriate for recent decades (Pb-210, Cs-137), analysis of sediments for heavy metals which provided supplemental chronologic control for recent deposits, and radiocarbon dates on marsh peat. Sediment composition and stratigraphy were assessed by visual classifications based on root abundance, gravimetric analysis of sediment weight (bulk density and organic content), and elemental analysis (for total C, H, and N). Estuarine sediment deposits were classified as marsh sediments based on sediment organic content, the visual identification of roots and rhizomes in growth position, and sediment C/N ratios. Tidal flat sediments, for which the organic matter source is algae, tend to have lower C/N ratios than tidal marsh sediments, which tend to have a 'terrestrial" C/N ratio. Determinations of marsh vs. tidal flat habitat were made for each 25-cm interval in order to reconstruct the past distribution of estuarine wetlands in different periods. We partnered with the National Lacustrine Core Repository (Laccore) to scan and archive reference cores representing key geographic regions and stratigraphic 'archetypes' (Table 1). These sediment cores were split, x-rayed, logged for magnetic susceptibility using a Geotek XYZ multi-section automated split core logger, and analyzed using a Cox analytical Itrax x-ray fluorescence core scanner, located at the Large Lakes Observatory XRF facility. Archive core halves are currently available at Laccore for future investigation by collaborators.

We had originally planned a hybrid method of sediment core analysis supplemented with acoustic profiling in order to reconstruct marsh extent, however, we determined that the necessary equipment requires water depths that are never achieved over salt marshes, and thus direct assessments of sediment stratigraphy was the primary tool used for marsh extent reconstruction. Acoustic profiles were, however, used as a tool in understanding tidal channel processes (Levey et al. 2011): both recent, with respect to identifying locations of channel erosion and stability, and longer-term, by looking at changes in tidal channel position and sinuosity occurring over millennia. Profiles were also examined for evidence of faulting. Where acoustic profiles and sediment cores were taken from the same vicinity, good correspondence was found between stratigraphy and acoustic signature. However, acoustic signatures around Elkhorn Slough did vary for reasons probably unrelated to marsh peat: gas deposits were present, the acoustic basement was in some cases very shallow (a few decimeters), and sediment density was highly variable.

2) Characterize past and current processes supporting marsh sustainability to understand future trajectories

In order to increase our understanding of recent rates of sediment accumulation at Elkhorn Slough, this "rapid profiling" study was supplemented with more detailed study of specific marsh regions of Elkhorn Slough. Shallow sediment cores were collected from healthy and degrading salt marsh at Elkhorn Slough: at five locations paired sediment cores were collected from healthy marsh and from degraded marsh located nearby (mean = 40 m distance), and three additional shallow sediment cores were collected from different localities within a large area of degraded marsh found in the upper Slough. These shallow cores (13 in total) were analyzed for sediment composition (gravimetric water and organic content, bulk density, porosity), and for recent accumulation rates using radiometric techniques appropriate for recent decades, supplemented by analysis of sediments for heavy metals. Analyzing a large number of sediment cores for recent accumulation rates using Pb-210 and Cs-137 methods allowed us to determine spatial variability in sediment accumulation, and specific factors that promote sediment accumulation. This data was critical to model marsh sustainability, in order to establish spatial variability (for error analysis), and to link spatial variability in sediment accumulation rates to specific environmental variables (for the purposes of developing accurate spatially explicit models and predictions).

Current sedimentation rates were examined using various on-going ESNERR monitoring datasets (surface elevation tables, feldspar horizons, accretion tiles). In addition, terrestrial Laser Scanning (TLS) was used to document rates and distribution of long- (>1 year) and short-term (months/days) geomorphologic change in key estuarine habitats of Elkhorn Slough. At ten sites, a geodetic network of foresights, backsights and control points was created and, when possible, tied to the Elkhorn Slough elevation control network. TLS surveys were carried out with a Trimble VX Spatial Station. This state-of-the-art spatial station is equipped with Direct Reflex (DR) technology, a direct drive system with robotic servo-mechanisms and a built-in digital camera. The instrument is operated via radio-link by a controller unit and can collect accurate (<3 mm), rapid (15 points/s) spatial data (point clouds). The range of operation of the DR laser is 2 to 500 m; while on target mode the acquisition can work as far as 2 km. See Aiello and Endris (2012) for more details on the TLS methods.

During the course of this project, it became clear that subsidence might be an important current driver of marsh sustainability. It has been postulated that eutrophic conditions can drive marsh subsidence by decreasing below-ground marsh biomass (Turner et al. 2009) and by increasing decomposition rates (Wigand et al. 2009). We thus initiated a study examining marsh biomass (above and belowground) and decomposition rates (using litterbags) at sites with varying nutrient concentrations within Elkhorn Slough, and as a comparison, at another regional estuary with much lower nutrient loading, Morro Bay (Watson et al. 2011c).

3) Model future marsh sustainability and migration and develop visualization tools

Our geospatial decision support system was implemented by adapting and extending the open source *Sea Level Affecting Marshes Model* (SLAMM) (Park et al.1986). SLAMM has been under development for more than 25 years and is used by a variety of agencies and organizations including the US Environmental Protection Agency, the US Fish and Wildlife Service, the National Wildlife Federation, The Nature Conservancy, Ducks Unlimited, and others (http://warrenpinnacle.com/prof/SLAMM/).

Our system was developed through a process of stepwise refinement, allowing coastal manager and stakeholder participation early in the project schedule. Initial scenarios, incorporating a range of sea level rise, regional subsidence, and sediment availability assumptions, were explored through the conceptual model, providing the project team (both developers and early users) with a basic understanding of the sensitivity of the marshes to climate change and other environmental parameters—as well as insight into any fundamental limitations of the model. These insights directed further development of the decision support system through two mechanisms: incremental improvements to the internal conceptual model, and incorporation of results from field studies and external modeling tools through the system's open interface.

We adapted the SLAMM code (version 6.0.1) for Elkhorn Slough and incorporated parameter values acquired from remote sensing, from our past and current field investigations, and from the published literature (Van Dyke 2011). Baseline data included detailed wetland habitat extents (from classified aerial imagery), precise water levels (from tide gauge data), and precise wetland elevations (from processed LiDAR imagery). Tidal continuity and tidal barriers (levees, etc.) were verified in the field and incorporated into the elevation base. Historic and recent sediment accretion and erosion rates were determined from paleoecological studies and from surface elevation table measurements. A range of six possible rates of future accelerated sea level rise were adopted based on scenarios published by the IPCC (Houghton et al. 2001) and from subsequent studies (e.g. Vermeer and Rahmstorf 2009).

The SLAMM model has been both defended and criticized in the published literature. A frequent objection (e.g. Kirwan and Guntenspergen 2009) is that by neglecting feedbacks between wetland vegetation, water depth, and sedimentation rate, the model predicts exaggerated rates of wetland loss. To address this concern, we extended SLAMM by incorporating a dynamic sediment accretion strategy as developed by Morris et al. (2002).

We ran our SLAMM-based decision support system through the 95-year period beginning with 2005 (date of our LiDAR and other base data) and ending at 2100. Simulations for specific regions ran under a 5-year time cycle; slough-wide simulations ran under a 25-year cycle (compute time with a shorter cycle would have been prohibitive). We investigated each of the six sea level scenarios, comparing quantitative results (predicted marsh acreage, sediment accretion rate, and marsh plain elevation) after each cycle and producing geospatial visualizations to allow visual comparisons of model results. For model calibration and sensitivity analysis, we varied initial habitat elevations, tidal range, accretion rate, global sea level rate, and regional subsidence rate and assessed the effects of these adjustments on model predictions.

Collaboration methods

The goal of our collaborative methods was **to inform strategic planning for salt marsh conservation and restoration by jointly exploring future scenarios using visualization tools with key stakeholders.**

This project is unusual in that it was, in part, developed in response to the explicit needs of end-users already engaged in a collaborative process with coastal decision-makers focused on conservation and restoration of estuarine ecosystems in the Elkhorn Slough watershed, the Tidal Wetland Project (TWP). It was designed and directed by NERR staff coordinating an ecosystem-based management initiative, launched in 2004. The strategic plan for this initiative is posted at http://www.elkhornslough.org/tidalwetlandproject/. In this strategic plan, TWP stakeholders prioritized two of the research questions explored with support of this grant:

- Quantify historic sedimentation rates, sources, and vegetation patterns to determine the role of sediment and current patterns of marsh degradation and to better understand past habitat characteristics for Elkhorn Slough.

- Improve modeling of likely effects of predicted (maximum and minimum) sea-level rise to inform restoration strategies.

These questions were two of ten prioritized in the plan, and so the answers provided provide a substantial portion of the information thought necessary when the plan was written.

The TWP collaborative stakeholders were variously involved with the CICEET-funded project. For instance, TWP stakeholders reviewed initial findings and visualizations on the past, present and future evolution of Elkhorn Slough salt marshes at a workshop held during the first year of the grant. Researchers obtained feedback on geographic boundaries, desired model refinements, and desired outputs during that meeting. In the second year of the project, researchers presented the TWP stakeholders results refined from those previously presented. This iterative process of joint fact-finding (Susskind 1999) will continue between the PIs and TWP stakeholders beyond the duration of the current grant.

In our original proposal, the research and collaboration team focused entirely on stakeholders engaged in the Tidal Wetland Project. However, as the project evolved, it became clear that there were other stakeholders critical for conserving and restoring salt marsh. The Elkhorn Slough Coastal Training Program stepped in to assist with linking the researchers with these stakeholders. A recent, extensive survey of the needs of coastal managers in California with regard to climate change found that there is a critical and unmet need for such "boundary organizations" to serve an intermediary function between science and practice (Tribbia and Moser 2008). The Elkhorn Slough Coastal Training Program (CTP) worked with the grant-funded researchers to further explore the need for the information and visualizations generated by this grant and to coordinate with researchers in exploring how to best meet those needs. The CTP conducted two additional workshops which had not originally been anticipated, one for landowners in region surrounding Elkhorn Slough, to explore possible consequences of sea level rise, and another in the San Francisco Bay region, designed to link scientists and managers in an evaluation of the most effective tools for characterizing sea level rise and marsh sustainability.

Evaluation methods

We followed the structure for formative evaluation in product development pioneered by Sanders and Cunningham (1973). We implemented a process of on-going feedback in order to recognize and respond to the learning that occurs during the process of product development and in order to adapt to the needs of the end-users.

Initial feedback was solicited from technical projects immediately after the project began. Co-PI Watson visited local scientific laboratories at UC Berkeley, UC Davis, UC Santa Cruz, and Moss Landing Marine Laboratories in late 2010 and early 2011 to obtain early advice and feedback prior to beginning field sampling. Local scientists with expertise in stratigraphic analyses recommended a field research plan based primarily on sediment profiling using a coring device rather than the acoustic or geophysical methods outlined by the proposal, and also suggested making extensive use of a calibration data set, in order to bracket uncertainty associated with habitat reconstructions. We also obtained early feedback from key local coastal management audiences. We gave a powerpoint introducing the project and led a discussion soliciting feedback, to the Central Coast Wetlands Working Group and the Monterey Bay National Marine Sanctuary's Research Activities Panel.

After this initial feedback we obtained formative feedback on the technical and scientific content of our project from a Technical Advisory Committee (TAC). The TAC was convened three times during this project, for 1.5 hr conference calls facilitated by Wasson each time. TAC membership consisted of Drs. R. Anderson, D. Belknap, J. Callaway, D. Cahoon, J. Donnelly, M. Hornberger, J. Lacy, A. Kolker, G. Lessa, J. Morris, A. Paytan, D. Proosdij, D. Schwartz, D. Smith, and K. Swanson. This panel of experts included local and national experts in estuarine stratigraphy, regional fluvial and coastal geomorphology, and marsh sustainability modeling incorporating expertise from university researchers from several countries, and also the expertise of the U.S. Geological Survey. At the first TAC call, Watson presented her stratigraphic approach and initial findings and solicited feedback on focused questions about the analyses. In the second, Van Dyke presented his modeling approach and solicited feedback on model inputs and modifications. Vital formative feedback received was incorporated and improved the rigor of both their work. In the final TAC call, Watson and Van Dyke presented their findings to the TAC, in preparation for presentation to the regional stakeholders the following month. The TAC concurred with the broad results and their interpretations, and provided numerous specific suggestions to improve their presentation and clarity.

We obtained formative and summative evaluations of the success of the project in informing the needs of regional coastal decision-makers and other stakeholders through discussions at the four workshops and in subsequent survey-monkey evaluations for two of the workshops. Suggestions made both at the workshops and on the anonymous evaluation forms were incorporated as possible into the project design and implementation.

Knowledge dissemination methods

The most important end-users for this project were the local coastal managers represented by the Tidal Wetland Project whose needs generated this project in the first place. As described above, these were engaged throughout the project, and specifically by two workshops and by representation on the technical advisory committee. We presented the geospatial visualization tools resulting from this project at these workshops, and created a new webpage to summarize and disseminate the findings of this project:
http://www.elkhornslough.org/research/conserv_marsh.htm

We have and will continue to share the tools and lessons learned of this project with the NERRS community through presentations at RC, SC, and general NERRS meetings, as well as with the broader scientific and coastal management community through publications and presentations at workshops and conferences.

RESULTS AND DISCUSSION

1) Assess ancient marsh extent to inform the setting of restoration targets

The high spatial and temporal resolution of reconstructed marsh extent yielded some surprising results with regard to marsh baselines at Elkhorn Slough. We had reported marsh die-back in the past century (Van Dyke and Wasson 2005), but had assumed that this marsh loss was unprecedented, and that marsh extent a century ago was a suitable restoration target for the estuary, representing typical conditions. The visualization of ancient marsh extent (Figure 3) instead revealed that marsh cover was variable over time at Elkhorn Slough, with three separate episodes of marsh expansion and die-back. The loss in the past century may be more rapid than in previous episodes, but marsh die-back itself is not new for this estuary. The reconstruction of ancient marsh extent also revealed that aerial extent of marsh today is low relative to baselines generated from early maps, but high relative to past millenia (200-3,000 years). This is critical information for setting restoration targets for the estuary. The marsh reconstruction is presented in greater detail in Levy et al. 2011, Watson 2011, and Watson et al. 2011b.

Acoustic profiling revealed that the position and size of the main channel adjacent to the marshes has been relatively stable over thousands of years, apart from minor channel avulsions related to point bar (island) deposits (Levey et al. 2011). Profiles document continual infilling of the Elkhorn Slough estuary during the Late Holocene, and suggest that small sub-surface gas deposits (CO_2/CH_4) are present in shallow Elkhorn Slough muds. These gas deposits may make marsh platforms susceptible to subsidence under the weight of enhanced sediment deposition. In many locations, extremely good correspondence was found between sediment core and acoustic profiles, however acoustic signatures also vary for reasons unrelated to sediment composition, and in some cases acoustic basement is very shallow, making acoustic signature a less reliable method for reconstructing wetland extent through time. Overall, no evidence was found suggesting differential subsidence related to faulting.

2) Characterize past and current processes supporting marsh sustainability to understand future trajectories

This project has elucidated the processes underlying marsh sustainability at Elkhorn Slough (Watson et al. 2011a). In the recent past, until about 1940, marsh extent was stable or increasing. Our investigations suggest marshes had modest rates of sedimentation, but this was sufficient to track sea level rise. Marshes were high in the tidal frame and resilient to fluctuations in sediment availability and tidal inundation. After the 1946 opening of an artificial mouth to Elkhorn Slough to support Moss Landing Harbor, tidal range increased, shifting marshes to a lower position in the tidal frame and decreasing their resilience.

Sediment accumulation rates show meaningful spatial variation. Accumulation rates are higher at lower elevations, and near tidal creeks (Figure 4), indicating that sediment availability is greater closer to tidal channels, and under greater immersion times. We compared sediment accumulation in nearby healthy marsh vs. unvegetated marsh panes, and found significantly higher accumulation in the more stable marsh (Figure 5). This suggests that healthy marsh plants play a key role in supporting marsh elevation, either through belowground root volume, or the sediment trapping ability of plant stems. Terrestrial laser scanning revealed that mudbanks and mudflats, and channel edges of marsh, are eroding throughout the estuary (Figure 6; Aiello and Endris 2012). However, there is little evidence for physical erosion of marsh surfaces, except at channel initiation points. Rather, the lower elevation of degraded marsh can be accounted for by a lower rate of accumulation.

However, the large area of degraded marsh in the upper Slough appears to have experienced some sort of subsidence event: post-1950s accumulation rates found here are typically greater than found in healthy marsh, yet the platform elevation is c. 40 cm lower than in intact marsh platforms. This situation appears to be a recent development as air photos dating to 1930s-1980s show healthy marsh, which would not have been the case if the marsh platform was as low as it is today. This suggests, first, that the low elevation of this area is not due to physical erosion. Secondly, as acoustic profiles show no evidence of faulting across the tidal channel separating healthy marsh from degraded marsh, some localized positive feedback process must have occurred. Perhaps loss of root volume exerts positive feedbacks (plant mortality = subsidence of marsh up to 1m away = enhanced inundation = more plant mortality = enhanced subsidence), or alternatively, perhaps the high sediment loads in this area of the slough due to agricultural erosion have acted as a stressor by acting as a weight, and thereby decreasing the buoyancy of high-porosity gas-filled marsh peat.

Current sediment accumulation rates at most Elkhorn Slough marshes would appear sufficient to track sea level rise, yet marshes have not been gaining elevation – they have been undergoing "marsh drowning". The mechanism responsible does not appear to be physical erosion, or a lack of accumulation, but an umbrella term described in the literature as "shallow subsidence": the difference between marsh accumulation and marsh elevation change. While in most Pacific Coast salt marshes, marsh elevation change tends to track marsh accumulation (minus some amount of consolidation, termed autocompaction), that is not the case at Elkhorn Slough. For instance, we compared our results to those at the next major estuary to the south, Morro Bay, and found very different patterns – Morro Bay salt marshes are gaining elevation as they accumulate sediment (Gillespie et al. 2011). Marsh elevations at Elkhorn Slough have changed little over the past five years, despite healthy accumulation rates, and in fact, there is a modest, although significant negative correlation between accumulation and elevation change (i.e. the marsh elevation declines when surface accumulation occurs). This loss of elevation may be caused by year-to-year declines in belowground biomass, or enhanced mineralization of organic sediment, or some unknown process. We are currently testing the hypothesis that enhanced nutrient loading leads to more rapid or more complete decomposition of wetland plant stems or roots/rhizomes through deployment/collection of plant litter in high (Elkhorn Slough, Jamaica Bay) and low (Morro Bay, Shelter Island) nutrient estuaries (Watson et al. 2011c, Watson 2012). An additional explanation may be that plants grown under higher nutrient conditions incorporate more organic acids, and therefore are more labile, than plants grown under low nutrient conditions. A related survey of plant biomass conducted in different portions of Elkhorn Slough suggests that peak root biomass (November) is lower under higher nutrient loads (Figure 7). This might reflect a difference in resource allocation (fertilized treatments experience less stress, and therefore allocate more energy to aboveground biomass), or alternatively, plant roots may be *more* stressed by higher levels of toxic sulfides (the sulfate reduction cycle is organic matter limited, so under higher nutrient loading situations, more phytoplankton / algae productivity would enhance sulfide production).

3) Model future marsh sustainability and migration and develop visualization tools

We used the geospatial decision support system to develop numerical models corresponding to a range of sea level rise scenarios (Figure 8). We created visualizations from modeled results, enabling stakeholders to explore marsh sustainability strategies (Van Dyke 2011).

We compared results produced with our dynamic sediment accretion model, in which sedimentation rates varied according to vegetation and water depth, with results predicted under simple (static) sedimentation rates. Under the enhanced model, a threshold at which the wetland system transitions from stable to unstable was apparent (Figure 9). As long as the marsh plain remains above this critical elevation (0.58 meters above mean tide at Elkhorn Slough), increased inundation resulting from sea level rise is compensated for by increasing rates of organic and inorganic sedimentation. But below this threshold, increased inundation yields lower sedimentation rates. Therefore marshes that are high relative to the tidal frame will be robust with regard to marsh loss, but marshes that are low (as is currently the case at Elkhorn Slough) are subject to rapid deterioration. Our paleoecological studies demonstrate that historic sedimentation rates were relatively low (within the stable region), indicating that the marsh plain was relatively high in the tidal plain. In contrast, sedimentation rates in today's lower elevation marshes are relatively high—likely at or near the threshold of marsh instability. Simulation results confirm these findings, which have important management implications: they indicate that Elkhorn Slough's salt marshes are already vulnerable to changes in parameters that are affected by ongoing human land uses. Therefore even minor climate change-driven increases in the rate of sea level rise will pose significant challenges for the sustainability of Elkhorn Slough's marshes.

Modeled results show that even the moderate sea level rise associated with the IPCC's "A1B mean" scenario (0.4 meter rise by year 2100) would lead to greater than 10% loss in marsh acreage by the end of the century (Figures 10 and 11). With a 0.7 meter rise by the end of the century, marsh loss would increase to 40%. With sea level rise at 1 meter or greater, more than 90% of Elkhorn Slough's marshes would disappear, converting to mudflats and open water.

These results provide important motivation for conservation and restoration projects such as sediment addition to ensure that at least some parts of the estuary can retain sufficient elevation to support salt marsh.

The modeling and visualization tools were also used to explore contrasting hypotheses about causes of marsh dieback over the past sixty years (Van Dyke 2011). A one-time perturbation, the increased tidal range from the opening of the harbor mouth, yielded initial loss followed by recovery and marsh stability. A gradual impact, continual shallow subsidence, yielded slow marsh decline. A combination of both of these hypotheses appears to best fit the empirical data on marsh loss at Elkhorn Slough: increased tidal range from the harbor mouth construction led to immediate marsh loss and a lower position of the remaining marshes in the tidal frame, while on-going subsidence is contributing to current continued marsh die-back (Figure 12). Elkhorn Slough salt marshes are not succeeding in tracking current rates of sea level rise, and will almost certainly be lost if rates of sea level rise increase dramatically, unless management actions can be taken to support increased marsh elevation in the future.

We used our decision support system to investigate marsh conservation strategies (Van Dyke 2011). We created visualizations to explore regions that might support marsh migration, using different scenarios of levee maintenance or removal. Overall, the steep topography adjacent to marshes resulted in very few opportunities for migration (Figure 13). Anecdotally, stakeholders had pointed to the northeastern part of the estuary, along Carneros Creek, as holding the greatest potential for future marsh habitat in the face of sea level rise. However, the modeling revealed that due to extensive subsidence in this region, there is very limited potential for increased marsh acreage. Instead, the SLAMM analysis revealed the greatest potential for marsh migration to the south of the estuary. This is now a region of highly productive farmland, so land trusts cannot readily secure this land as a corridor for future migration.

4) Inform strategic planning for salt marsh conservation and restoration by jointly exploring future scenarios using visualization tools with key stakeholders

This project was originally developed to meet research needs of stakeholders associated with the Tidal Wetland Project but in the process other key stakeholders were identified as end users with important influence over the sustainability of the Elkhorn Slough's salt marshes. The TWP stakeholders had long identified the need for a better understanding of the paleoecology of the Slough as a priority research need (Elkhorn Slough Tidal Wetland Project Team, 2007). During the initial stages of research associated with this grant, the sea level rise analyses suggested that the marsh migration pathways were onto private properties, and the team decided it was important to involve these stakeholders as potential end users. In the process, the team realized that visualization tools for sea level rise and marsh sustainability were being rapidly developed from a number of organizations simultaneously, and that managers, funders, and scientists throughout coastal central California were grappling with the same set of questions. This realization suggested the need to engage a third group of potential end users at a larger geographic scale. And so, the Elkhorn Slough Coastal Training Program (CTP) worked to link the researchers associated with this grant with these three end user groups in separate processes. Collaboration with each of these different groups of end-users is described separately below.

Collaborative strategic planning for Elkhorn Slough by the Tidal Wetland Project stakeholders

Tidal Wetland Project stakeholders were engaged in the project at stages throughout the project. Scientists associated with the TWP also served on the Technical Advisory Committee and shaped the scientific design and analysis. A workshop was held in the first year of the grant, on 22 September 2010, to obtain early feedback on the scope and design of the research and the desired components of the final products. Discussion at the workshop and analysis of the evaluations confirmed that the proposed approach was considered highly relevant to decision-making for Elkhorn Slough, and set the geographic boundaries for the research (participants preferred intense focus on the relatively small area around the Elkhorn Slough estuary, rather than a larger geographic focus). A workshop was held in the second year of the grant, on 12 September 2011, to share findings of the project with stakeholders (Van Dyke 2011, Wasson 2011, Watson 2011, Hayes 2012c). Overall, workshop participants indicated during the discussions and in their evaluations that the new scientific findings would shape their input to strategic planning for the estuary, so the goal of the project had been broadly met. More specifics on particular areas are described below.

<u>Setting restoration targets</u>: An original goal of the project had been to use the new information on ancient marsh extent to set restoration goals, but the TWP end users were ultimately unwilling to use paleoecology data alone to set such targets. At the first TWP workshop, participant evaluations confirmed that they considered the paleoecological analysis highly relevant to setting restoration goals. Of various ancient parameters that could be characterized (salinity, tidal inlet configuration, range of variability, etc.), the one that ranked highest was past habitat extent. However, when the results of the study emerged, there was reluctance among TWP end users to set restoration goals for marsh extent based solely on the new information. Some TWP participants expressed hesitation about using past trend information given future changes especially sea level rise, which could make mimicking the past less feasible. Others suggested that anthropogenic changes to the Slough might make restoration of past targets difficult. In sum, the TWP end users have suggested including not just past trends but also other ecological considerations (threatened species needs, regional conservation trends etc.) as well as social and economic concerns.

The historic information generated from this grant gives broad parameters to TWP decision makers when considering restoration targets in the future. While aerial extent of marsh today is much lower than it was during early European-American settlement, it is actually higher than in much of the past thousands of years. The reconstruction of past dynamics also indicated that there have been previous episodes of marsh die-back. So paleoecology alone cannot be used to justify restoration targets of a very high extent of marsh, as had been anticipated by some TWP participants. Instead of setting marsh restoration targets at the second workshop, TWP stakeholders will consider restoration goals for the estuary as a part of a slower and more thorough process of revising the TWP strategic plan. With the new realizations about the potential impacts of sea level rise, the TWP will also consider changing the geographical boundaries under consideration.

<u>Designing restoration projects:</u> Another original goal of the project had been to inform design of restoration projects for the estuary, by providing a better understanding of the mechanisms that have driven extensive marsh die-back over the past century and which may hamper future sustainability. At the first TWP workshop, attendees indicated that they felt the stratigraphic analyses and modeling both provided key information about the current trajectory of Elkhorn Slough tidal wetlands that is critical for environmental decision making. At the second TWP workshop, participants indicated that they learned much that was highly relevant for restoration

planning. The modeling indicated that Elkhorn Slough's existing salt marshes are extremely sensitive to environmental conditions, and would likely not be resilient to significant sea level rise. Some participants indicated that this means that it would not be realistic to set high marsh extent goals for conservation or restoration for the future. On the other hand, other participants felt this underlined the need to ensure that at least some salt marshes maintain a high position in the tidal frame, for instance through sediment addition projects. The modeling, sediment monitoring and stratigraphy indicated that subsidence may be a major cause of current marsh die-back in the estuary. This represents a significant change in perspective. We (Van Dyke and Wasson 2005) had earlier assumed that the harbor mouth was the main cause of marsh die-back, and exploration of large-scale management options for the estuary, such as a submerged sill near the mouth, were based on this assumption. The data from this project paint a more complex picture. The increased tidal range associated with the harbor mouth led to initial die-back and may have greatly decreased the resilience of marshes to subsequent stressors by lowering their position in the tidal frame. However, much of the current marsh drowning seems to be related to continued elevation loss, which does not appear to be directly consequence of a larger inlet (such as through surface erosion of marsh sediment). The causes of the subsidence are not known, but we have initiated research to test the hypothesis that it is being driven by enhanced nutrient loads, which can decrease marsh elevation capital by increasing decomposition rates or decreasing root biomass. Apart from nutrient loading, it is also possible that these high rates of shallow subsidence may be natural feedbacks given the relatively low elevation and high immersion times of Elkhorn Slough wetlands. This change of perspective has major implications for planning of large-scale restoration projects, because understanding this process of subsidence (and ideally reversing it) has emerged as an important priority. This affects consideration of a submerged sill at the mouth (which might benefit marshes by lowering tidal range, but might harm them by increasing anoxia and pore-water sulfide concentrations and also planning for sediment addition projects (because these new marshes are in danger of losing elevation to subsidence as well). Because the paradigms are new and studies are still on-going to better understand the mechanisms of subsidence, this information will be gradually incorporated to strategic planning for restoration projects in the estuary over the next years.

Enabling marsh migration: One goal of the project was to identify potential corridors for salt marsh migration in the face of rising sea level. This would allow land trusts and landowners to begin to explore strategies for retaining levees and existing land uses in some areas, while allowing barriers to be breached to allow marsh migration in other areas. Prior to the modeling, there had been consideration of the potential for marsh migration at the head of Elkhorn Slough, in the floodplain of Carneros Creek. This might be a feasible strategy, since the Elkhorn Slough Foundation owns or manages extensive property along Carneros Creek. However, our modeling results suggest only very limited potential for future marsh habitat along Carneros Creek. The modeling results reveal that by far the greatest potential for marsh migration lies to the south, along the old Salinas river channel and its floodplain and around Tembladero Slough. These are highly valuable and productive farmlands, and are outside the major focus areas for acquisition by the Elkhorn Slough Foundation. Thus it will prove more challenging to enable marsh migration in this region than along Carneros Creek. However, some workshop participants, after observing the modeling findings, were intrigued by the potential to explore new partnerships and programs to support future marsh in this area. For instance, one representative from The Nature Conservancy considered opportunities to work with landowners in this southern region to develop incentive programs for sales of lands likely to be threatened by sea level rise. So our modeling results may drive the development of such future programs.

Exploring sea level rise with the larger community around Elkhorn Slough

The ESNERR Coastal Training Program has engaged stakeholders at a larger landscape scale than the Tidal Wetland Project, including those whose decisions affect Elkhorn Slough less directly. Sea level rise is not only relevant to salt marsh sustainability, but also to the larger community of landowners and other stakeholder around Elkhorn Slough. We thus conducted a needs assessment of landowners and decision-makers working on low lying parcels in the broader Elkhorn Slough region, where sea level rise would be most likely to inundate land and create restoration opportunities for coastal wetlands. This needs assessment led to and informed a workshop (held on 22 September 2010) to explore the potential value of sea level rise modeling to the larger community (Hayes 2012c). Stakeholder concerns and suggestions for improved tool design and sea level scenario development were captured. These included 1) improved visualization tools to include human features such as cities, towns, and highways, 2) incorporation of economic impact analyses into sea level rise scenarios, and 3) inclusion of effects of storm surge co-occurring with freshwater flooding events which may be an additive, and harbinger effect for sea level rise to coastal landowners. Overall, this group of stakeholders also desired simplification of communication materials and tools relative to what was appropriate for the more technically-savvy Tidal Wetland Program stakeholders. The team synthesized and considered these participant desires, and decided that the resources provided by the CICEET grant were insufficient for addressing the needs and concerns of this broader community, and that these goals were so divergent from the original CICEET focus on salt marsh sustainability. Instead, the Coastal Training Program has taken the lessons learned and incorporated them into regional collaborations on sea level rise issues with Stanford's Center for Ocean Solutions and The Nature Conservancy's Coastal Resilience program.

Developing tools to support marsh sustainability on California's central coast

In order to influence the larger decision maker community of funders, agencies, and estuarine managers (which, in turn, influence what is feasible at Elkhorn), the team's sea level rise and marsh sustainability modeling helped inform a more critical analysis of the parallel efforts taking place in the larger region. The Coastal Training Program began this larger regional engagement by conducting a needs assessment of key tidal wetland managers throughout especially central California, to determine the types of information most critical to their decision-making (Hayes 2012a). Through this needs assessment, we discovered that the relevance of paleoecology in informing adaptation and restoration strategies for tidal marshes is largely underappreciated due to lack of understanding of the importance of these analyses. This is especially apparent given the overshadowing concerns with sea level rise impacts and the lack of recognition of how paleoecology can inform sea level rise adaptation strategies. We also learned that there is a general divergence between three central processes in adaptation strategies for sea level rise. Generally speaking, those involved with modeling deliver products with unknown relevance. Those involved with monitoring, which is crucial to improve the inputs in sea level rise modeling do not have direction from modelers on the kinds of information needed to create more robust models. And, those managing tidal wetlands rely principally on outside consultants for project design, and are thereby largely disconnected from the ongoing discussion of improving sea level rise predictions and adaptation strategies.

As a result of these findings, the CTP helped link ESNERR researchers with regional scientists and managers and designed a workshop to evaluate and improve approaches to informing marsh sustainability in the face of climate change (Hayes 2012b). The goal was to better link those doing the monitoring, the modeling, and the management of these marshes. The workshop was held on 15 September 2011 in Oakland, jointly hosted by ESNERR, SFBNERR and the USGS. The workshop webpage makes available all the materials presented: http://www.elkhornsloughctp.org/training/show_train_detail.php?TRAIN_ID=:%20VYF86

This workshop explored (1) the status of marsh accretion modeling for California's estuaries, (2) what model inputs/improvements are needed to adequately predict the future sustainability of marsh habitats, and (3) interest in developing a white paper on modeling, monitoring, and management needs for California's estuaries in the face of sea-level rise. Modelers compared the strengths and weaknesses of three models (our CICEET team presenting SLAMM, and others introducing WARMER and MARSH98). Scientists conducting monitoring reviewed datasets available for parameterizing the models. Managers indicated their needs for information relevant to restoration and policy. Evaluations revealed a high level of satisfaction with the workshop. Moreover, a subset of participants has moved forward from this workshop to draft a white paper on marsh sustainability monitoring and modeling and an adaptive approach to engage scientists with estuarine managers. This community of tidal marsh managers and scientists are critical members in a culture of decision-making, whose approaches create the norms of tidal wetland management in California.

NEXT STEPS

The characterization of ancient marsh extent and of past sediment accumulation has been completed, and will soon be published in various manuscripts. This area of investigation was fruitful, but having answered the original questions, we do not anticipate an immediate need for further stratigraphic analyses at Elkhorn Slough. However, through our publications and presentations, we hope the approach of high spatial resolution of coring to reconstruct past environments can be applied at other estuaries.

Studies of causes of current marsh die-back and mechanisms of marsh sustainability must continue, because there are multiple hypotheses to be tested. The relative role of different human perturbations (an enlarged oceanic inlet, groundwater overdraft and poor water quality) need to be better understood and assessed in light of relevant feedbacks. We are continuing both monitoring and experiments to determine which hypotheses are best supported (Watson et al. 2011b, Watson 2012).

The sensitivity of our numerical models was a surprise. Whether Elkhorn Slough's marshes will sustain or whether they will rapidly disappear under even moderately increased rates of sea level rise depends on relatively minor adjustments to parameter values. Although the complex decision tree which underlies SLAMM is mature, like all numerical modeling systems, it has limitations. In particular, it operates in long (5 to 25 year) time steps with processes that are assumed to be steady state. Tidal, seasonal, astronomic, and other cycles are not accounted for—nor are storms, floods, and similar episodic events. Perhaps more important at Elkhorn Slough, the model neglects below ground processes including compaction, decomposition, and subsidence. Therefore we consider our modeling results preliminary and a work-in-progress.

Alternative approaches for modeling the effects of climate change on tidal wetlands are available (Fagherazzi et al. 2012). At least three are currently under development for use at San Francisco Bay Area wetlands. They include enhancements to the mass balance method pioneered by Krone and others (Krone 1985, 1987) and the sediment cohort accounting method pioneered by Callaway and others (Callaway et al. 1996). In addition, sophisticated commercial and academic hydrodynamic circulation models (e.g. DELFT-3D and TRIM-3D) are being developed for several estuarine sites. A key outcome from this project has been the establishment of collaborative relationships with proponents and developers of these alternative approaches. We hope to complement our SLAMM-based modeling with results from one or more of these approaches, thereby gaining additional insights and increased confidence in our predictions.

The Tidal Wetland Project has ambitious plans for strategic planning for Elkhorn Slough over the next years. The TWP strategic plan will be updated, setting out restoration priorities for the estuary for the next decade. Large-scale restoration alternatives designed to decrease impacts of the artificial harbor mouth will be evaluated, with recommendations provided by ESNERR staff to the key TWP decision-makers. In addition, TWP will lead a major sediment addition project to restore marsh on ESNERR. The new information and visualization tools provided by this project will prove essential for all of these initiatives. An understanding of past marsh baselines, of processes that sustain marsh, and of outcomes under different scenarios will be critical for collaborative decision-making about Elkhorn Slough's future. The researchers and the work they produced with this grant are anticipated to be a focal point for consideration of a newly formed TWP Geomorphology Technical Advisory Committee, which will use this and other technical information when making recommendations to the TWP.

The Coastal Training Program at ESNERR has become heavily engaged in climate change issues, partly as a result of this CICEET project. When conducting the needs assessment of coastal managers in the central California region (Hayes 2012a), it became clear that there are many unmet needs for linking emerging climate science to management and policy. The workshop hosted in partnership with USGS to evaluate different sea level modeling tools from a scientific and management perspective is one example of a key role the Elkhorn Slough Coastal Training Program can play in this arena (Hayes 2012b). In the future, we will build on the foundation laid by this CICEET grant by continuing to engage land managers, funders, and policy makers in better communicating their needs to scientists and researchers.

ACKNOWLEDGMENTS

We are grateful to our collaborators at Elkhorn Slough National Estuarine Research Reserve, especially V. Guhin, B. Largay, V. White, and A. Woolfolk, for their support of this project. M. Silberstein of the Elkhorn Slough Foundation provided instrumental guidance. We are indebted to our Technical Advisory Committee members for the thoughtful critiques and suggestions they provided: R. Anderson, D. Belknap, J. Callaway, D. Cahoon, J. Donnelly, M. Hornberger, J. Lacy, A. Kolker, G. Lessa, J. Morris, A. Paytan, D. Proosdij, D. Schwartz, D. Smith, and K. Swanson. H. Griffith, J. Nelson and S. Wheatley were key partners for the marsh biomass and decomposition study. This project would not have been possible without the grant we received from the Cooperative Institute for Coastal and Estuarine Environmental Technology. Additional funding was also provided by a grant from the Estuarine Reserves Division of NOAA to the Elkhorn Slough Foundation, in support of the Elkhorn Slough National Estuarine Research Reserve, a partnership between NOAA and California Department of Fish and Game.

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Table 1. Archival reference core locations and descriptions. These cores representing key geographic regions and stratigraphic 'archetypes' were scanned and archived at the National Lacustrine Core Repository.

Core Location UTM 10N	Region	Depositional Sequence	Core length
610700 4079950	Hudson's	Sedge peat topped by 30 cm of intertidal marsh sediments	3.1 m
610500 4075150	Rubis Creek	Panne sediments topped by 65 cm of intertidal marsh sediments	3.02 m
611900 4077150	Big Creek	Low organic content marsh sediments	2.65 m
608080 4072725	Harbor	Laminated silt and sand fluvial deposits	2.65 m
611711 4075706	Round Hill	Marsh sediments composed of alternating layers of pure sedge peat and highly mineral marsh sediments	3.02 m

Figure 1. Conceptual model of marsh sustainability. Human alterations are shown in yellow. Global climate change may interact with other regional anthropogenic alterations. To model future marsh trajectories, a thorough understanding of both those processes in brown and in yellow is critical.

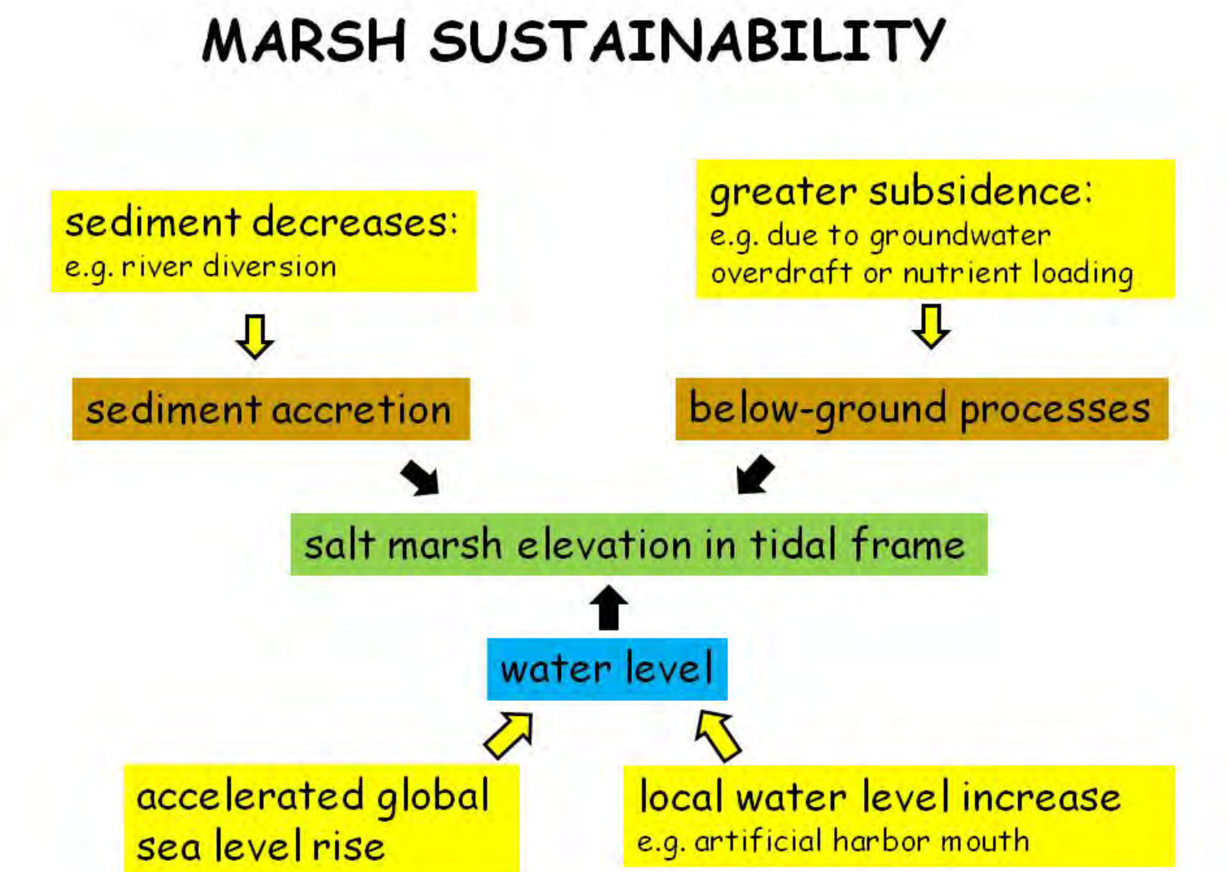


Figure 2. Conceptual model of this CICEET project. New science was conducted to fill critical gaps in understanding of marsh sustainability, past, present and future. This science was then incorporated into tools designed for coastal managers. Managers are currently employing the new information and tools to inform strategic planning of salt marsh conservation in the estuary.

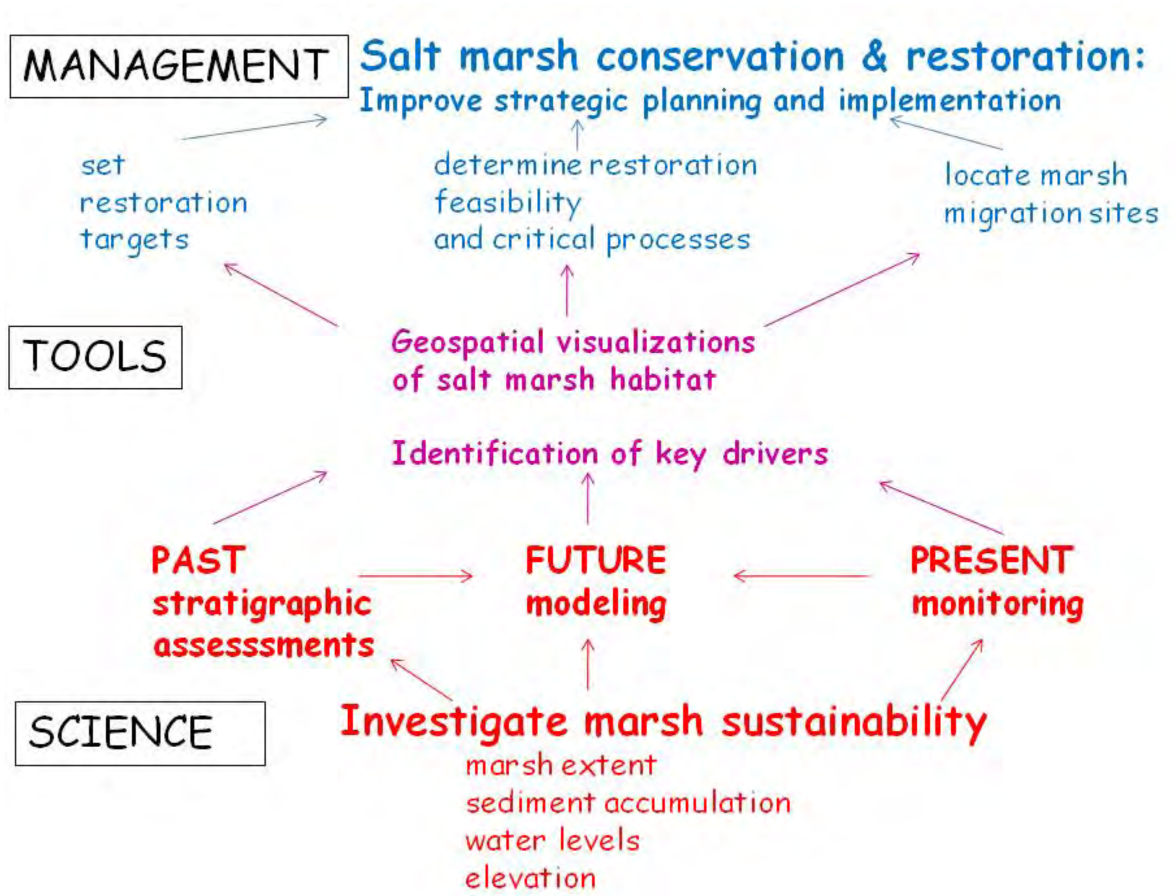


Figure 3. First map shows coring locations; remainder show marsh extent during different recent time periods.

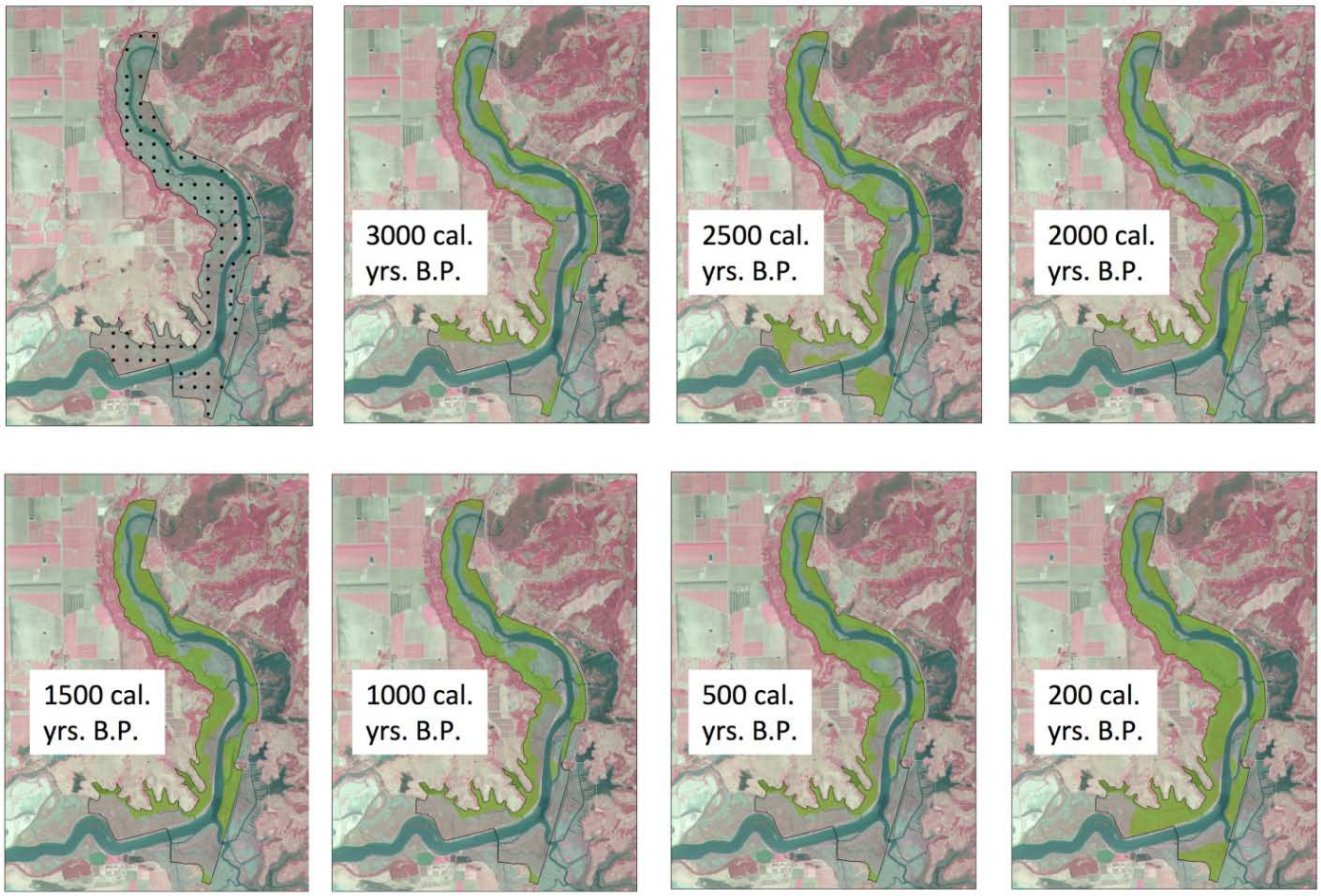


Figure 4. Sediment accumulation varies with geomorphic variables. Top panel shows that sediment accretion is higher at lower elevations. Bottom panel shows that sediment accretion rates are higher closer to creeks.

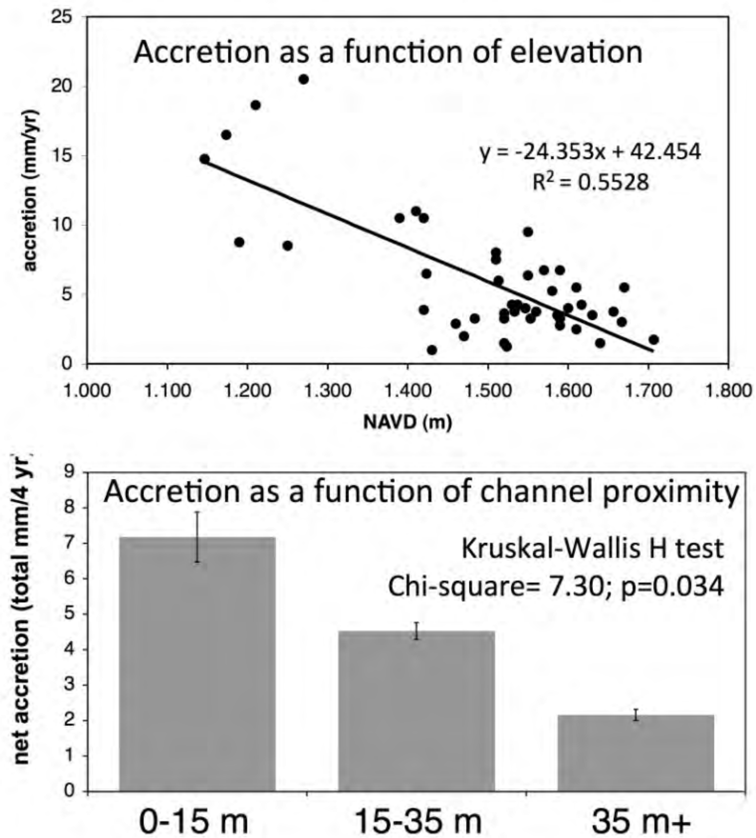


Figure 5. Radioisotope dating results from Elkhorn Slough tidal wetlands. Sediment accumulation is greater in healthy than in degrading marshes.

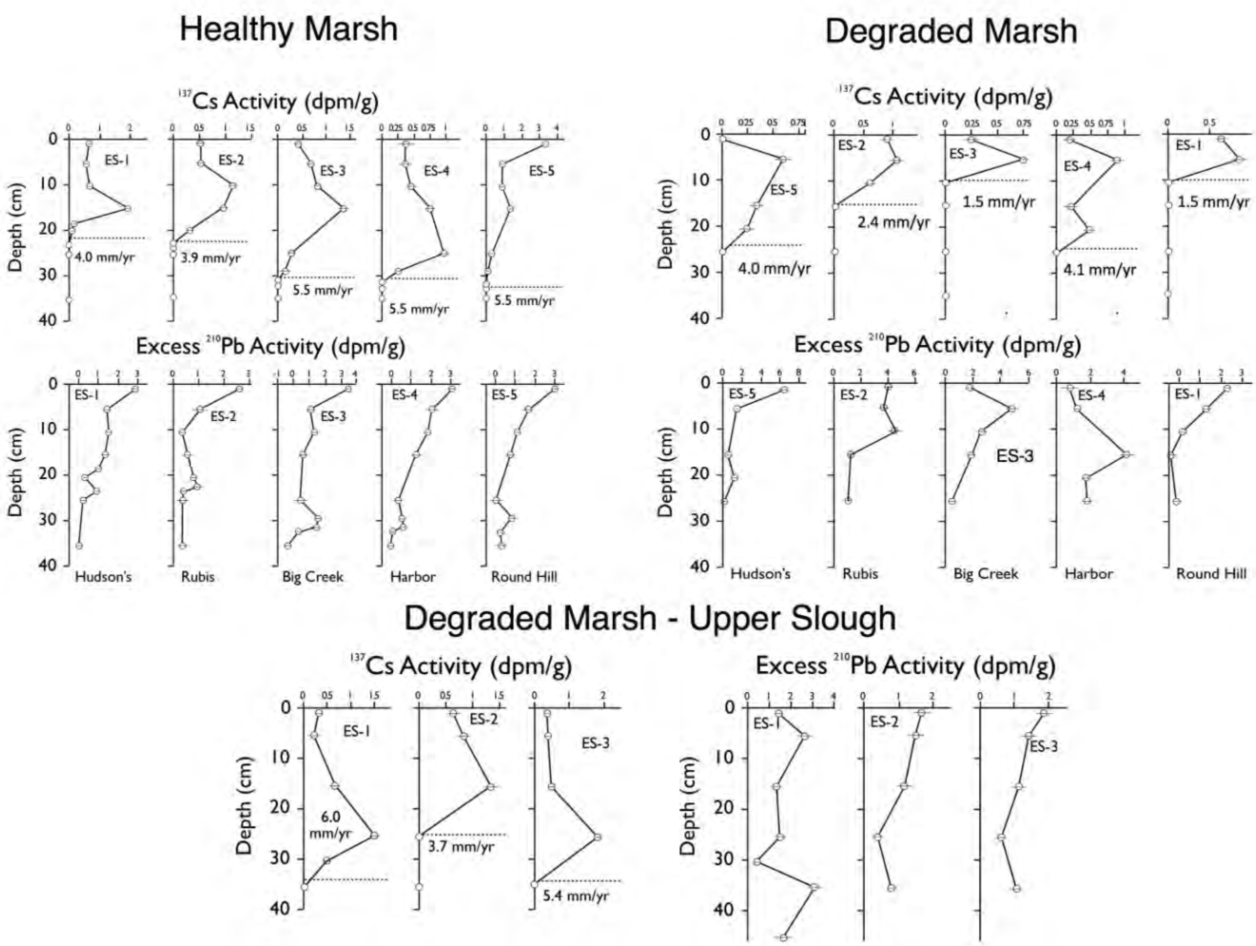
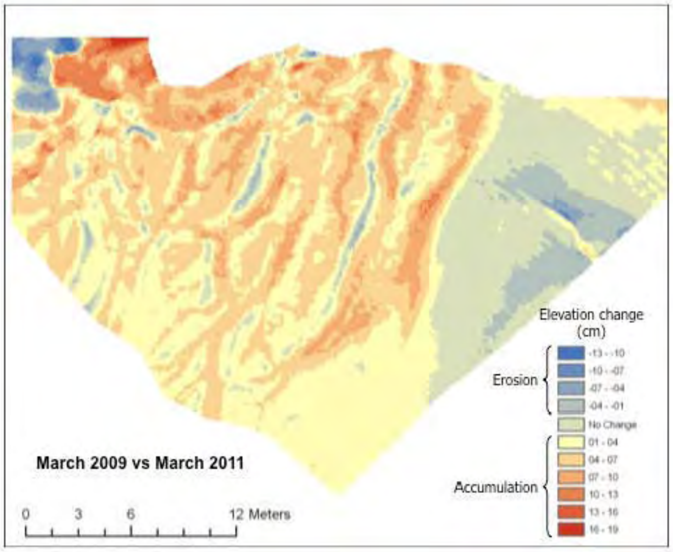


Figure 6. Results of terrestrial laser scanning from one site. These data illustrate how fine temporal and spatial resolution of sediment accumulation or erosion rates can be obtained by this methodology.



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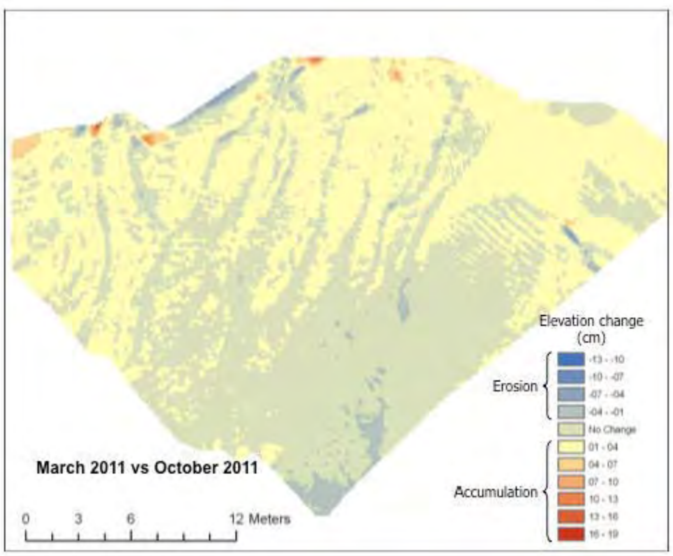

Figure 7. Root to shoot ratio variation between sites. All of these sites have significant nutrient loading. The most nutrient loaded sites ("highest-N") sites have lower root to shoot ratios than some of the less nutrient loaded ("high-N") sites. (From J. Nelson, in prep.)

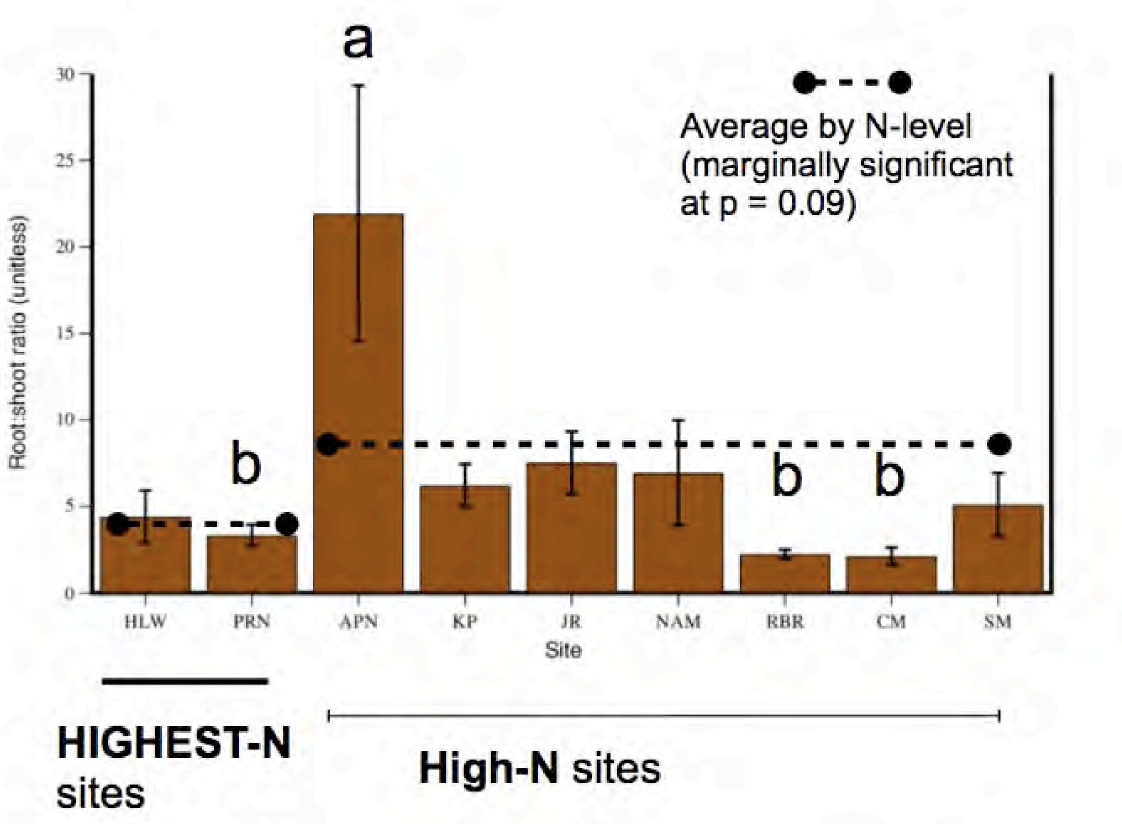

Figure 8. Six accelerated sea level rise scenarios used for model predictions and visualizations.

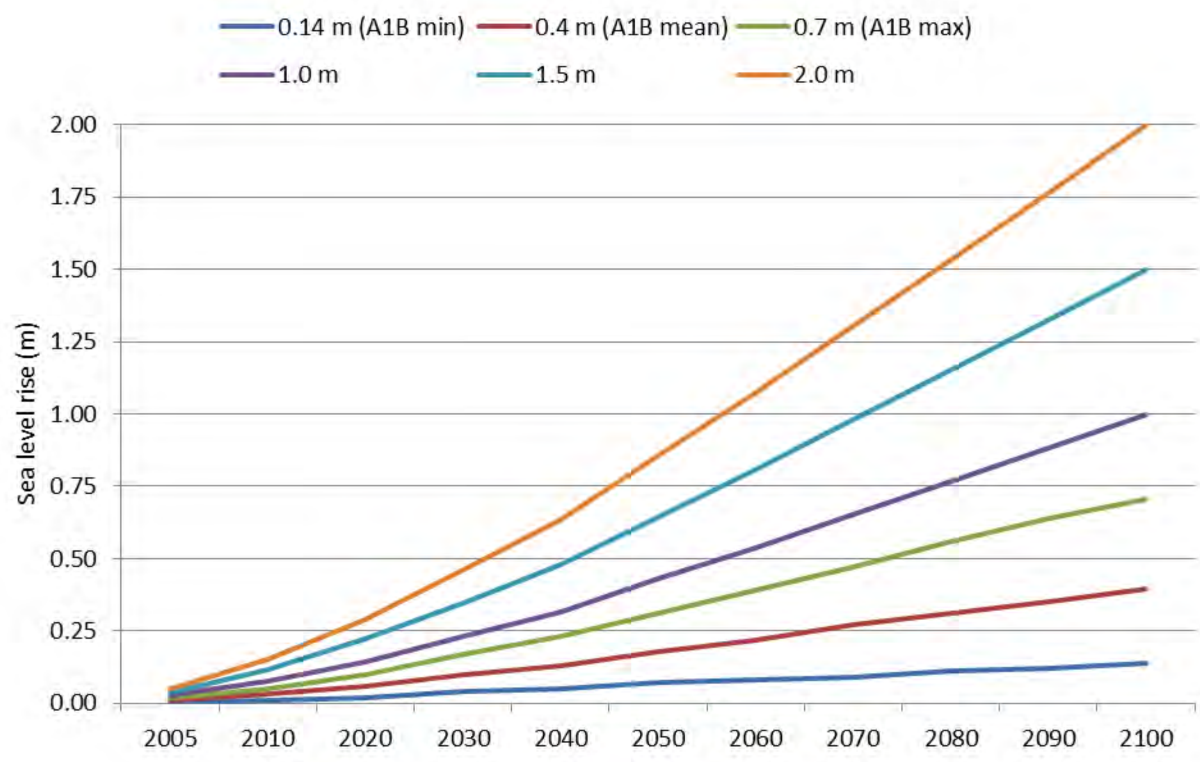

Figure 9. Dynamic sediment accretion. On vegetated marsh, accretion rate varies with inundation depth. Historic marshes, with low accretion rate, were stable (lower circle); current marshes are near or at instability (upper circle).

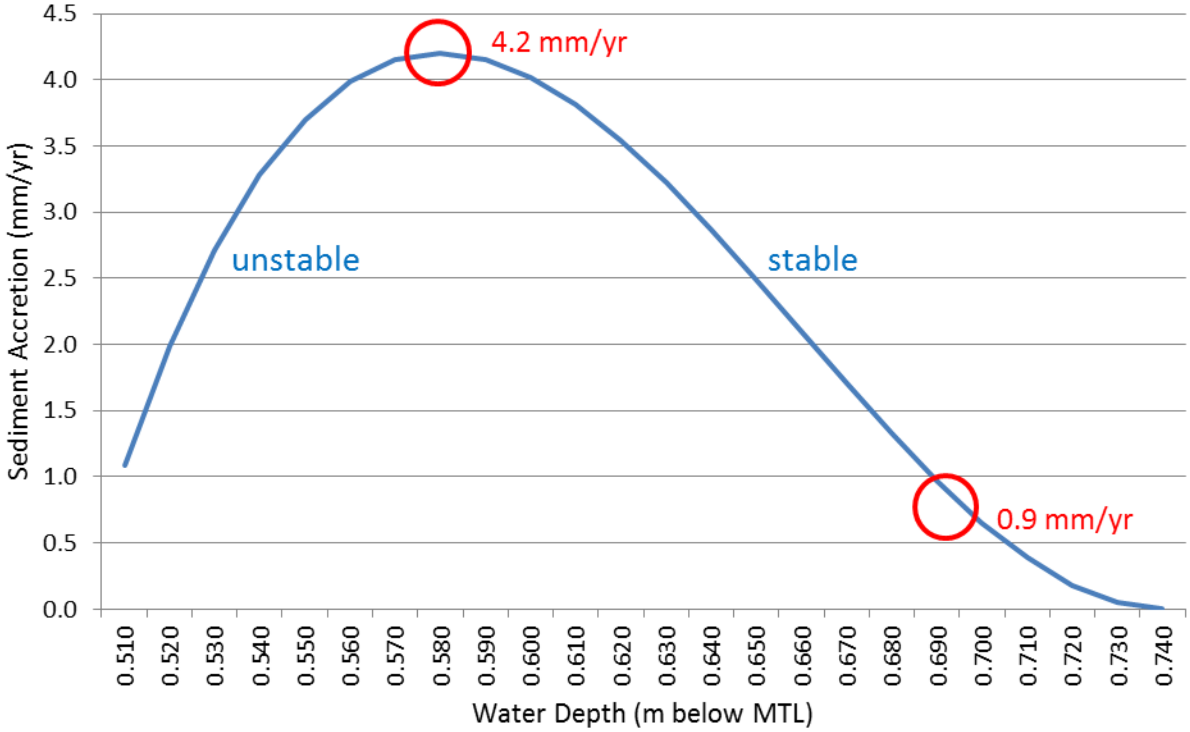

Figure 10. Model results showing marsh acreage change under six sea level rise scenarios. At year 2100, predicted marsh loss ranges from zero to 40% under moderate IPCC scenarios. Under more recent estimates of 1m and above, marsh loss would be more than 90%.

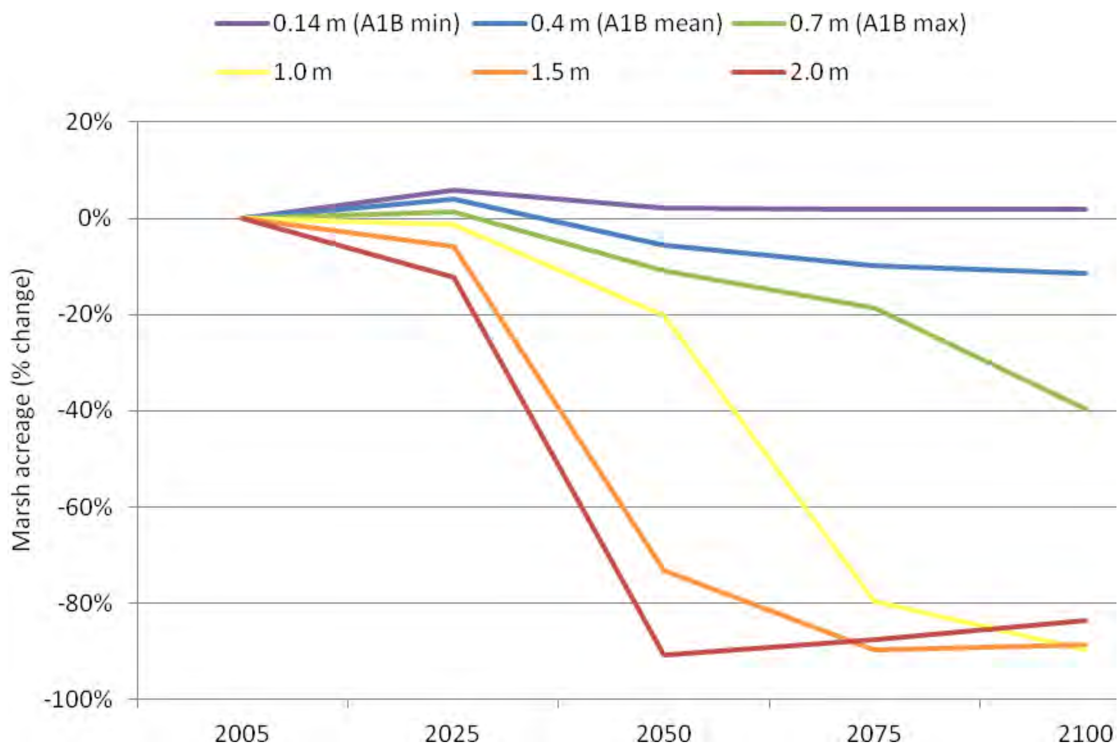

Figure 11. Model visualizations showing marsh acreage under three sea level rise scenarios at year 2100. Marsh loss would be 10% with 0.4m sea level rise (top), 40% with 0.7m rise (middle), and >90% with 1m rise (bottom).

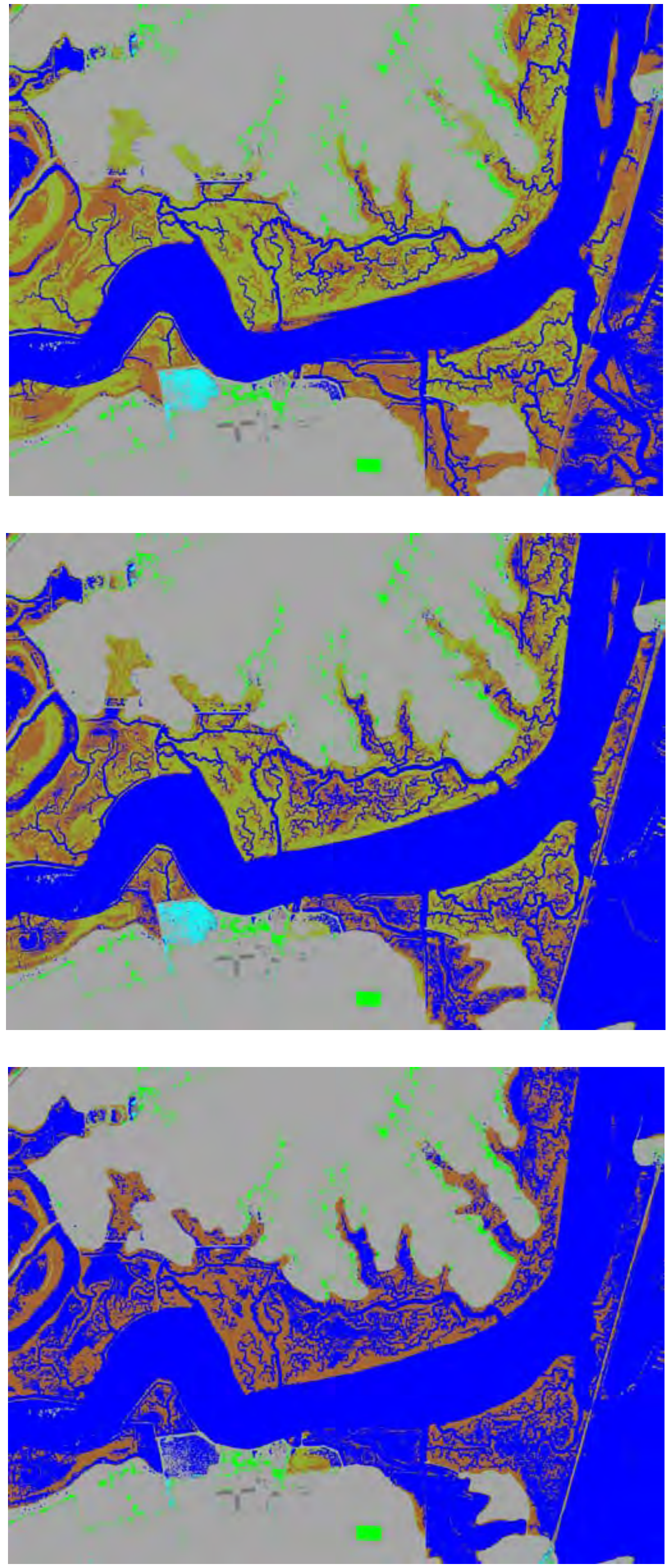

Figure 12. Hindcast model results showing marsh acreage change under three alternatives: 1947 marsh opening (sudden tidal increase), subsidence since 1947 (gradual elevation loss), and a mixture of the two processes. Ongoing marsh loss at Elkhorn Slough is best explained by a combination of the two processes.

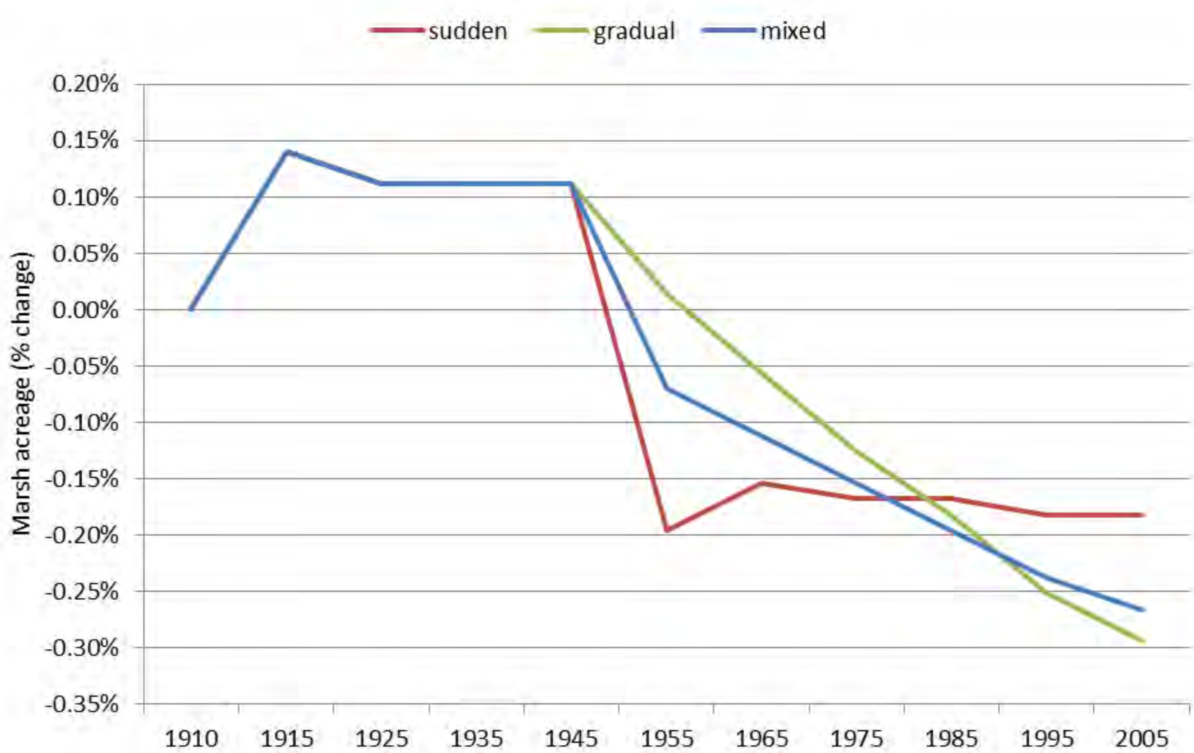

Figure 13. Model visualization showing limited opportunities for marsh migration. Red areas could support marsh after 0.4m sea level rise, yellow after 0.7m rise, and red after 1m rise.