CALFED BAY-DELTA PROGRAM

CALFED SCIENCE FELLOWS PROGRAM

Sea Grant California

In cooperation with the

California Sea Grant College Program

FELLOWSHIP APPLICATION COVER PAGE

APPLICANT TYPE [ ] Postdoctoral Researcher [X] Ph.D. Graduate Student

PROJECT NUMBER ______________

PROJECT TITLE Tidal wetland vegetation response to climate change in the San Francisco Bay-Delta: predictive modeling of species distributions in a changing environment

FINANCIAL SUMMARY

First Year CALFED Funds Requested: $42,513
Total CALFED Funds Requested: $125,750
Duration: 3 years
Proposed Start/Completion Dates: 09/01/07-08/31/10

APPROVAL SIGNATURES

FELLOW:

Name: Lisa M. Schile
Position/Title: PhD student, beginning Fall 2007
Department: Environ. Sciences, Policy, & Management
Institution: University of California, Berkeley
Address: 137 Mulford Hall #3114
City, State & Zip: Berkeley, CA
Telephone: (415) 378.2903
Fax: (510) 642.1477
E-mail: lmschile@gmail.com

MENTOR/PRINCIPAL INVESTIGATOR:

Name: Dr. N. Maggi Kelly
Position/Title: Adjunct Associate Professor
Department: Environ. Sciences, Policy, & Management
Institution: University of California, Berkeley
Address: 137 Mulford Hall #3114
City, State & Zip: Berkeley, CA
Telephone: (510) 642.7272
Fax: (510) 642.1477
E-mail: mkelly@nature.berkeley.edu

AUTHORIZED INSTITUTIONAL REPRESENTATIVE:

5/30/07

Name: Jyl Baldwin
Position/Title: Assistant Director, Compliance & Special Projects
Department: Sponsored Projects Office
Institution: The Regents of the University of California
Address: 2150 Shattuck, Suite 313
City, State & Zip: Berkelley, CA 94720-5940
Telephone: (510)642-8117
Fax: (510)642-8236
E-mail: jbaldwin@berkeley.edu

Will animal subjects be used? [ ] Yes [X] No
APPROVAL DATE: ______ PROTOCOL #: ______ PENDING: ______

Does this application involve any recombinant DNA technology or research? [ ] Yes [X] No

PROPOSED RESEARCH

Introduction

Many studies have been conducted on the variable effects of salinity, inundation, and competition on wetland plants on the East and Gulf coasts of the United States (McKee and Mendelssohn 1989; Lessman 1997; Baldwin and Mendelssohn 1998; Howard and Mendelssohn 2000; Donnelly and Bertness 2001; Crain et al. 2004; Konisky and Burdick 2004; Pennings et al. 2005), but, to date, a comprehensive investigation has not occurred in wetlands along the Pacific coast. Differences in climate, hydrology, vegetation, and landscape context require the examination of vegetative responses to changes in salinity, inundation, and competition in this system. More importantly, predictions of regional effects of climate change for the San Francisco Bay-Delta and other coastal California watersheds present a future with reduced summer freshwater input and increased sea levels. These effects would result in higher water salinities throughout the growing season, increased saline influence in brackish and freshwater marshes, and increased depth and duration of inundation. Because marshes act as ecotones between terrestrial and marine environments, it is crucial to understand how these vital ecosystems might respond to predicted climate change. Testing, analyzing, and spatially modeling the responses of dominant wetland vegetation to the substantial changes that are predicted with climate change are the critical links to understanding how this estuary and others along the Pacific coast might respond to significant changes in physical drivers.

Importance of Tidal Marshes of San Francisco Bay-Delta

Most of coastal California is characterized by a mediterranean-type climate, with warm, dry summers and rainy, cool winters (Josselyn 1983). Within the San Francisco Bay-Delta (Bay-Delta), run-off from Sierran snow pack and rain creates fresher water conditions in the estuary during the winter and spring, after which the estuary receives drastically reduced freshwater influx during the summer and fall (Conomos 1979). This, combined with high evapotranspiration rates, causes salt accumulation on marsh and upland surfaces, resulting in marshes with mixes of halophytic and freshwater species.

The Bay-Delta wetland landscape is an intricate mosaic of natural and restored wetlands intermixed with diked baylands, all surrounded by one of the country's largest urban areas. Since European settlement, roughly 90% of the wetlands in the Bay-Delta have been destroyed, primarily through agricultural practices and urban development (SFEP 1991; Fretwell et al. 1996). This has caused dramatic functional changes to the region over the last 150 years, including alterations in salinity regimes and nutrient cycling, that have made the estuary more vulnerable to plant and animal invasions than any other coastal environment in the U.S (Nichols et al. 1986; Cohen and Carlton 1998). These changes had a devastating impact on the region's natural ecosystem functions that continue presently. Loss of wetland habitat affects endangered endemic species, such as the salt marsh harvest mouse (*Reithrodontomys raviventris*), the California clapper rail *(Rallus longirostris obsoletus*), and the soft bird's beak (*Cordylanthus mollis spp mollis*). Therefore, there is considerable interest to maintain the integrity of current wetlands and facilitate restoration of the multiple diked baylands throughout the Bay-Delta.

Tidal marshes of the Bay-Delta line the bay and river margins, and in most cases, abut levees along urban and agricultural land. They are characterized by a mixed semi-diurnal tide cycle and span a salinity gradient from fresh to saline conditions. Salt marshes are found along San Francisco and San Pablo Bays, brackish marshes are located along the Napa River and Suisun Bay, and freshwater marshes occur in the Sacramento-San Joaquin delta. Each habitat type has a distinctive assemblage of plant species that is often species-rich (Grewell et al. 2007); however, there can be broad overlap in species occurrence. Tidal salt marshes within the Bay-Delta are dominated by *Sarcocornia pacifica* (pickleweed; formerly known as *Salicornia virginica*) throughout the majority of the marsh and dense stands of *Spartina foliosa* (California cordgrass) line channel edges and bay margins. Despite the dominance of these two species, Pacific coast salt marshes are diverse compared to Atlantic and Gulf Coast marshes (Zedler et al. 1999). In brackish tidal marshes, *Bolboschoenus maritimus* (alkali bulrush; formerly known as *Scirpus maritimus*), *S. pacifica*, *Typha angustifolia* (cattail), and *S. foliosa* are the most common plant species. *Bolboschoenus maritimus* and *S. pacifica* tend to occupy mid to high marsh elevations whereas *T. angustifolia* and *S. foliosa* are abundant at mid to low marsh elevations. All species commonly co-occur. The majority of sub-dominant diversity occurs along channel edges, with diversity reaching up to 13 species within four meters of a channel edge (Schile, Parker, Callaway, and Vasey, unpublished IRWM data). Further up the estuary into the delta, freshwater tidal marshes are dominated by *Schoenoplectus acutus* (tule; formerly known as *Scirpus acutus*), *Schoenoplectus californicus* (California tule; formerly known as *Scirpus californicus*), *Typha* species, *Phragmites australis* (common reed), *Schoenoplectus americanus* (common three-square; formerly known as *Scirpus americanus*), and *Salix lasiolepis* (arroyo willow). The latter two species are more abundant at higher marsh elevations whereas the other species are commonly found in lower marsh regions. As with the brackish marsh communities, there is broad overlap in species distributions. Freshwater tidal marshes have a very species-rich subdominant community, and species assemblages differ depending on marsh location (Vasey, Parker, Callaway, and Schile, unpublished IRWM data).

The estuarine setting within the Bay-Delta provides an ideal study location to examine how altered inundation and salinity regimes might affect species assemblages and dominance. Within each marsh type, particular species are more commonly found at lower marsh elevations (i.e. *S. foliosa, Typha* species, and *S. acutus*) whereas others are more abundant at higher marsh locations (i.e. *S. pacifica*, *B. maritimus*, and *S. americanus*). The influences of flooding, salinity, and competition have been shown to drive plant zonation patterns in southern California salt marshes (Pennings and Callaway 1992), but few data exist to document how plants will respond across an estuarine salinity gradient. Significant changes in estuarine conditions, specifically predicted effects of climate change, would likely shift species distributions across the Bay-Delta, both along salinity and inundation gradients. Thus, we need a better understanding of specific plant responses to changes in edaphic conditions to predict how these distributions might change in the future.

Effects of salt, inundation, and competition on plant growth

Plants growing in estuaries have specific morphologic and physiologic characters that enable them to persist in saline and regularly inundated environments. Salt can not only be directly toxic to most plant species but also can alter the osmotic potential within a plant, resulting in dehydration, wilting, and death (Mitsch and Gosselink 2000). Halophytic plants have adapted to saline environments by a variety of methods, such as excluding salt at the root surface, excreting salt directly from glands on the leaf surface, and sequestering salt solutes in enlarged vacuoles within the cells, producing thick, succulent leaves (Cronk and Fennessy 2001; Grewell et al. 2007). The main effects of inundation on plant growth are the reduction in soil aeration and excessive inundation (Chapman 1974; Ungar 1991). To tolerate growth under these low oxygen conditions, wetland plants commonly have aerenchyma, which is a tissue type with large air-filled cavities, have lenticels that enable increased oxygen uptake, or create rhizospheres, which are intentionally oxygenated areas directly around the root surface (Mitsch and Gosselink 2000). All of these adaptations facilitate growth in environments that most plants cannot tolerate; however, there are often limitations associated with growing in a wet environment that can result in reduced performance and even mortality. Data from a New England salt marsh have documented a landward shift in distribution for low marsh plants with accelerated sea-level rise, resulting in a decrease in area and performance of high marsh plant communities (Donnelly and Bertness 2001). Additionally, increases in sea level have been shown to reduce high salt marsh metabolism (Miller et al. 2001). Under water-logged conditions, toxins, such as hydrogen sulfide, can be produced as a result of the reduced soil environment and adversely affect rhizomes and roots (Goodman and Williams 1961; Cronk and Fennessy 2001) and limit nutrient uptake, growth, and biomass (Mendelssohn and Seneca 1980; Koch and Mendelssohn 1989), among other deleterious effects. Not all wetland plants are capable of existing under saline and/or water-logged conditions; therefore, measuring dominant tidal marsh plant survival, growth, and fecundity is crucial to understanding how plants will respond to changes in salinity and inundation predicted under future climate change scenarios.

Competition amongst co-occurring species is another crucial driver in plant distributions in tidal marshes (Crain et al. 2004). Sharp boundaries are often found within marshes where changes in edaphic conditions are gradual, which suggests that competition is important in structuring communities (Ungar 1998). Many studies have supported the hypothesis that the combined effect of salinity, inundation, and competition structure tidal wetland communities (Barbour 1978; Bertness 1991a,b; Pennings and Callaway 1992; Crain et al. 2004). Therefore, it is important to consider how species interactions will change under altered edaphic conditions predicted from climate change.

Predicted Effects of Climate Change

Mediterranean-climate tidal wetlands are particularly susceptible to the effects of climate change. As with other tidal wetlands, they share the threat of submersion if accretion rates are not in equilibrium with sea-level rise (SLR) (Morris et al. 2002, Turner et al. 2004) and differential impacts of CO_2 fertilization on C3 and C4 plants (Rasse et al. 2005). However, Mediterranean-climate tidal systems are additionally threatened by salt accumulation during the lengthy dry summers that will accelerate with warmer temperatures. Changes in patterns of precipitation and water management will exacerbate this impact, especially given the increased societal demands for water in a semi-arid climate. The composition, structure and dynamics of tidal wetland plant communities, among others, will be significantly changed by these influences, but current predictions are merely speculative. Consequently, a relatively limited history of basic research informs our current understanding of how tidal systems will respond, as well as management and policy actions.

Multiple models predict that a warmer global climate in a mediterranean-climate system will result in a reduced snowpack storage in mountain ranges, increased flooding during the rainy season, and reduced input of snowmelt during the summer, (Gleick 1987a,b; Roos 1989; Lettenmaier and Gan 1990; Gleick and Chalecki 1999; Knowles and Cayan 2002, 2004; Dettinger et al. 2004; Knowles et al. 2006); most of these models concur for changes in the California climate (Dettinger 2005). These hydrologic changes would influence ecosystems downstream, resulting in an altered salinity regime (Knowles and Cayan 2002). During the late spring and summer, the lower stream flows and increased salinities would affect many species that depend on the estuary and rivers. While several studies have examined current ecological conditions along the salinity gradient (Atwater et al. 1979, Pearcy and Ustin 1984), few have investigated how ecological systems in the estuary would respond to these changing conditions (Josselyn and Callaway 1988; Williams 1989).

Sea-level rise (SLR) is also likely to affect estuarine conditions and is projected to increase up to 89 cm over the next 100 years (Cayan et al. 2005; IPCC 2007), an acceleration of the recent rate of 23 cm/century (Flick and Cayan 1984). In response to increased rates of SLR, tidal marshes must either accumulate more sediment to keep pace with SLR, migrate inland to adjacent terrestrial areas, or face increased inundation (Donnelly and Bertness 2001; Morris et al. 2002). Most tidal marshes accumulate 2-8 mm of sediment per year (Stevenson et al. 1986; Reed 1995; Callaway et al. 1996), and this compensates for SLR and other processes. However, substantial data from Louisiana, Chesapeake Bay and modeling studies have shown that as increases in relative sea level get close to 10 to 12 mm/yr, most marshes can not keep pace and vegetation eventually may be inundated and converted to open water/mudflats (Baumann et al. 1984; Kearney and Stevenson 1991; Boesch et al. 1994; Morris et al. 2002; Rasse et al. 2005). Historic data from other systems have shown that slower increases in relative sea level (or loss in elevation) can lead to shifts in vegetation communities over time (Warren and Niering 1993). Although it may be possible for marsh accretion in the San Francisco Bay to keep up with SLR (Orr et al. 2003), bathymetric mapping studies have shown a decline in bay sediments over time (Foxgrover et al. 2004), and future large-scale tidal marsh restoration projects will further deplete existing bay sediments. Furthermore, in the heavily impacted Bay-Delta system, filled, diked, and developed baylands tidal systems are severely restricted in terms of adjacent terrestrial habitats for upslope migration in response to SLR. Thus there is a high level of uncertainty about tidal marsh responses to SLR. SLR contributes another significant stressor to the Bay-Delta system because most of the delta region is leveed and under agricultural practices.

Modeling Species Distributions

Species distribution models (SDM), also known as niche models or bioclimatic models, are growing in popularity as tools for predicting potential shifts in species' distributions as a result of climate change (Pearson and Dawson 2003; Thuiller 2004; Araujo et al. 2005). This empirical approach has distinct practical advantages because it provides more data-driven predictions than theoretical/analytical models, has greater precision than mechanistic or process-based models, and can also provide a high level of generality given proper inputs and informed ecological assumptions (Guisan and Zimmerman 2000). Most SDM work has been conducted at a broad scale, often at spatial resolutions of grid cells 1 km^2 or greater. Furthermore, the great majority of such modeling work has been done for upland terrestrial habitats. Very little species distribution modeling work has been conducted explicitly for coastal systems (but see Rehfisch et al. 2004), which necessitate a relatively fine-scale approach due to their limited narrow extent. An integrated approach using field surveys, field and greenhouses experiments, and predictions of changes in estuarine physical processes with climate change is necessary to produce accurate species distribution models, and all will be used in this proposed research.

Objectives and Hypotheses

Using a combination of field sampling, greenhouse and field transplant experiments, I propose to address the following overall question: *How will alterations in salinity and tidal inundation due to predicted climate change influence the distribution of dominant tidal marsh plant species?* To address this question, I will incorporate observational surveys, field experiments addressing individual and mixed species' responses to changes in inundation and salinity, and individual species responses to specific inundation and salinity regimes in a greenhouse experiment. Specific objectives and hypotheses are as follows:

Objective 1. Through intensive vegetation sampling tied in with elevation surveys and measures of inundation depth and duration, I plan to determine the lower elevation limits of dominant plant species across all habitat types and document patterns in inundation regime and salinity ranges within monospecific and assemblages of dominant species. I will collect baseline species and physical processes data through these surveys.

Objective 2. Through the field transplant experiments, I will examine how dominant species from freshwater, brackish, and salt marshes respond to increases in salinity and inundation when transplanted to marshes with higher salinity and into low marsh regions both within its current site and sites with higher salinity. Additionally, I will examine how those responses change when plants are in competition with co-occurring species, since competition can play a crucial role in wetland species distributions (Pennings and Callaway 1992; Crain et al. 2004). The control species for testing inundation effects are those that are currently found in the low marsh (i.e. *Typha* species, *S. acutus,* and *S. foliosa*), and the control species for measuring salinity effects are those that are found in brackish marshes (i.e. *B. maritimus* and *S. pacifica*). Specific hypotheses include, but are not limited to:

Hypothesis 1. Species transplanted into regions of either increased salinity or increased inundation will have lower performance (i.e., shorter stature, lower fecundity, and increased mortality) compared to species transplanted into their native habitat and marsh location.

Hypothesis 2. The combined effect of increased salinity and inundation will have the strongest negative effect on plant performance compared to the individual effects alone.

Hypothesis 3. Plants in competition with plants of another species will have lower performance under increased salinity and inundation regimes than plants that are transplanted with conspecifics only.

Objective 3. Through a greenhouse experiment, I will measure the performance of individual dominant species and one common invasive species from salt, brackish, and freshwater marshes under a variety of salinity and inundation regimes. Data collected will provide parameters for species and habitat distribution models. Specific hypotheses include, but are not limited to:

Hypothesis 4. Species adapted to saline conditions will have maximum performance when grown under brackish salinity conditions than either fresh or salt water (i.e., sea water) conditions.

Hypothesis 5. Species that commonly occur in low marsh regions will be less affected by increases in inundation than increases in salinity.

Hypothesis 6. Species that commonly occur in mid to high marsh regions will be less affected by increases in salinity than increases in inundation.

Hypothesis 7. The combined effects of increased salinity and inundation will result in the lowest performance when compared to individual stressors alone.

Objective 4. Using existing spatially explicit species distribution models (i.e., MaxEnt), I will model the potential niche of each of the target species, conditioned by salinity, inundation, elevation, and land use parameters derived in Objectives 1 through 3 for current Bay-Delta conditions and predicted climate change scenarios. I will incorporate previously collected data, including data from five CALFED-funded grants. My goal with this objective is to understand large scale potential habitat shifts and losses under these scenarios. The likely model outcomes will show an increase in salt and brackish marsh habitat further up into the estuary and a resulting decrease in freshwater marsh area. Additionally, species adapted to frequent tidal inundation will likely increase in cover across the entire estuary.

Approach / Plan of Work

This study will examine the effects of increased salinity and inundation on dominant tidal marsh plant species through a combination of field surveys, field transplants, and greenhouse experiments. Data collection and analysis will complement a recent CALFED-funded grant exploring the relationship between pelagic food webs and tidal wetlands in the Bay-Delta. The data collected under this fellowship will provide parameters for species occurrence and spatial modeling of marsh habitat change under a variety of predicted climate change scenarios. Although not explicitly defined in this proposal, I will work closely with the Principal Investigators involved in the CALFED-funded project and provide crucial inputs and calibration for the species distribution modeling that I will conduct by incorporating the effects of climate change on pelagic food web and plant distributions throughout the Bay-Delta. Although there is a small amount of overlap in the field surveys with this CALFED grant, the majority of the proposed research is independent of, but complimentary to, the funded grant.

Study Location

Research will be conducted at six natural marshes throughout the northern San Francisco Bay-Delta: China Camp State Park, Petaluma River Marsh, Coon Island, Rush Ranch Open Space Preserve, Brown Island, and Sandmound Slough (Figure 1). The sites span the estuarine salinity gradient and represent two each of salt, brackish, and freshwater wetlands. China Camp and Rush Ranch are part of the SF Bay National Estuarine Research Reserve.

Field Surveys

At each site, multiple vegetation and elevation surveys will be conducted along transects. Plant presence, abundance, and average height will be recorded within a 1 m-radius circular plot. Using real-time kinetic (RTK) GPS equipment, elevations of each vegetation survey will be measured, and the transect locations will be marked. Appropriate benchmarks will be located and geoid models will be created for each site in order to achieve positional accuracy of less than 5 cm. Two pressure transducers will be installed at each site, one along a channel edge and one within the marsh plain. Sandmound Slough, however, will only have one pressure transducer due to its small size. Data will be recorded at regular intervals to characterize inundation patterns, specifically depth and duration of inundation. During specific periods important to plant growth (early spring and mid summer), a simple technique to measure inundation depths utilizing wooden dowels and water soluble glue will be included to measure specific inundation depths in areas close to the pressure transducers. The depth measurements will be calibrated using data from the pressure transducers. Data from these surveys will address Objective 1. Data will be analyzed using general linear models.

Some of the data collection methods described above will be conducted under the CALFED funded pelagic food web grant and are, therefore, not novel to this proposal; however, the incorporation of monitoring inundation and focusing on the distributional extremes of plant species are unique to this proposal and are necessary for a clearer understanding of these systems.

Transplant experiment

In order to monitor the individual and combined effects of competition and salinity and inundation regimes on plant communities, I will conduct a transplant experiment using dominant species from fresh, brackish, and saline sites. The goal of the experiment is to measure how plants grow under natural marsh conditions in areas of increased salinity and inundation regimes and to quantify how plant performance changes when grown in competition with regularly co-occurring species. Since the majority of predicted outcomes of climate change in the Bay-Delta assume increased inundation and salinity, I will not focus on plant responses to decreased salinity and inundation (i.e., transplanting species into fresher marshes under drier conditions). Additionally, I acknowledge the importance of monitoring the responses of subdominant plant communities to changes in edaphic conditions; however, the focus of this research is specifically on responses of dominant plant species assemblages. Soil plugs roughly 0.027 m^3 containing monospecific and fully-factorial mixtures of dominant freshwater species, specifically *S. acutus, Typha* species, and *S. americanus*, will be removed and transplanted into each brackish marsh (Table 1). This will result in seven different conspecific and mixed species combinations. Additionally, soil plugs of each species and species mixture will be transplanted within their native habitat to monitor effects of transplantation and also transplanted into areas of increased inundation within its native marsh. The same procedure will be followed with species from the brackish sites, specifically *B. maritimus*, *S. americanus*, and *T. angustifolia*, which will be transplanted only into the salt marsh sites (Table 1). In the salt marshes, plugs of *S. pacifica* will be transplanted into areas with increased inundation only (Table 1). Ideally, *Lepidium latifolium* (pepperweed; invasive) should be incorporated into this experiment, but I will not introduce an invasive plant to areas where it currently is not found.

Differences in the inundation regime will be manipulated by locating the plots in low marsh areas, both within the native marsh and marshes with increased salinity. The effects of increased salinity will be addressed by moving plants downstream in the estuary. I will also address competitive interactions by 1) transplanting plugs with mixtures of species and 2) placing the plugs into plots with and without existing vegetation. A variety of plant characteristics, including but not limited to height, number of inflorescences, and survival, and physical characters, including depth and duration of inundation, redox potential (a measure of soil saturation and potential plant stress), and pore water salinity, will be measured on a monthly basis for two growing seasons, after which plants will be removed to determine biomass. This experimental approach will address Objective 2 and Hypotheses 1 through 3. Data will be analyzed using general linear models and structural equation modeling.

Greenhouse experiment

A greenhouse experiment will be conducted in two phases. I will conduct a preliminary growth experiment to address variation in growth between multiple individuals of the same species collected from different sites. The amount of variation in measured response variables will determine the sample size and number of replicates for the main experiment. Data will be entered into to the software PASS to determine adequate sample sizes for the maximum statistical power.

In the main greenhouse experiment, multiple individuals of the following plant species will be collected from two to three sites each: *S. pacifica*, *S. foliosa*, *B. maritimus*, *S. americanus*, *S. acutus*, *T. angustifolia*, and *L. latifolium* (invasive). Plants will be rinsed of native soil, transplanted into a clay-sand soil mixture, fertilized, and left to acclimate for two months. After acclimation, replicates of each species will be subjected to multiple salinity regimes, with target salinity levels of 0, 5, 15, 25, and 35 ‰ NaCl, and two to three inundation regimes representing current and predicted sea levels (i.e., 10 (current), 20, and 40 cm depth). Each group of containers with a specific salinity will be connected to its own reservoir and water will be pumped every 12 hours to mimic diurnal tides. Weekly soil salinity and redox potential measurements will be taken. A variety of plant characteristics, including but not limited to survival, height, and number of inflorescences, will be measured every two weeks for 6 months, after which all surviving plants will be rinsed of all sediment and dried to a constant weight to determine biomass. This experiment will address Objective 3 and Hypotheses 4 through 7. Data will be analyzed using general linear models incorporating effects of species, site, salinity, inundation, and the resulting interactions.

Species and Habitat Modeling

With the guidance of a community mentor, the faculty mentor, and researchers involved in the CALFED-funded grant on the effects of climate change on pelagic food webs and tidal marshes, I will incorporate the data collected from the experiments and observational studies into species-specific and habitat models. Species occupancy models will be populated with data collected in the field surveys to determine the probability of occurrence given certain site parameters (MacKenzie et al. 2006). Additionally, spatially explicit species distribution modeling, specifically maximum entropy models (i.e., MaxEnt; Phillips et al. 2006) will be run using GIS (geographic information system) layers, such as topography, land use, and seasonal salinity, to predict changes in species distribution. Other modeling methods, such as classification and regression trees (CART), generalized linear models (GLM) and generalized additive models (GAM), will also be incorporated.

Using these models, I will predict changes in tidal wetland habitat distribution under a range of climate change scenarios. The species data that will be used in the model will come from a variety of sources. Specifically, data from this proposed research will be fundamental in parameterizing the models. From the work that I have conducted in collaboration with multiple Principal Investigators on the Integrated Regional Wetland Monitoring (IRWM) program, a CALFED-funded project conducted from 2003 through 2007, species distributions and elevation, salinity, and inundation data will be incorporated. Additionally, vegetation data collected during the BREACH 1 and 2 studies, another grant that received CALFED funding, will be used. For estimates of future salinity, I will incorporate predictions generated by the CALFED-funded CASCaDE project (http://sfbay.wr.usgs.gov/cascade/), an extension of previous California climate modeling work conducted by the principal investigators (Knowles and Cayan 2002; Dettinger et al. 2004; Knowles et al. 2006). For estimates of future inundation data, I will model tidal inundation data using continuous water level data from NOAA, various municipalities, and restoration projects, including sites monitored during the IRWM program. I will develop tidal inundation graphs for each tide gauge location and calculate total monthly and maximum daily tidal inundation during the growing season (June/July), as well as tidal range. Inundation metrics will be interpolated across the subtidal and intertidal portions of the Bay-Delta, and adjusted for each SLR scenario to estimate future inundation metrics. Sediment accretion will be incorporated using a variety of conditions, including scenarios where marshes maintain elevation with SLR, gain sediment but at rates not in equilibrium to SLR, or remain at current elevations. All data will be maintained with common projection and GIS metadata standards.

Anticipated Products

The results from this proposed research will help local resource managers and researchers to manage and predict changes in this valuable ecosystem under an uncertain future. First, a greater understanding of edaphic factors driving current species distributions will be produced. I will document species distributions along salinity, elevation, and inundation gradients, which will aid in restoration planning for resource managers and policy makers. Second, comprehensive data on species responses to altered salinity and inundation regimes will be produced, which will provide critical parameterization of climate change models for the Bay-Delta and other Pacific coast watersheds. Additionally, understanding how species respond to changes in their physical environment both individually and in competition with others is critical for predicting changes in species assemblages. Third, I will collaborate with my faculty mentor, Dr. Maggi Kelly, and one of my community mentors, Dr. Mark Herzog, to generate scientifically valid models of dominant plant species occurrence and predicted habitat changes throughout the Bay-Delta under various climate change scenarios. The model outputs will benefit multiple agencies, including but not limited to, PRBO Conservation Science, which might use the predicted habitat changes to predict bird species distribution, and the San Francisco Estuary Institute (SFEI), which conducts broad landscape monitoring of tidal wetlands. Fourth, I will actively promote and disseminate the findings of this research to policy makers, resource managers, academics, and the general public in order to raise awareness of how predicted climate change will affect local tidal marsh communities. As examples of planned outreach, I will create a webGIS of the data produced and of the model outputs, I will attend multiple regional and national science conferences, and I will collaborate with one of my community mentors, Dr. Drew Talley, to generate other effective methods to disseminate the data and other priority topics for CALFED research. Additionally, Dr. Kelly, my faculty mentor, is part of the Cooperative Extension program at the University of California, Berkeley. She incorporates short courses, workshops, presentations, printed material and use of the web to disseminate information to the general public and I will be involved in incorporating my finding inter her Cooperative Extension model. Finally, I will incorporate data generated from five CALFED-funded projects in addition to the proposed research to generate comprehensive models that not only aid in climate change research but directly benefit CALFED by consolidating long-term data and integrating them into cohesive, Bay-wide models.

Over the past three and a half years, I have worked intensely in many natural and restored marshes across the Bay-Delta through my involvement in the IRWM grant and a grant monitoring sedimentation rates in the South Bay salt pond island ponds. This work has solidified my strong desire to preserve and restore wetlands and has provided a solid background in estuarine processes in the Bay-Delta. The research proposed in this grant would build upon my current understanding of tidal wetlands and will enable me to interact further with local and state agencies to expand and disseminate my knowledge.

The results from this proposal will directly apply to two of CALFED's main PSP priority areas: 'Trends and Patterns of Populations and System Response to a Changing Environment' and 'Habitat Availability and Response to Change'. The first PSP priority area is addressed directly through the experimental investigation into tidal wetland plant tolerance to changes in key physical processes and the spatial modeling of plant distributions under a variety of predicted climate change scenarios. The second PSP priority area is addressed through the spatial modeling exercises as well. Model outputs will be highly beneficial to other researchers and resource managers who are modeling Bay-Delta dynamics.

The objectives presented in this proposal will be addressed over three years of research (Table 2). The first objective relating to observational studies of dominant plant distribution along elevation, inundation, and salinity gradients will be addressed during the late spring/early summer of years 1 and 2 of the study. I will initiate the transplant experiment addressed under the second objective during year 1, and I will monitor plant responses monthly over two years. The initial stage of the greenhouse experiment discussed in Objective 3 will be conducted during year 1, while the main experiment will occur during year 2. All of the modeling described in objective 4 will occur during the third year of research. Across all years, data will be entered, analyzed and summarized to expedite report and manuscript generation during year 3. Combined, these research objectives will produce a thorough investigation of how dominant tidal marsh plant species might respond to predicted climate change in the San Francisco Bay-Delta.

Table 1. Proposed experimental design for the transplant experiment. In each species group, soil plugs containing individual species, all combinations of paired species assemblages, and a mixture of all three species will be transplanted into each marsh and marsh location.

		Typha sp., S. acutus, S. americanus group		*T. angustifolia, B. maritimus, and S. americanus* group		*S. pacifica*	
Site	**Marsh Type**	**Collect From**	**Transplant To**	**Collect From**	**Transplant To**	**Collect From**	**Transplant To**
Sandmound Slough	freshwater	X	low marsh				
Browns Island	freshwater	X	low marsh				
Rush Ranch	brackish		mid & low marsh	X	low marsh		
Coon Island	brackish		mid & low marsh	X	low marsh		
Petaluma River Marsh	salt				mid & low marsh	X	low marsh
China Camp	salt				mid & low marsh	X	low marsh

Table 2. Schedule for proposed research.

	2007			
	Sep	Oct	Nov	Dec
Locate areas for surveys and transplant experiment	■	■		
Compile existing data on Bay-Delta marshes	■	■	■	■

	2008											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Conduct field surveys				■	■	■						
Collect plants for preliminary greenhouse experiment		■										
Run preliminary greenhouse experiment					■	■	■	■				
Field transplant experiment		■	■	■	■	■	■	■	■	■	■	■
Summarize data										■	■	■
Analyze data and run spatial models												

	2009											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Conduct field surveys, cont				■	■	■						
Collect plants for greenhouse experiment		■										
Run greenhouse experiment					■	■	■	■	■	■		
Field transplant experiment, cont.	■	■	■	■	■	■	■	■	■	■	■	■
Summarize data, cont.	■	■										■

	2010							
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Field transplant experiment, cont.	■	■	■	■	■	■		
Summarize data	■	■	■	■				
Analyze data and run spatial models					■	■	■	■
Write reports and manuscripts	■	■	■	■	■	■	■	■

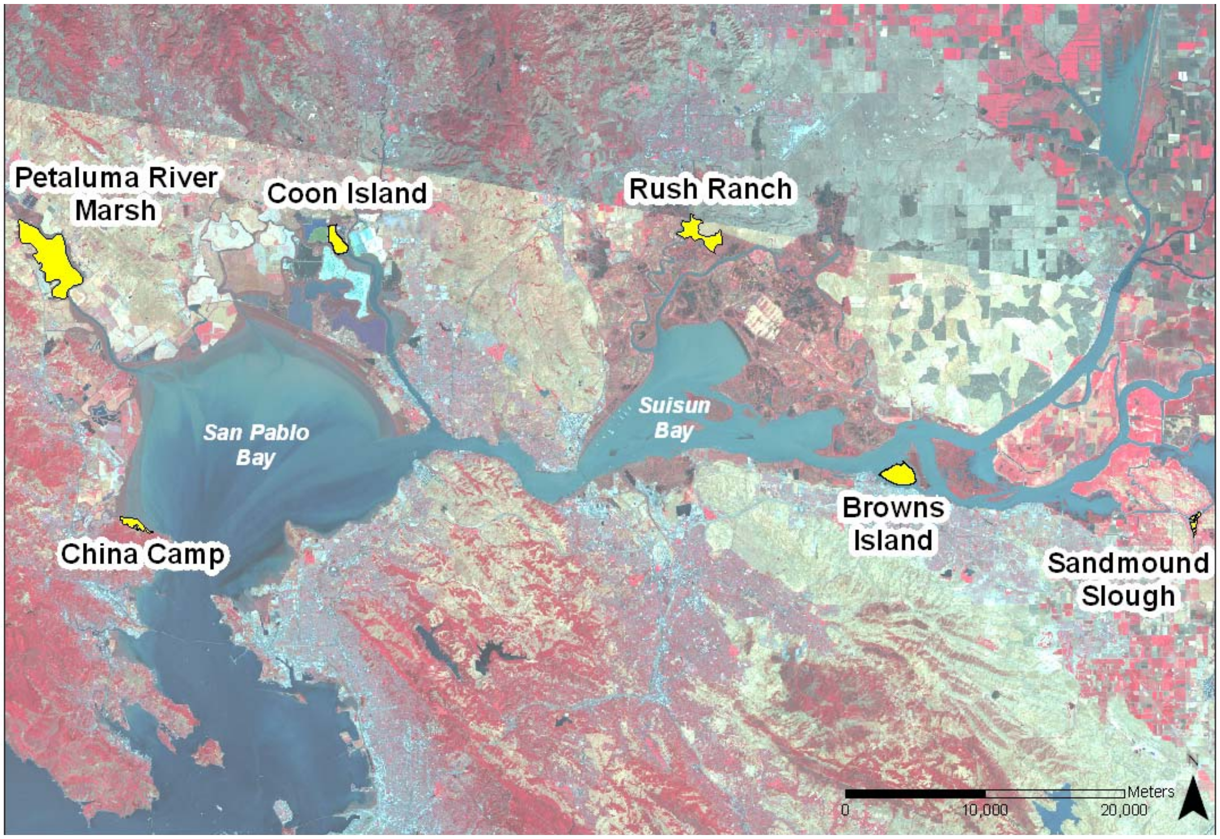

Figure 1. Distribution of study sites across the northern stretch of the San Francisco Bay-Delta.

Literature Cited

Araujo, M.B., R.G. Pearson, W. Thuiller, and M. Erhard. 2005. Validation of species-climate envelope models under climate change. Global Change Biology 11: 1504-1513.

Atwater B.F.S., G. Conard, J.N. Dowden, C.W. Hedel, R.L. MacDonald, and W. Savage. 1979. History, landforms, and vegetation of the estuary's tidal marshes. In: Conomos TJ (ed.) San Francisco Bay: the urbanized estuary. Pacific Division AAAS, San Francisco, pp 347-385.

Baldwin, A.H. and I.A. Mendelssohn. 1998. Effects of salinity and water level on coastal marshes: an experimental test of disturbance as a catalyst for vegetation change. Aquatic Botany 61: 255-268.

Barbour, M.G. 1978. The effects of competition and salinity on the growth of a salt marsh plant species. Oecologia 37: 93-99.

Baumann, R.H., J.W. Day, Jr., and C.A. Miller. 1984. Mississippi deltaic wetland survival: Sedimentation versus coastal submergence. Science 224:1093-1095.

Bertness, M.D. 1991a. Interspecific interactions among high marsh perennials in a New England salt marsh. Ecology 72: 125-137.

Bertness, M.D. 1991b. Zonation of *Spartina patens* and *Spartina alterniflora* in a New England salt marsh. Ecology 72: 138-148.

Boesch, D.F., M.N. Josselyn, A.J. Mehta, J.T. Morris, W.K. Nuttle, C.A. Simenstad, and D.J.P. Swift. 1994. Scientific assessment of coastal wetland loss, restoration and management in Louisiana. Journal of Coastal Research Special issue 20:1-103.

Callaway, J.C., J.A. Nyman, and R.D. DeLaune. 1996. Sediment accretion in coastal wetlands: A review and a simulation model of processes. Current Topics in Wetland Biogeochemistry 2:2-23.

Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2005. Projecting Future Sea Level. California Climate Change Center Report (CEC-500-2005-202-SD), December 2005. http://www.energy.ca.gov/2005publications/2005_pubs_alpha_order.html.

Chapman, V.J. 1974. Salt marshes and salt deserts of the world, 2nd edition. J. Cramer, Berlin, Germany.

Cohen, A.N. and J.T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. Science 279(5354): 555-558.

Conomos, T.J. 1979. Properties and circulation of San Francisco Bay waters. In San Francisco Bay: the urbanized estuary. T.J. Conomos (ed). San Francisco, California: Pacific Division of the American Association for the Advancement of Science. 493 p.

Crain, C.M., B.R. Silliman, S.L. Bertness, and M.D. Bertness. 2004. Physical and biotic drivers of plant distribution across estuarine salinity gradients. Ecology 85(9): 2539-2549.

Cronk, J.K. and M.S. Fennessy. 2001. Wetland plants: biology and ecology. Lewis Publishers, Boca Raton, Florida.

Dettinger, M.D. 2005. From climate change spaghetti to climate-change distributions for 21st Century California. San Francisco Estuary and Watershed Science 3(1) Article 4. http://repositories.cdlib.org/jmie/sfews/vol3.iss1.art4

Dettinger, M.D., D.R. Cayan, M.K. Meyer and A.E. Jeton. 2004. Simulated hydrologic responses to climate variations and change n the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099. Climatic Change 62:283-317.

Donnelly, J.P. and M.D. Bertness. 2001. Rapid shoreward encroachment of salt marsh cordgrass in response to accelerated sea-level rise. Proc. Nat. Acad. Sci. (USA) 98: 14218-14223.

Flick, R.E. and D.R. Cayan. 1984. Extreme sea levels in San Diego, California: winter 1982-1983. Coastal Engineering, pp 886-898.

Foxgrover, A.C., S.A. Higgins, M.K. Ingraca, B.E. Jaffe, and R.E. Smith. 2004. Deposition, erosion, and bathymetric change in South San Francisco Bay: 1858-1983: U.S. Geological Survey Open-File Report 2004-1192.25 p.

Fretwell, J.D., J.S. Williams, and P.J. Redman, editors. 1996. National Water Summary on Wetland Resources. Water-Supply Paper 2425, U.S. Geological Survey. Washington, DC.

Gleick, P.H. 1987a. The development and testing of a water-balance model for climate impact assessment: Modeling the Sacramento Basin. Water Resources Research 23:1049-1061.

Gleick, P.H. 1987b. Regional hydrologic consequences of increases in atmospheric carbon dioxide and other trace gases. Climatic Change 10:137-161.

Gleick, P.H., and E.L. Chalecki. 1999. The Impacts of Climatic Changes for Water Resources of The Colorado and Sacramento-San Joaquin River Basins. Journal of the American Water Resources Association 35:1429-1441.

Goodman, P.J. and W.T. Turner. 1961. Investigations into 'die-back'. Journal of Ecology 49: 391-398.

Grewell, B.J., J.C. Callaway, and W.R. Ferren, Jr. In press. Estuarine Wetlands. In Terrestrial Vegetation of California, 3rd edition. M. Barbour, T. Keeler-Wolf, and A.A. Schoenherr (eds). University of California Press, Berkeley, California.

Guisan, A., and N.E. Zimmermann. 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135: 147-186.

Howard, R.J. and I.A. Mendelssohn. 2000. Structure and competition of oligohaline marsh plant communities exposed to salinity pulses. Aquatic Botany 68: 143-164.

IPCC. 2007. Cimate Change 2007: The Physical Science Basis.

Josselyn, M. 1983. The ecology of San Francisco Bay tidal marshes: a community profile. Biological Report FWS/OBS-83/23. U.S. Fish and Wildlife Service, Division of Biological Services, Washington, DC.

Josselyn, M., and J. Callaway. 1988. *Ecological Effects of Global Climate Change: Wetland Resources of San Francisco Bay*. Prepared for the Environmental Research Laboratory, U.S. Environmental Protection Agency. Romberg Tiburon Center for Environmental Studies, Tiburon, CA. 39 p. Journal of Ecology 64:793-809.

Kearney, M.S., and J.C. Stevenson. 1991. Island land loss and marsh vertical accretion rate evidence for historical sea-level changes in Chesapeake Bay. Journal of Coastal Research 7:403-415.

Knowles, N. and D.R. Cayan. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary: Geophysical Research Letters 29:1-5.

Knowles, N., and D. Cayan. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed: Climatic Change 62:319-336.

Knowles, K., M.D. Dettinger, and D.R. Cayan. 2006. Trends in Snowfall versus Rainfall in the Western United States. Journal of Climate 19:4545-4559.

Koch, M.S. and I.A. Mendelssohn. 1989. Sulphide as a soil phytotoxin: differential responses in two marsh species. Journal of Ecology 77(2): 565-578.

Konisky, R.A. and D.M. Burdick. 2004. Effects of stressors on invasive and halophytic plants of New England salt marshes: a framework for predicting response to tidal restoration. Wetlands 24(2): 434-447.

Lessmann, J.M., I.A. Mendelssohn, M.W. Hester, and K.L. McKee. 1997. Population variation in growth response to flooding in three marsh species. Ecological Engineering 8: 31-47.

Lettenmaier D.P., and T.Y. Gan. 1990. Hydrologic sensitivities of the Sacramento-San Joaquin River basin, California, to global warming. Water Resources Research 26:69-86.

MacKenzie, D.I., J.D. Nichols, J.A. Royle, J.A., K. Pollock, L. Bailey and J.E. Hines. 2006. Occupancy estimation and modeling - inferring patterns and dynamics of species occurrence. Elsevier Publishing.

McKee, K. and I. Mendelssohn. 1989. Response of a fresh-water marsh plant community to increased salinity and increased water level. Aquatic Botany 34(4): 301-316.

Mendelssohn, I.A. and E.D. Seneca. 1980. The influence of soil drainage on the growth of the salt marsh cordgrass *Spartina alterniflora* in North Carolina. Estuarine and Coastal Marine Science 11: 27-40.

Miller, W.D., S.C. Neubauer, and I.C. Anderson. 2001. Effects of sea level induced disturbances on high marsh metabolism. Estuaries 24(3): 357-367.

Mitsch, W.J. and J.G. Gosselink. 2000. Wetlands, 3rd edition. John Wiley and Sons, Inc, New York, New York.

Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. Ecology 83: 2869-2877.

Nichols, F.H., J.E. Cloern, S.M. Luoma, and D.H. Peterson. 1986. The modification of an estuary. Science 231: 567-573.

Orr, M., S. Crooks, and P.B. Williams. 2003. Will Restored Tidal Marshes Be Sustainable? San Francisco Estuary and Watershed Science. 1:Article 5. http://repositories.cdlib.org/jmie/sfews/vol1/iss1/art5.

Pearcy, R.W. and S.L. Ustin. 1984. Effects of salinity on growth and photosynthesis of three California tidal marsh species. Oecologia 62(1): 68-73.

Pearson, R.G., and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Global Ecology and Biogeography 12: 361-371.

Pennings, S.C. and R.M. Callaway. 1992. Salt marsh plant zonations: the relative importance of competition and physical factors. Ecology 73(2): 681-690.

Pennings, S.C., M. Grant., and M.D. Bertness. 2005. Plant zonation in low-latitude salt marshes: disentangling the roles of flooding, salinity, and competition. Journal of Ecology 93: 159-167.

Phillips, S.J., R.P. Anderson, and R.E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. Ecological Applications 190:231-259.

Rasse, D.P., G. Peresta and B. G. Drake. 2005. Seventeen years of elevated CO2 exposure in a Chesapeake Bay wetland: sustained by contrasting responses of plant growth and CO2 uptake. Global Change Biology 11: 369-377.

Reed, D.J. 1995. The response of coastal marshes to sea-level rise: Survival or submergence. Earth Surface Processes and Landforms 20: 39-48.

Rehfisch, M.M., G.E. Austin, S.N. Freeman, M. J.S. Armitage, and N H.K. Burton. 2004. The possible impact of climate change on the future distributions and numbers of waders on Britain's non-estuarine coast. Ibis 146: 70-81.

Roos, M. 1989. Possible climate change and its impact on water supply in California. Oceans ’89 Conference, Seattle, WA. Proceedings: Marine Technology Society, Washington, DC.

SFEP. (San Francisco Estuary Project). 1991. San Francisco Estuary Project status and trends report on wetlands and related habitats in the San Francisco Estuary. ABAG Public report to US-EPA, Oakland, CA.

Stevenson, J.C., L.G. Ward, and M.S. Kearney. 1986. Vertical accretion in marshes with varying rates of sea level rise. Pages 241-259 in D.A. Wolfe, editor. Estuarine variability. Academic Press, San Diego, CA.

Thuiller, W. 2004. Patterns and uncertainties of species' range shifts under climate change. Global Change Biology 10: 2020-2027.

Turner, R.E., E.M. Swenson, C.S. Milan, J.M. Lee and T.A. Oswald. 2004. Below-ground biomass in healthy and impaired salt marshes. Ecological Research 19:29-35.

Warren, R.W., and W.A. Niering. 1993. Vegetation change on a northeast tidal marsh: Interaction of sea-level rise and marsh accretion. Ecology 74:96-13.

Williams, P.B. 1989. The impacts of climate change on the salinity of San Francisco Bay. In: Smith J.B., Tirpak D.A., editors. The potential effect of global climate change on the United States. Appendix A, Water Resources. Prepared for the United States Environmental Protection Agency, Office of Policy Planning and Evaluation. EPA-230-05-89-051. Washington DC: US EPA. p 3-1 to p 3-29.

Ungar, I.A. 1991. Ecophysiology of vascular halophytes. CRC Press, Boca Raton.

Ungar, I.A. 1998. Are biotic factors significant in influencing the distribution of halophytes in saline habitats? Botanical Review 64: 176-199.

Zedler J.B., J.C. Callaway, J.S. Desmond, G. Vivian-Smith, G.D. Williams, G. Sullivan, A.E. Brewster, and B.K. Bradshaw. 1999. Californian salt-marsh vegetation: An improved model of spatial pattern. Ecosystems 2(1): 19-35.