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Exhibit A - Project Narrative

Linking trophic ecology with slough and wetland hydrodynamics, food web production and fish abundance in Suisun Marsh

PROJECT PURPOSE

Fish and plankton populations have been in decline in the San Francisco Estuary for many years. Steep declines occurred in 1986 , following the invasion of the benthic clam *Corbula amurensis* (Nichols et al. 1990, Kimmerer 1996), and after 2002, when declines of a number of estuarine fishes occurred, including the threatened Delta smelt (*Hypomesus transpacificus*) (Sommer et al. 2007, Mac Nally et al. 2009). However, certain regions of the Estuary seem less affected by this collapse and merit study and comparison with adjacent areas that show severe declines.

Suisun Marsh, a brackish tidal and diked marsh system in the upper San Francisco Estuary (SFE), maintains a remarkably high level of biological productivity. Zooplankton density may be many orders of magnitude greater than that seen in the open waters of Suisun Bay, to the south (Schroeter 2008). Fish species that are largely depleted from Suisun Bay and the Sacramento-San Joaquin Delta continue to persist there at moderate, though declining, abundance (Meng et al. 1994, Matern et al. 2002), probably attracted to the abundance of planktonic food produced in certain sloughs. These highly productive sloughs, such as the Denverton-Nurse complex (Fig. 1), are characterized by some combination of high residence times, shallow bottoms or stratified water columns (Durand 2006, Doyle et al. 2011), and offer a partial refuge from grazing by *C. amurensis* (Ball and Arthur 1979) and from alien hydromedusae invasions (Schroeter 2008). This kind of habitat, moderately abundant in Suisun Marsh, contrasts with much of nearby Suisun Bay, in which low primary productivity, low residence time, and intense bivalve grazing leave little food for higher trophic levels (Kimmerer and Orsi 1994). However, the Marsh itself is a diverse ecosystem (Fig. 1), comprised of a network of sloughs that vary in terms of geomorphic structure and anthropogenic impact, and there appears to be wide variability in productivity among sloughs (Matern et al. 2002).

This variability is due in part because physical conditions link sloughs in different ways. For example, salinity patterns are linked strongly among Denverton, Nurse and Montezuma Sloughs, but not with Goodyear or Boynton, and this pattern is likely a function of regional hydrodynamics (Fig. 1). Likewise, temperature does not vary among these sloughs in the same way, and is probably driven by other factors such as wetland connectivity and residence time (Enright et al. 2006). In addition, connectivity among sloughs varies with season, monthly tidal cycle and slough morphology (Culberson et al. 2003). Even the timing and magnitude of unidirectional flows during storm events will differ among sloughs depending upon the degree that they are leveed or connected to inflowing streams.

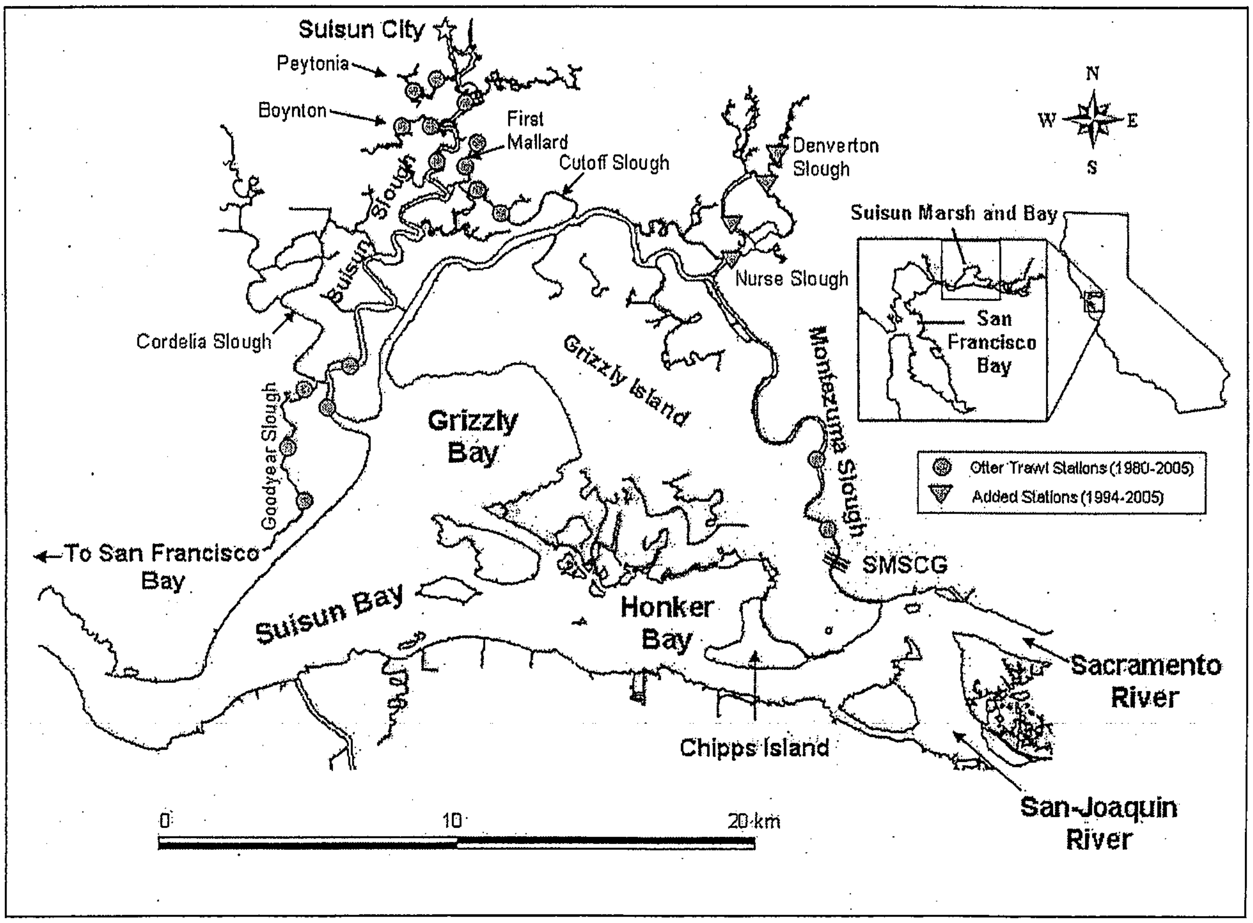

Figure 1. Suisun Bay and Marsh, showing the main sloughs that are sampled by the UC Davis Suisun Marsh Fisheries project (Schroeter 2008).

Suisun Marsh has been cited as a key component of the ecosystem restoration of the Estuary (Blue Ribbon Task Force 2008, Lund et al. 2010). In order for restoration to be effective, it is necessary to incorporate mechanisms that enhance habitat and direct food web production toward the native species that uniquely characterize the SFE, and away from alien species that may intercept the food web through direct competition or by re-directing carbon to less edible species (Durand 2008, Healey et al. 2008). Moyle et al. (2010) suggest that increasing habitat variability, such as salinity, may be effective at promoting native species that have evolved to tolerate such conditions. Highly productive regions of Suisun Marsh, such as the Denverton-Nurse Slough complex (which includes Little Honker Bay), offer a model for understanding and developing such mechanisms, especially when contrasted with nearby sloughs of low fish zooplankton abundance.

The goal of this research is to understand and predict the kinds of physical variability and structure that create attractive habitat for fish in Suisun Marsh, in order to 1) develop a template for wetland and subtidal habitat restoration in the Estuary and 2) anticipate the effects of sea level rise, levee failure and salinity increases that are expected to have a large impact on the Marsh in the near future. We propose to answer the following questions: How do environmental conditions predict zooplankton and fish species assembly and abundance? How can physical conditions be modified to support a more productive food web? What changes in zooplankton and fish can be expected in Suisun Marsh under future conditions? In order to achieve these goals we will:

- Assemble as much as possible of the known historical, geographic and scientific literature and data on Suisun Marsh;
- Identify clusters of sloughs with similar physical and biological characteristics;
- Determine how local environmental conditions predict zooplankton and fish species assembly and abundance;
- Analyze the impact of regional environmental and flow changes on local slough conditions;
- Evaluate changes in physical and biological conditions over time;
- Analyze the effect of hydrodynamic mixing and residence time on zooplankton production;
- Predict how physical and environmental conditions will shift under scenarios of future climate change and water regulation and where in the SFE optimal conditions for native fish may occur.

Our research will be divided into three tasks. Tasks 2 and 3 will be further divided into subtasks with specific hypotheses as follows:

Task 1: Project Management

Task 2: Statistical modeling

2.1- Determine how species distributions and environmental characteristics differ among sloughs using ordination and cluster analysis.

H_1: Sloughs can be characterized by functional habitat, based upon prevailing physical conditions.

H_2: Species' spatial distributions will vary by functional habitat type.

2.2- Develop a series of maximum likelihood models using environmental conditions to predict food web structure and fish species' abundance.
- H_1: Chlorophyll a and zooplankton abundance can be explained by water quality conditions, insolescence, hydrodynamic residence time, and predator abundance.
- H_2: Fish abundance can be explained by food abundance and time of year.
- H_3: Fish species assembly can be described by water quality conditions, time of year, wetland floodplain connectivity, and food web structure.

2.3- Evaluate the influence of regional effects at a number of scales on Marsh-wide species' trends using multivariate autoregressive (MAR(1)) analysis.
- H_1: Changes in long-term biological and physical trends across the Marsh can be attributed to broad-scale processes related to nutrient inputs, alien species invasion, water management, or climate.
- H_2: Differences in long-term trends among sloughs can be identified as the interaction of local and regional effects.

Task 3: Hydrodynamic and life history modeling to determine the effect of residence time and mixing on zooplankton abundance.

3.1- Develop a hydrodynamic model of slough function in Suisun Marsh.
- H_1: There are differences in the tidally-averaged residence time of neutrally buoyant particles among sloughs.
- H_2: Residence time is a function of slough length, tidal range, and connectivity among sloughs.

3.2 Effects of slough structure and hydrodynamics on copepod life histories.
- H_1: Copepod abundance among sloughs varies as a function of egg production and loss rates.
- H_2: Loss of individuals to advection is more important than predation loss across low residence time sloughs.
- H_3: Loss of individuals to predation is more important than advection loss in high residence time sloughs.
- H_4: Biological productivity is optimized when monthly tidal cycles and slough residence times are synchronized with the time scales of chlorophyll a production, copepod egg production and copepod export.

PREVIOUS RESEARCH

A number of reports use data from the UC Davis Suisun Fish Survey to summarize patterns of species diversity and abundance among sloughs within Suisun Marsh (Matern et al. 1995, 1996, 1998, 1999, Schroeter et al. 2006, O'Rear and Moyle 2009, 2010). Using more formal analyses, Moyle et al. (1986) suggested that native fish assemblages were more likely to occur in backwater sloughs, while a decade later Meng et al (1994) found that these assemblages had become less distinct. Matern et al (2002) used ordination to identify differences in water quality and catch data among sloughs, and found that native fish tended to be more abundant in small sloughs, while non-natives were abundant and ubiquitous. The mechanism behind spatial differences in abundance has not been addressed, and since Matern et al. (2002) was published, another decade of fish and environmental data have been accumulated, with an additional emphasis on invertebrate abundance, particularly zooplankton. Differences in species abundance and assembly among sloughs suggest the presence of different "functional habitats" (*sensu* Kemp et al. 1999) that result from local water quality and slough conditions.

Declines in species abundance across the wider SFE have been documented in a number of analyses. Phytoplankton and zooplankton depletion were documented notably in Nichols et al. (1990) and Kimmerer and Orsi (1996) which attributed declines to *Corbula amurensis*, a benthic grazer that invaded the Estuary in 1987. Kimmerer (2006) suggested that northern anchovy (*Engraulis mordax*) declined in the Suisun Bay region in response to food limitation induced by the clam. The more recent steep decline in fishes since 2000 was described by Sommer et al. (2007) as a pelagic organism decline (POD). Bennett (2005) conducted a life history analysis of delta smelt (*Hypomesus transpacificus*) in order to understand competing sources of mortality and predicted that the population was quite vulnerable and would continue to decline.

A Bayesian hierarchical change-point analysis of survey data from the upper SFE (Thomson et al. 2009) confirmed marked declines in 2002 for delta smelt, longfin smelt ((*Spirinchus thaleichthys*), striped bass (*Morone saxatilis*), and threadfin shad (*Dorosoma petenense*) and linked increased water clarity to declines in delta and longfin smelt and striped bass. A companion paper used a multivariate autoregressive (MAR) approach on similar data, explicitly incorporating community interactions and abiotic factors as covariates (Mac Nally et al. 2009), providing a path-type analysis for time series data. These papers showed some overlap in the prevailing effects of the 2 psu isohaline, water clarity and exports, but also found differences in fish species' responses to environmental covariates. Trophic relationships may have obscured the effect of abiotic influences through indirect pathways because of the lack of explicit partial correlations in the model.

The latter papers did not incorporate explicit spatial and temporal data into their models, and as a result, Suisun Marsh and seasonal dynamics are essentially omitted from the analysis. The processes controlling Suisun Marsh are considerably different (Matern et al. 2002), and so hypotheses about the physical and biological relationships in the Marsh remain largely untested, as are the efficacy of proposed restoration actions.

CRITICAL UNKNOWNS

Considerable knowledge exists on many of the species that occupy Suisun Marsh. However, the influence of multiple biotic and abiotic factors on the community ecology of the Marsh is largely unknown. In addition, the Marsh and the entire SFE have been subject to a number of stressors (Kimmerer et al. 2005) that have altered system function. A number of these stressors have occurred within the time scale of the Suisun Fish Survey data, or affect only a portion of the Marsh. For example, floodplain wetland areas that were once highly connected to sloughs are largely separated by levees in Peytonia and Boynton Sloughs, while the Nurse-Denverton complex of sloughs remains largely undyked. These dyked ponds are maintained as freshwater systems, maintained in part by the Montezuma salinity control gates, which became operational in the mid-1980's. Regionally, the Sacramento-San Joaquin Delta has experienced increased water withdrawals from the State and Federal pumping plants and increased exposure to agriculture, sewage and urban runoff. On a larger scale, three shifts in both the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation have occurred since 1979 (Di Lorenzo et al. 2008), incurring patterns of drought and El Nino Southern Oscillations (ENSO), which have in turn affected outflows from the Sacramento River and ambient temperatures. Finally, at the global scale, eleven of the warmest years since 1850 occurred during 1995-2006 (Alley et al. 2007). The implications of past changes to the Marsh system merit examination in order to anticipate future changes that are almost certain to occur, including sea level rise, levee failures and increasing salinity, and may have a profound impact on current restoration actions.

Our proposed analysis of the spatial structure of the Marsh using ordination and cluster analysis on biotic and abiotic data will help address how species utilize the different environmental conditions in Suisun Marsh. The maximum likelihood models will refine this understanding, offering some predictive capacity to explain fish distribution in relation to biotic and abiotic variables, and the time series analysis will help understand species responses to broad-scale drivers of change. Finally, we expect to gain a robust understanding of how restoration of slough and wetland habitat can be optimized by examining the interaction of slough hydrodynamics with the life histories of important food web species.

BACKGROUND AND CONCEPTUAL MODEL

DATA ANALYSIS

Certain sloughs and slough complexes (such as the Denverton-Nurse-Little Honker Bay complex) appear to be much more productive than others. In this study, we seek patterns in species and water quality data among sloughs that offer explanatory mechanisms for differences in species abundance. The data we will use derive primarily from the UC Davis Suisun Marsh Fish Survey, which has been monitoring the Marsh monthly since 1979 for fish, pelagic and invertebrate abundance and water quality. Early reports and papers suggest that the patterns of fish abundance are related to slough type or structure, but changing trends across the 30+ years of data make it difficult to clearly identify these patterns without formal analysis. A number of statistical techniques from community ecology are useful for these kinds of analyses, and quite recently, a multivariate autoregressive model (Mac Nally et al. 2009) was used for a broad-scale study of species trends, but without consideration of regional differences, which we will emphasize here.

ZOOPLANKTON LIFE HISTORY

Secondary productivity in the open Estuary has been declining for decades, but Suisun Marsh continues to have relatively high zooplankton abundance in certain regions. It is likely that some combination of high food availability and high residence times contribute to local production; understanding this mechanistically can lead to more effective restoration of sloughs and wetlands for fish species. We have data from 2007-08 for the stage abundance of two copepod species, *Eurytemora affinis* and *Pseudodiaptomus forbesi*, both of which are sometimes important to the diet of certain juvenile and adult fish.

Zooplankton abundance can be understood to vary as a function of egg production and loss of individuals, where loss is a function of natural death, predation and net advection from the population (Ohman et al. 2001). Egg production can be estimated because both species carry eggs in sacs attached to the urosome. Loss can be estimated by using a vertical life history approach because copepods have 11 morphologically distinct nauplius and copepodite stages before reaching the adult stage, and the duration of each species (as a function of temperature) is known (Durand *expected* 2010). Assuming steady state in population parameters and population size between monthly sampling (Aksnes and Ohman 1996), these loss patterns can be useful in decomposing how ecological and physical factors interact to determine abundance.

While the assumptions can be difficult to meet (although see Landry (1978) for an exception), a vertical life table approach remains the most reliable means of estimating mortality in a species with overlapping generations (that is, continuous spawners), and violations of the assumptions can be accounted for and managed when mortality rates are paired with raw abundance estimates (Aksnes et al. 1997). For instance, spring blooms may show high loss terms because the early stages are abundant while later stages scarce. However, some periods of the annual cycle approach steady state, and these are more reliable estimators of loss. The variance in estimates is incorporated as uncertainty in the model.

Because most zooplankton populations are open, the loss term can seldom be decomposed into actual mortality (Landry 1978). This is because advection and dispersion of individuals to and from the population cannot be estimated. Here, we capitalize upon the availability of RMA2 and RMA11, fixed element hydrodynamic models that have been calibrated to the SFE and Suisun Marsh, to correct the loss term so that it reflects actual loss of individuals to predation (or natural death).

CONCEPTUAL MODEL

Our conceptual model of important drivers of slough function and productivity is found in Fig. 2. Here, drivers influence outcomes through a system of filters that scale the effect. The model includes both abiotic and biotic factors that affect slough function and the aggregation of zooplankton and native fishes.

Broad-scale drivers, represented by red arrows, include water regulation policies, ammonium, climate change, and species invasions. Water regulation of the SFE at export facilities in the Delta, and at the Montezuma salinity control gate at the eastern end of the Marsh, control when and how much water from the Sacramento River is available to enter the Marsh. This in turn has a large impact on water quality, particularly salinity. There may also be effects on tidal energy, and therefore residence time, within the Marsh. Ammonium is an important driver of water quality, and has been cited recently as having a controlling influence on the quantity and quality of primary production. Climate change is expected to cause shifts in sea level, which will in turn affect residence time and the connectivity of sloughs to adjacent terrestrial or pond habitats. Species invasions—in the Marsh, invasive hydromedusae and bivalve grazers have been a concern—have caused interceptions to the food web, causing productivity to be re-directed away from native fishes.

Slough morphology and levee condition, shown by yellow arrows, directly control the functions of the local filters (in green boxes): particle residence time, the degree of connectivity to adjacent wetlands and ponds, and water quality. These filters can either amplify or mute the effect of drivers on the food web and native fishes. Wetlands and ponds affect residence time, water quality and food production for export to sloughs. Under some conditions, they may benefit fish species by providing foraging habitat. Residence times in turn, directly control the impact of water quality and the rate at which food web production accumulates and is retained within or exported from a slough. Water quality conditions, influenced by the drivers, and scaled through the other two local filters have an important direct impact on both the local outcomes (in blue boxes): food web condition and structure, and native fish abundance.

In summary, it is the triad of residence time, connectivity, and water quality that most controls native fish abundance. Among sloughs in Suisun Marsh, these conditions vary enormously. Wetland connectivity optimizes food production and water quality. High, or tidally mixed, residence times can maximize food production and accumulation. Water quality is the final filter in that poor oxygen conditions can eliminate most species, while salinity shifts can select for certain fish species. Many native estuarine species, including Sacramento splittail (*Pogonichthys macrolepidotus*), tule perch (*Hysterocarpus traskii*) and others tolerate changing salinities better than certain introduced fish and invertebrates.

Suisun Marsh's ecosystem response to broad-scale drivers of change, then, will be largely mediated by the filters. Restoration activities should center on the modification of these functions. If it is clearly understood how filters interact with each other and the biotic components of the system, Suisun Marsh can be managed or even re-designed as a highly productive component of the SFE, even as drivers shift and apply new pressures.

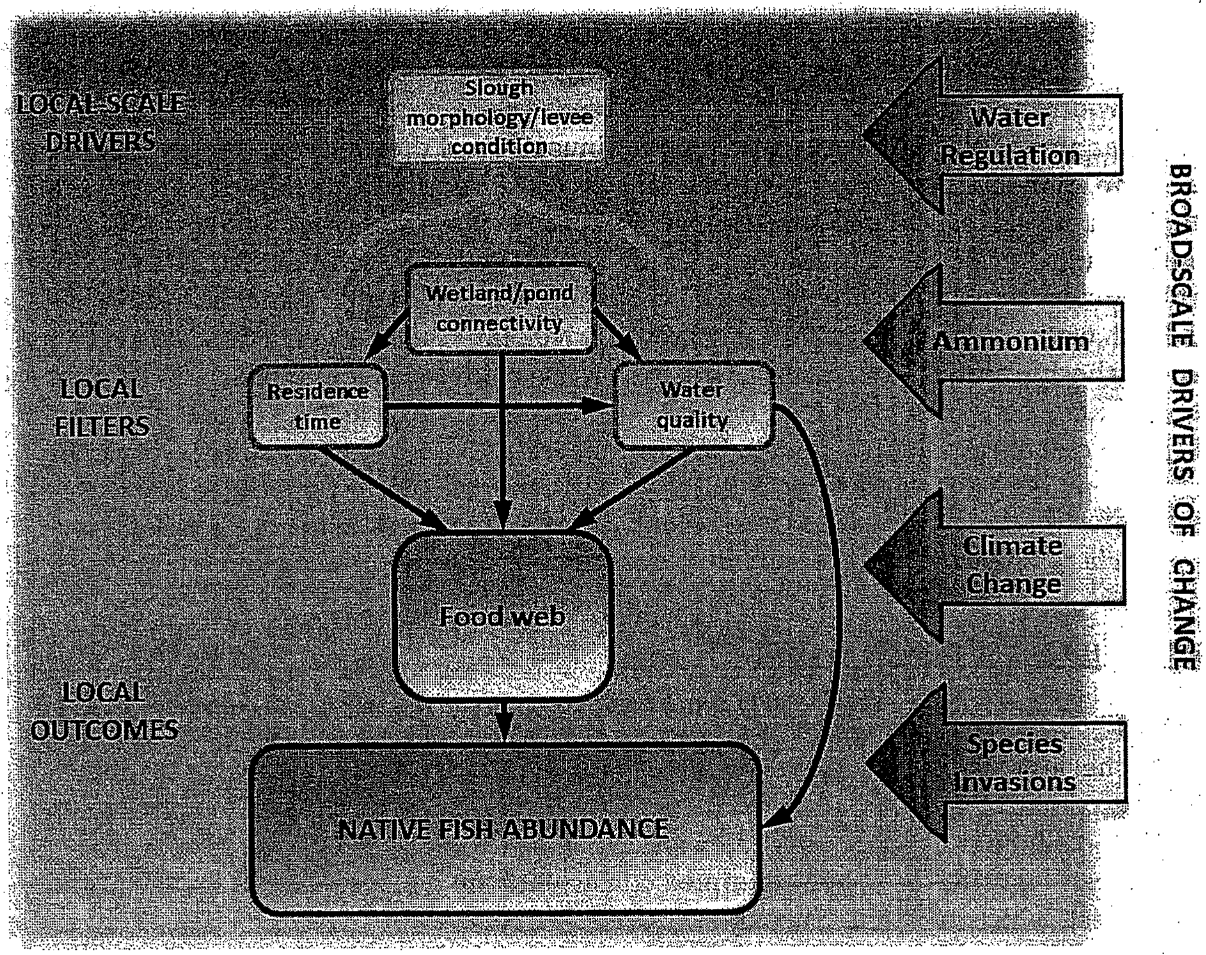

Figure 2. Conceptual model of factors influencing food web structure and native fish abundance in Suisun Marsh. Broad-scale drivers (in red) are influences that occur at any scale larger than an individual slough, ie at the scale of the Marsh, the SFE or beyond. Local drivers (in yellow) occur at the scale of a slough and are largely a function of slough morphology and hydrology. Filters (in green) are links between drivers that can either exacerbate or mitigate the destabilizing effect of drivers at the local scale. The effects of the broad scale drives are largely manifested through these filters to the outcomes, here identified as food web structure and native fish abundance. Note that the filters consist of hydrodynamic and other abiotic factors of direct ecological relevance to life histories of local organisms. They are the ecological factors that can be most easily manipulated during restoration actions.

DESCRIPTION OF PHYSICAL SETTING

The San Francisco Estuary consists of 1500 km^2 of aquatic habitat, ranging from fresh water in the upper Delta to coastal salinities at the mouth of the Bay (Cohen and Carlton 1998). It receives runoff from a 163,000 km^2 watershed that experiences high annual and seasonal variation in water flow, despite an extensive system of damming, water diversion, and flood control. Suisun Marsh is a brackish water system covering approximately 340 km^2 of the northern SFE. One-third of the area is formed by a system of tidally influenced sloughs, while the rest is a combination of diked seasonal ponds and upland grasslands

(DWR 1999, Meng and Matern 2001). Cattle grazing is common on adjacent slopes, and cattle utilize certain sloughs for fresh water. Sloughs average between 2-3m in depth, 10-100m in width, and have margins of tules and reeds (Feyrer et al. 2003), but there are large differences among sloughs in terms of length, sinuosity and the degree to which they are leveed and connected to adjacent habitat. Suisun Marsh receives the majority of its fresh water from the eastern side of Montezuma Slough, but a series of creeks make additions to various sloughs throughout the system. Tertiary-treated sewage effluent from the town of Fairfield enters the Marsh through Boynton Slough on the west side, which is a source of both fresh water and nutrients. Saline water is driven into the marsh via tidal action from three southerly-located bays, Suisun, Grizzly, and Honker (Meng and Matern 2001). Salinity levels fluctuate seasonally between 0 and 16‰, with the lowest levels occurring in winter and spring due to rain and snowmelt. Water temperatures also vary seasonally, typically ranging from 5-25ºC (Feyrer et al. 2003). Hydrodynamic properties appear to also vary widely between sloughs, with certain regions maintaining a high degree of recirculation and particle residence time due to complex patterns of water flow and slough morphology.

APPROACH AND SCOPE OF WORK

This project makes use of long-term mostly extant data for statistical modeling. The Suisun Marsh Fisheries survey has collected geomorphologic, water quality and fisheries data from approximately 20 sites since 1979. In addition, phytoplankton (as chlorophyll a) and zooplankton abundance (as counts) data are available from 4 (discontinuous) years at certain sites. Most sites have been sampled consistently on a monthly basis for the duration of the project, which continues through the present day.

Additional data are historical, derived from literature, or modeled. For hydrodynamic modeling, we will use output from two models developed by Resource Management Associates, RMA2 and RMA11, finite element models (King et al. 1973) which have been adapted for use in the San Francisco Estuary, including the major sloughs of Suisun Marsh. Using historical tide, Delta outflow and regional flow data to produce output as flow vectors or particles, we will estimate particle residence time, advection and dispersion for each slough. Slough condition over time is based upon interviews with individuals familiar with the system, historical data, maps, publications, and Suisun Marsh Fish Survey observations of levee condition, slough depth, substrate type, and wetland connectivity.

A structural diagram showing the relationship of some important variables for which we have data is found in Fig. 3. Circles show latent variables, while boxes are indicator variables for which direct measurements exist.

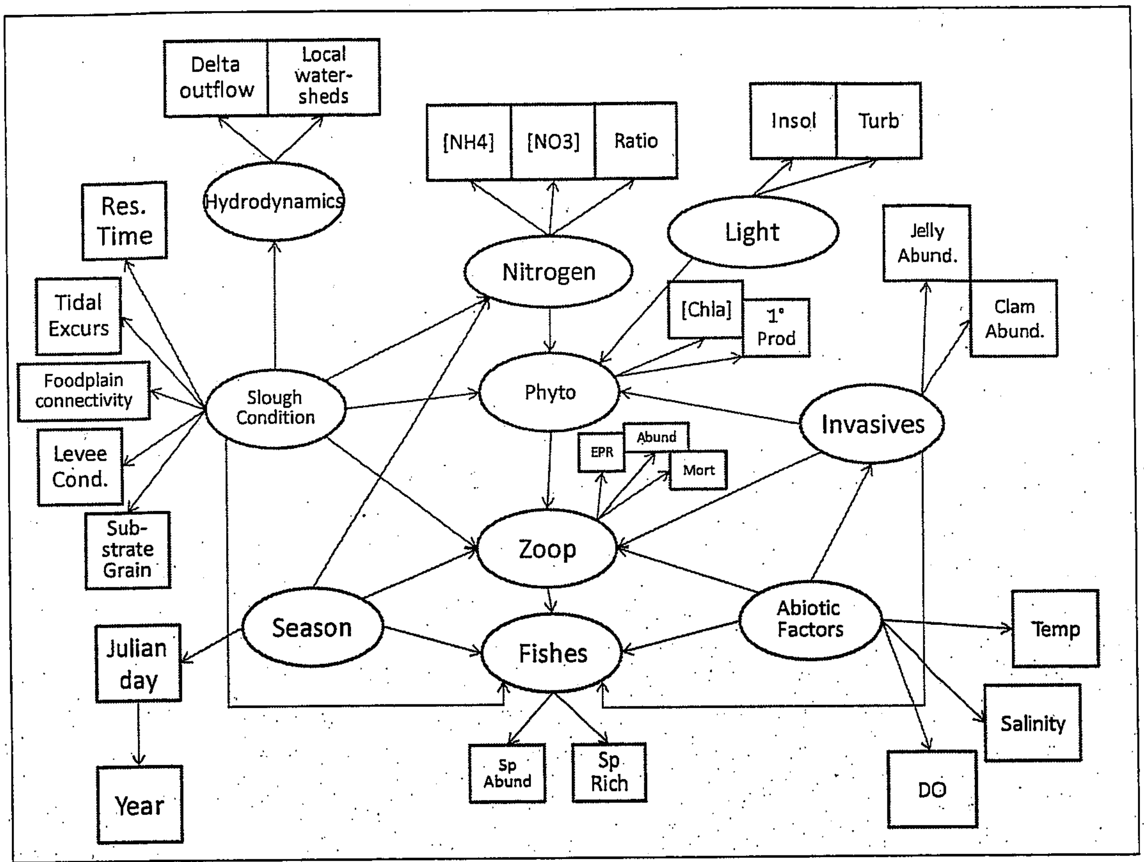

Figure 3. Important variables available from the Suisun Marsh Fish Survey and related studies, organized as a structural model of ecosystem function. Circles are latent variables, boxes are indicator variables.

TASK 1—PROJECT MANAGEMENT

This research program will be directed by Dr. Peter Moyle, Professor of Wildlife, Fisheries and Conservation Biology at the University of California, Davis, who will serve as the lead PI for all tasks. Dr. Cathryn Lawrence of the Watershed Science Center, U.C. Davis, will provide management and logistical support throughout the project. Dr. William Fleenor, Research Engineer in Department of Civil & Environmental Engineering, U.C. Davis, will provide support for hydrodynamic modeling for Task 2. Doctoral student John Durand of the Graduate Group in Ecology, U.C. Davis, will be responsible for executing the analyses. Weekly meetings will be held among Dr. Moyle, Dr. Lawrence, Dr. Fleenor and Mr. Durand to review progress and make management decisions. All the analyses will be performed at the University of California, Davis. Deliverables will be produced as outlined in Table 1.

TASK 2—STATISTICAL MODELING

2.1 Differences among sloughs

In order to understand the variance-covariance structure of the data, we will use an ordination technique, such as principle components analysis (PCA) for normally distributed data, or non-metric multidimensional scaling (NMDS) for nonlinear distributions. Although both techniques differ in the way they scale and handle data, the purpose of both techniques is to cluster units of shared variation. NMDS is more robust to ecological data sets that contain discontinuous or non-normal data, and it may prove useful for the very large, aggregated data set that we are proposing to use. In the ordinations, species and environmental data will be run separately, and interpreted using joint plots and overlays to develop an understanding of slough-species and slough-environmental relationships (McCune et al. 2002). These approaches are useful for qualitative comparisons in which the data can be sub-set and used to run separate analyses by slough, season, or year. Color-coded overlays for individual sloughs help interpretation by giving a graphic representation of how sample units cluster by slough, offering a way to "see" temporal and spatial relationships.

In order to further characterize sloughs by environmental and ecological characteristics, we will use hierarchical polythetic cluster analysis to produce dendograms that emphasize the similarities and differences of selected variables among sloughs. This will create a classification scheme (not unlike a phylogeny) of sloughs linked by similarity (or "relatedness") of sampled characteristics. Different classifications may result from the use of different variables, i.e., species abundance versus environmental data. The resulting matrices can be tested for significant differences against the null hypothesis using Mantel's test (McCune et al. 2002). Non-significant results suggest concordance between two proposed clusters, suggesting linkages between classification schemes. For example, clusters of sloughs arranged by certain abiotic factors may parallel the clustering of a biotically driven scheme. If the null cannot be rejected, then we would accept that there are no significant differences between the two schemes, suggesting deeper relationships between the variables used.

Another clustering technique that may be useful is classification and regression tree (CART) analysis, which constructs dendograms organized as dichotomous clusters of explanatory variables (Program R; 'tree' package) and computes a distance measure that accounts for differences between sloughs. CART is exceptionally useful because it offers a great deal of explanatory power for the clusters, and can be used with complex non-normal data that include categorical variables (Vayssiéres et al. 2000).

2.2 Predicting food web structure and species' abundance

To determine if the physical habitat metrics of slough classification can be used to develop a predictive model of species assembly and abundance we will use predictor environmental variables derived from the previous ordination and cluster analysis. Individual species abundance will be explained using these environmental predictors, fit to a generalized linear model (GLM) using maximum likelihood estimation and AIC model comparison (Program R; 'bbmle' package for GLM; 'lme4' for hierarchical GLM) (Bolker 2008). Community interactions can be included by adding other species (such as zooplankton or prey fishes) to the model. Repeated sampling from nested sites will be managed using a hierarchical GLM approach, with "sloughs" as sample sites treated as varying or constant effects to achieve the best fit (Gelman and Hill 2007). Species abundance counts often require a Poisson or negative binomial distribution for an optimal fit. Species assembly models may require a multinomial distribution (suitable for predicting presence/absence of any given species). These and other distributions are readily solved iteratively in the bbmle package. AIC uses a comparative approach; any number of proposed models are simultaneously fit to the data. Models with the lowest AIC scores are considered to explain the most variation. This process allows for selecting parameters, establishing confidence, and making interpretations of the model based upon the likelihood of the data.

2.3-Evaluating changes through time and broad-scale effects

Changes in species abundance trends in a time series, as a result of broad-scale environmental shifts, will be identified with a multivariate autoregressive (MAR(1)) model (Ives et al. 2003, Mac Nally et al. 2009). MAR (1) is a first-order stochastic model, using abundance at time t-1 plus environmental information in a time series to predict abundance at time t. MAR(1) models start with the Gompertz equation, which describes fluctuations in population size:

$$N_t = N_{t-1} \exp[a + (b-1) \ln (N_{t-1})$$

where N represents population density, a represents the intrinsic rate of increase and b is a value describing density dependence. By taking the natural logarithm of the equation and expanding it to include a process error term (of mean zero and variance σ) and a covariate the following equation is derived:

$$X_t = a + bX_{t-1} + cU_{t-1} + E_t$$

where X is ln(N), U is a covariate, c is the strength of interaction between U and X, and E is the error. This is the univariate analog of a true matrix multivariate model, which is formulated as a matrix model (Viscido 2007).

While they require interactions between variables to be linear (or linear upon transformation), MAR(1) models may be useful for approximating non-linear or non-first-order stochastic processes that typify most ecological communities. The MAR(1) model effectively deals with the complexity of large time series data without stripping the data of its complexity (Ives et al. 2003). It allow us to address questions about changes over time within and among sloughs, and the environmental correlates that may be driving these changes at the local or regional level, by de-trending the data and seeking change points that suggest changes in trends. Lambda is a Matlab stand-alone platform that runs MAR(1) models on long term data sets using as formulated by Ives et al. (2003). It was developed at the Mathematical Biology program at the Northwest Fisheries Science Center in Seattle, WA by Steven Viscido and Elizabeth Holmes and is freely available online at: http://conserver.iugocafe.org/user/e2holmes/LAMBDA .

TASK 3—HYDRODYNAMIC AND LIFE HISTORY MODELING

3.1 Hydrodynamic modeling of sloughs

We will use RMA to estimate the effect of slough morphology on residence time and mixing between adjacent sloughs. RMA2/11(King 1988, 1997) is a full-featured, finite element hydrodynamic/water quality modeling system that has been calibrated extensively for the

SFE, including Suisun Marsh, using a grid with its downstream boundary at the Golden Gate and upstream boundaries up to the extent of tidal influence. It is capable of solving the shallow water equations in one, two, or three dimensions. The grid can be modified using geo-referenced ortho-quadrangles, which extends the capability of the model to include sample sites at very small sloughs. It also offers the opportunity to virtually manipulate slough configuration in order to estimate how changes in slough morphology and connectivity affect hydrologic functioning. RMA2 computes two-dimensional depth-averaged velocity and water surface elevation. Results from RMA2 can be passed to RMA11 which can estimate water quality parameters, including chlorophyll a concentration. Model output can be processed through filters to estimate particle residence time, tidal excursion and tidally averaged current and transport.

Estimates of residence time will be incorporated into the Tasks 2.1 and 2.2, evaluating differences in sloughs and predicting environmental effects on food web and fish species assembly and abundance. These results will also be used in the following Task 3.2, along with particle tracking output, to assist in modeling the effects on copepod mortality and production.

3.2 Hydrodynamic effects on copepod population dynamics.

Evaluating the effect of slough conditions on food web production will involve integrating results from hydrodynamic modeling with the life histories of *Eurytemora affinis* and *Pseudodiaptomus forbesi*, two copepods historically important to the SFE (Kimmerer 1996, Gould and Kimmerer 2010). Taking a vertical life table approach, we will use egg and stage abundance counts to estimate egg production and mortality rates among sloughs. Because copepod abundance is sensitive to slough residence time, estimates of mortality can be overestimated unless they are corrected by subtracting transport losses. Loss rates will be modeled in RMA for the exact time of each developmental stage. Individuals lost to tidal advection between $Stage_{ix}$ and $Stage_{jy}$ during $Time_{ix}$ and $Time_{jy}$ (where $Stage_{ix}$ and $Stage_{jy}$ represent numbers of individuals at stage "i" in cohort "x", and at stage "j" in cohort "y"; and where $Time_{ix}$ and $Time_{jy}$ represent the actual calendar time at the beginning of each cohort's stage) will be modeled from the precise tidal and outflow conditions occurring during that time. The transport loss rate may then be compared with the predation mortality rate, assuming that most mortality is due to predation. This assumption will be tested by fitting a GLM model using predator abundance to explain the mortality rate. By using AIC model comparison, the variation in mortality explained by predators will be described.

Finally, in order to determine the structural design of a restored slough complex that optimizes chlorophyll a production, copepod egg production and copepod export with the changing tidal excursion of the monthly tidal cycle, we will use the life table parameter estimates in conjunction with RMA simulations to model how abundance and export is influenced by slough morphology. This can be done by altering RMA's grid to perform "virtual" slough restorations and comparing the effect on phytoplankton abundance and copepod advection loss rates. This final stage of Task 3.2 will be performed after the other analyses, so that we have sufficient information to "virtually" re-configure sloughs in order to maximize plankton production for local accumulation or for export from the slough to adjacent areas (*sensu* Doyle et al. 2011). We can then assess what complex of factors are affecting copepod production both to provide insights into foodweb-related declines in fish populations (e.g. the POD) and to provide insights into potential solutions (re-structuring slough configuration). In addition, we expect these results to contribute to predicting the effects of sea level rise on Marsh foodwebs.

DELIVERABLES

Research findings and progress from these tasks will be distributed in quarterly reports, our final report, at presentations during national and local meetings, and in articles submitted to both the IEP Newsletter and peer reviewed publications. In the final year, a Suisun Marsh workshop will be held at U.C. Davis with guest presentations and discussion panels, in order to evaluate the state of knowledge and restoration. At the conclusion of the project, a white paper on Suisun Marsh will be submitted for publication, integrating our findings with the findings of the workshop and with broader research. Please see Table 1 for details.

Table 1: Tasks with key personnel and deliverables for each.

Task	Description	Personnel	Deliverables
1.	Project Management	All	• Semi-annual Reports • Final Reports • Project Summaries for public (beginning/completion) • Project closure report • Presentations at Delta Science Biannual Conference • Suisun Marsh workshop • White paper: Future changes and restoration options for preserving native species habitat
2.	Statistical Modeling	Moyle and Durand	• Presentations at regional and national/international conferences • Draft scientific paper: Identifying slough-wise differences in habitat • Draft scientific paper: Predicting fish species distribution and abundance using GLM of environmental parameters • Draft scientific paper: Evaluating long-term changes in species trends using MAR(1) analysis
3.	Hydrodynamic and Life History Modeling	Moyle, Fleenor and Durand	• Presentations at regional and national/international conferences • Draft scientific paper: Effects of slough structure and hydrodynamics on copepod life history parameters