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Effects of the South Bay Salt Pond Restoration Project on Mud Flats and their Carrying Capacity for Shorebirds
Annual Report for RLF contract #2009-0210

Abstract:

The availability of food resources on the mud flats and their carrying capacity will be a primary concern for conservation of shorebirds as the South Bay Salt Ponds are converted. This project develops a foraging model for Western Sandpipers and Dunlin using data from a recently initiated USGS study at the Dumbarton Shoals. By focusing on the bird year July 2009 to June 2010 this model represents the most current conditions before construction on pond RSF2 changes the sediment dynamics of the Dumbarton Shoals. At this time, invertebrate samples are still being processed by the USGS, and so comprehensive prey availability maps will be presented in forthcoming updates. Interpolated prey availability maps are provided for October of 2009 along with a discussion of the next steps in the modeling process.

Introduction:

The San Francisco Bay Estuary (SFBE) is part of the largest estuary in the western United States and supports a tremendous diversity of flora and fauna, including many special status species and millions of wintering and migratory water birds. The SFBE is of key importance to shorebird populations and hosts an average of 67% of all shorebirds travelling along the west coast (Page *et al.* 1999). Extensive urban and agricultural developments in the last 200 years have resulted in loss of 80% of historic SFB tidal salt marshes and 40% of intertidal mud flats (Foxgrover *et al.* 2004, Goals Project 1999).

The recent transfer of over 5,471 ha of evaporation ponds to government management in the South San Francisco Bay (South Bay) has resulted in the largest tidal restoration effort on the west coast (Goals Project 1999). A primary goal of the South Bay Salt Pond Restoration Project (SBSPRP) is to conserve populations of migratory and wintering bird species while providing additional resources for endangered species that rely on intertidal salt marsh. Most shorebirds feed on the intertidal mud flats adjacent to the salt ponds and in the salt ponds themselves (Takekawa *et al.* 2001, Warnock *et al.* 2002, Masero 2003). The effect that marsh restoration will have on South Bay shorebird populations is largely unknown because salt marsh supports a much lower density of shorebirds than the existing attenuated tidal salt pond habitat (Takekawa *et al.* 2001). Attempts have been made to identify management strategies to maximize water bird populations, and the availability of food resources and mud flats carrying capacity will be a primary concern for conservation of shorebirds as salt ponds are converted to tidal marshes (Stralberg *et al.* 2009).

Because numerous birds currently use these salt ponds, there is concern about whether alternative feeding grounds elsewhere in the estuary will be able to provide for their energetic needs (Stralberg *et al.* 2006). It is imperative to understand whether mud flats adjacent to salt ponds are currently at carrying capacity or if they can sustain increased numbers of foraging water birds. Determining the carrying capacity of South Bay intertidal mud flats is a critical need for the SBSPRP because it will help describe how changes to the sediment profiles of mudflats will impact the energy budgets of foraging shorebirds (Bearman *et al.* 2010).

Elevation controls the schedule of tidal exposure of mud flats and influences the distribution of intertidal macroinvertebrates (Balwin and Lovvorn 1994). Tidal exposure changes the salinity, pH, temperature, and degree of desiccation experienced by these invertebrates (Nichols and Pamatmat 1988). Effects of mud flat elevation and tidal exposure on macroinvertebrates may vary with season and variations in sediment grain size, organic content, and microtopography (Wolff and de Wolf 1977, Quammen 1982, Hicklin and Smith 1984, Baldwin and Lovvorn 1994). The sediment flux experienced by South Bay mud flats will be an important predictor of their ability to buffer possible changes due to sea level rise and sediment transport into breached subsided salt ponds (South Bay Salt Pond Restoration Project 2007). Because prey quality or shorebird foraging efficiency may be directly affected by a change in mud flat characteristics resulting from restoration, such effects should be identified before significant changes to mud flats occur (Quammen 1982, Shepherd and Boates 1999, Poulton *et al.* 2004).

Amphipods, bivalves, cumaceans, polychaete and oligochaete worms support large concentrations of foraging birds in the South Bay mud flats and will be the focus of this analysis (South Bay Salt Pond Restoration Project 2007, Table 1). The factors that drive the distributions of these invertebrates are poorly understood, but a recent study conducted by the USGS San Francisco Bay Estuary Field Station has provided detailed information on the ecology of a South Bay mud flat (Takekawa and Woo, unpublished data). Results from this empirical research will be published elsewhere. I will focus my efforts on modeling carrying capacity for the most abundant small shorebirds in the South Bay, the Western Sandpiper (WESA, *Calidris mauri*) and Dunlin (DUNL, *Calidris alpina*) (Page *et al*. 1999, Stenzel *et al.* 2002, Takekawa *et al.* 2006). These two species have been found to have a 97% prey size overlap (Davis and Smith 2001) and so will be considered together in the foraging analysis of the Dumbarton Shoals (Fig 1).

Objectives

(1) Review literature to determine what taxonomic groups and size classes are available to WESA and DUNL as profitable prey.
(2) Map the distribution of macroinvertebrate prey accessible to Western Sandpipers and Dunlin given variable tidal exposure along the Dumbarton Shoals

Next Steps

(3) Calculate the carrying capacity of the site during different seasons and describe the potential impact to foraging small shorebirds given possible scenarios of mudflat change (increased slope, overall loss of elevation, channelization).

Methods

Study Area

This study of mud flat habitat quality and shorebird carrying capacity will be based on field data collected from an intertidal mud flat adjacent in the Ravenswood complex of the SBSPRP in the South San Francisco Bay, California. This mud flat is bound by Ravenswood pond SF2 to the west, the Dumbarton Bridge to the north, and the Southern Pacific Railroad Bridge to the south (Figures 1a and 1b). The other two areas of mudflat study have not included in this analysis.

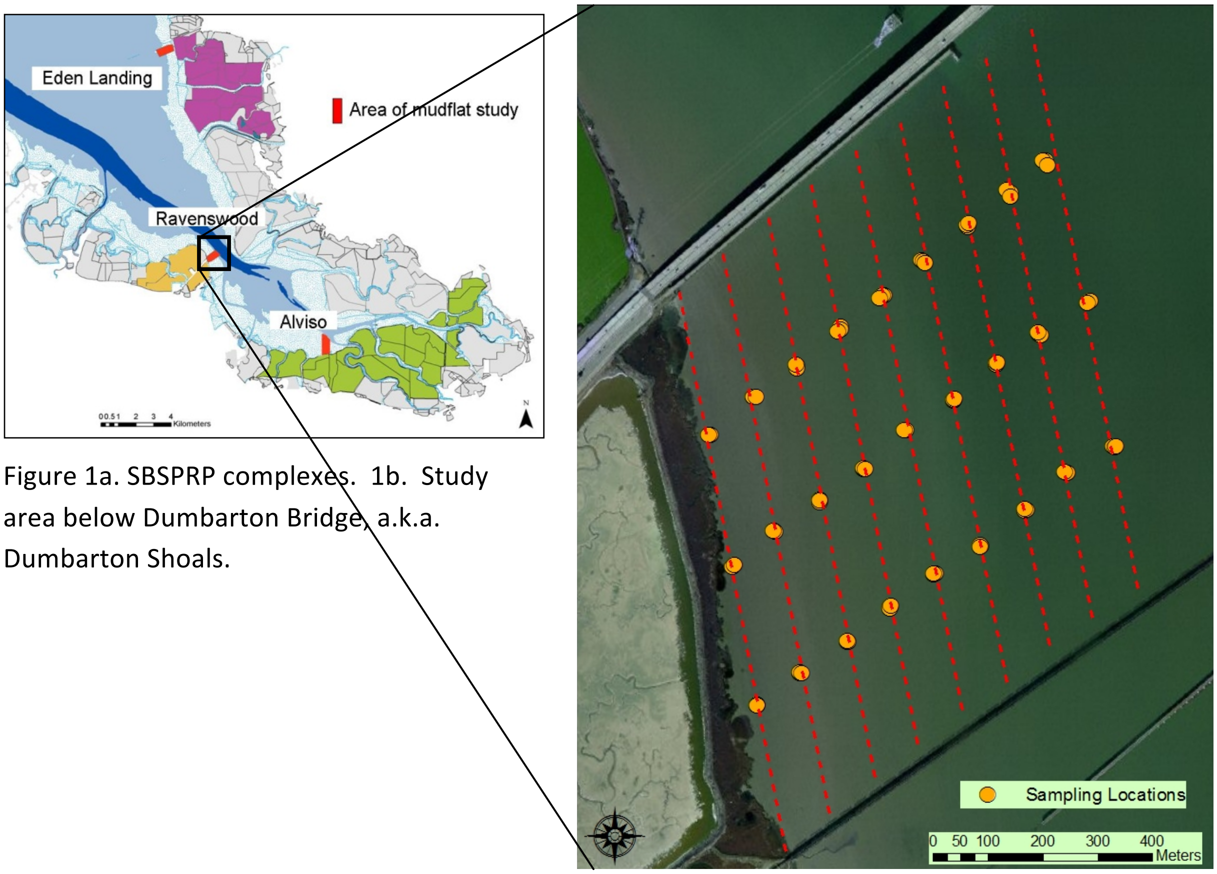

Figure 1a. SBSPRP complexes. 1b. Study area below Dumbarton Bridge, a.k.a. Dumbarton Shoals.

Sampling

Beginning in October of 2008, the technicians from the USGS SFBE field station began sampling invertebrates and sediment monthly by taking cores with 10cm depth and diameter along 3 transects (Fig. 1b). Each transect consisted of 9 stations of triplicate cores spaced 100m apart along each transect (n=81 for each sampling date). Technicians rinsed samples with saltwater through a 0.5mm sieve. They enumerated, weighted, measured and identified invertebrates to lowest taxonomic level possible, then dried samples to a constant weight at 60°C. Published values will be used to convert measured dry weights to ash free dry weights (AFDW, Ricciardi and Bourget 1998) USGS technicians also surveyed avian abundance within the study area during falling tides each month, and other USGS partners recorded tidal change with water level loggers.

In order to analyze prey availability before fall migration and after spring migration, my final analysis will focus on the ‘shorebird year’ from July 2009 to June 2010. This time period best represents the important biological conditions before/after the fall migration, during the over-wintering period, and before/after the spring migration. Invertebrate samples have not yet been fully processed by the USGS for this time period, and so this annual report presents the prey availability map from October 2009 only. Additional prey availability maps will be presented in future updates as the data becomes available.

Accessible Prey

Amphipods, bivalves, cumaceans, polychaetes and oligochaete worms were chosen from a literature review (Table 1) as the most important prey items for WESA and DUNL. According to Zwarts and Wanink (1993) the minimum profitable size of prey is determined by the weight of the predator as follows,

$$\text{Minimum prey weight (mg dry flesh)} = 0.0012W^{1.20}$$

Prey taxa	Prey species taken	Species	Size (mm)	n	Percent occurrence	Location	Sources
All Inverts		*C. mauri*	0-5	Spr: 68, Fall: 92	Spr: 73, Fall: 64 eso	Playa Lakes Region, Texas	Davis and Smith 2001
All Inverts		*C. mauri*	5-10	Spr: 68, Fall: 92	Spr: 26, Fall: 32 eso	Playa Lakes Region, Texas	Davis and Smith 2001
Amphipoda	Allorchestes angusta	*C. mauri*	-	Win: 7, Spr: 11	Win: 43, Spr: 9	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Amphipoda	Ampelisca	*C. mauri*	-	14	21 eso, 14 giz	Newark, California	Takekawa *et al*, unpublished
Amphipoda	Ampelisca	*C. mauri*	-	7	43 giz	Redwood City, California	Takekawa *et al*, unpublished
Amphipoda	Corophium spp	*C. mauri*	-	Fall: 12, Win: 7	Fall: 17, Win: 100	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Amphipoda	Gammaridae	*C. mauri*	-	Win: 7	Win: 71	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Crustacea	Harpacticoida	*C. mauri*	0.063-0.5	-	-	Frasier River Delta, Canada	Sutherland, Shephard, Elner 2000
Crustacea	Harpacticoida	*C. mauri*	-	Fall: 12, Win: 7	Fall: 58, Win: 57	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Crustacea	*Cyathura carinata*	*C. alpina*	-	244	26.2 pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Crustacea	Ostracoda	*C. mauri*	-	Fall: 12, Win: 7, Spr: 11	Fall: 25, Win: 100, Spr: 45	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Crustacea	Ostracoda	*C. mauri*	-	14	14 eso, 14 giz	Newark, California	Takekawa *et al*, unpublished
Crustacea	Ostracoda	*C. mauri*	-	7	57 giz	Redwood City, California	Takekawa *et al*, unpublished
Crustacea		*C. alpina*	-	Juvi: 25, Adult: 11	Juvi: 36, Adult: 27	Langenwerder, Germany	Dierschke *et al.* 1999
Cumacea	Cumella vulgaris	*C. mauri*	-	Fall: 12, Win: 7	Fall: 25, Win: 43	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Cumacea		*C. mauri*	0.5-1.0	-	-	Frasier River Delta, Canada	Sutherland, Shephard, Elner 2000
Cumacea		*C. mauri*	-	14	29 eso, 36 giz	Newark, California	Takekawa *et al*, unpublished
Cumacea		*C. mauri*	-	7	33 eso, 43 giz	Redwood City, California	Takekawa *et al*, unpublished
Insecta	Larvae	*C. mauri*	-	Fall: 12, Win: 7, Spr: 11	Fall: 68, Win: 14, Spr: 100	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Insecta	Sepsid larvae	*C. alpina*	4.5-10.5	Juvi: 25, Adult: 11	Juvi: 24, Adult: 73	Langenwerder, Germany	Dierschke *et al.* 1999
Mollusca	*Gastropoda*	*C. mauri*	-	14	35 eso, 79 giz	Newark, California	Takekawa *et al*, unpublished
Mollusca	*Gastropoda*	*C. mauri*	-	7	71 giz	Redwood City, California	Takekawa *et al*, unpublished
Mollusca	Gemma gemma	*C. mauri*	-	Fall: 12, Win: 7, Spr: 11	Fall: 50, Win: 57, Spr: 18	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Mollusca	*Gemma gemma*	*C. mauri*	-	14	29 giz	Newark, Redwood City	Takekawa *et al*, unpublished
Mollusca	*Hydrobia ulvae*	*C. alpina*	1.8 ± 0.03	216	39.3 pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Mollusca	*Macoma balthica*	*C. alpina*	3-7	-	-	Severn estuary, Europe	Worrall 1984
Mollusca	*Macoma balthica*	*C. mauri*	-	14	57 giz	Newark, California	Takekawa *et al*, unpublished
Mollusca	*Mytilidae*	*C. mauri*	-	14	14 giz	Newark, California	Takekawa *et al*, unpublished
Mollusca	*Mytilidae*	*C. mauri*	-	7	16 eso	Redwood City, California	Takekawa *et al*, unpublished
Mollusca	*Potamacorbula*	*C. mauri*	-	14	14 eso, 7 giz	Newark, California	Takekawa *et al*, unpublished
Mollusca	*Scrobicularia plana/ Abra sp*	*C. alpina*	7.1 ± 0.1	169	49.6 pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Mollusca		*C. alpina*	-	Juvi: 25, Adult: 11	Juvi: 56	Langenwerder, Germany	Dierschke *et al.* 1999
Oligochaeta		*C. alpina*	-	244	present pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Oligochaeta		*C. mauri*	-	Fall: 12	Fall: 50	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Polychaeta	Capitella capitata	*C. mauri*	-	Fall: 12, Win: 7	Fall: 75, Win: 86	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Polychaeta	*Hediste diversicolor*	*C. alpina*	7-31	Juvi: 25, Adult: 11	Juvi: 88, Adult: 82	Langenwerder, Germany	Dierschke *et al.* 1999
Polychaeta	*Hediste diversicolor*	*C. alpina*	37.8 ± 3.2	34	5.3 pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Polychaeta	*Nephtys hombergii*	*C. alpina*	-	244	0.8 pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Polychaeta	*Polydora ciliata*	*C. alpina*	-	244	present pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Polychaeta	Spionidae	*C. mauri*	-	Fall: 12	Fall: 42	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991
Polychaeta	*Streblospio shrubsolii*	*C. alpina*	-	244	present pel	Tagus Estuary, Portugal	Santos, Granadeiro, Palmeirim 2005
Polychaeta		*C. mauri*	>20	-	-	Frasier River Delta, Canada	Sutherland, Shephard, Elner 2000
Polychaeta		*C. mauri*	-	14	21 eso, 71 giz	Newark, California	Takekawa *et al*, unpublished
Polychaeta		*C. mauri*	-	7	50 eso, 71 giz	Redwood City, California	Takekawa *et al*, unpublished
Protista	Foraminifera	*C. mauri*	-	Fall: 12, Win: 7, Spr: 11	Fall: 50, Win: 86, Spr 9	Elkhorn Slough, California	Ramer, Page, Yoklavich 1991

Table 1. Summary of diet studies examining WESA (*C. mauri*) and DUNL (*C. alpina*). eso= esophageal samples, giz= gizzard samples, pel= pellet samples, juvi= juvenile birds, win= samples collected in winter, spr= samples collected in spring

Thusly, I calculated that prey items weighing less than 0.06 mg AFDW were unprofitable for WESA and excluded them from this analysis. DUNL require a slightly larger minimum prey size (0.13 mg AFDW), but we will use the lower bound for WESA so that we can consider all prey items available to the two species. For bivalves, an upward bound value of 6mm was selected (Goss-Custard *et al.* 2006, Worrall 1984). A maximum of 40mm was chosen for polychaetes and oligochaetes based on DUNL diet studies in the Tagus estuary, Portugal (Santos 2005). We assume that all sizes of amphipod and cumaceans greater than the minimum weight threshold were available to foraging WESA and DUNL. Larger prey are usually not taken by small shorebirds because the significant handling time involved limits their profitability.

Mapping

I created prey distribution maps that model the biomass density of macroinvertebrates from 27 sampling locations on the Dumbarton Shoals. I used the method of inverse distance weighting (IDW, ArcGIS Geostatistical Analyst, ESRI, Redlands, CA) to interpolate macro-invertebrate densities from values at the nearest sampling stations (Lovvorn *et al.* 2009). The sum of all macroinvertebrate prey species of the proper size class is presented in this analysis. Because triplicate cores were sampled at each of the 27 stations, I used the average biomass from the triplicate cores in the interpolation. For comparability with other studies, I presented macroinvertebrate density as biomass per unit area (grams ash-free dry weight per meter squared).

<u>Results/ Discussion:</u>

Accessible Prey

Polychaetes and bivalves were the main prey sources available to WESA and DUNL at the study site in October of 2009. Other prey items are present at such low densities as to be unprofitable during this month. Bivalves are concentrated within the first 300m from shore while polychaetes are found across the entire site (Figure 2).

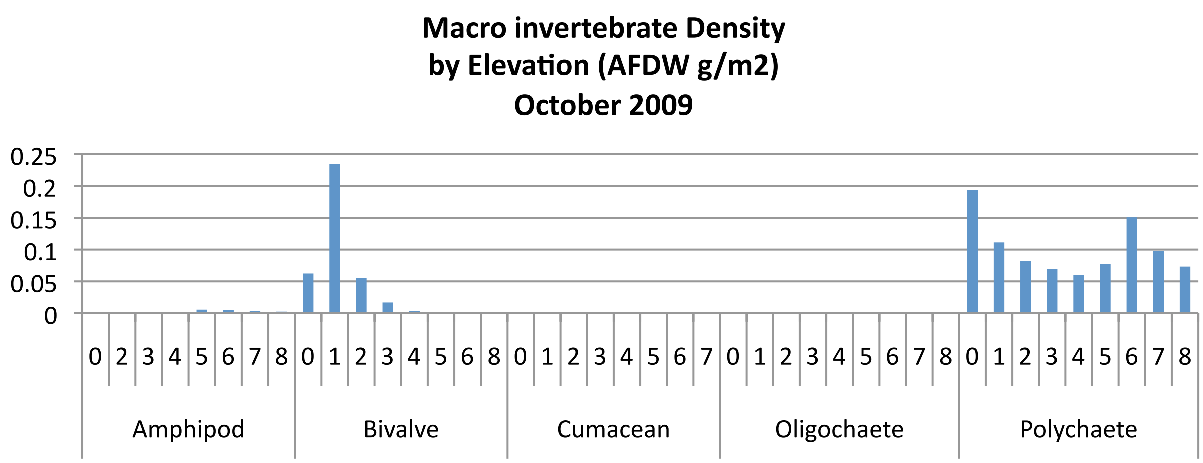

Figure 2. Density of available WESA and DUNL macroinvertebrate prey at 100m intervals from shore. Density is presented as ash free dry weight per square meter detected in October 2009 summed across the nine cores collected from each elevation band.

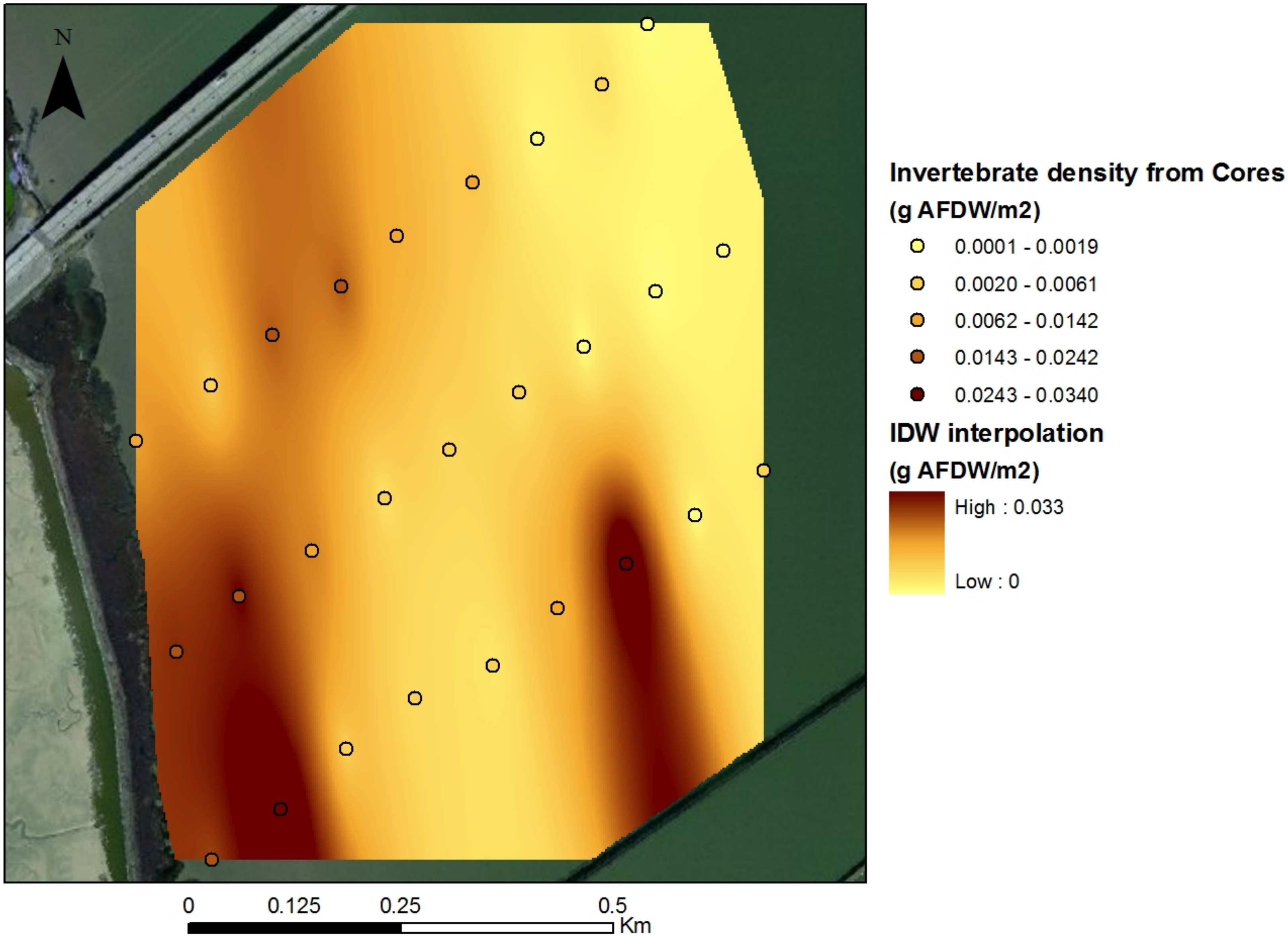

Figure 3. Interpolated map of WESA/DUNL prey availability based on macroinvertebrate densities detected in benthic cores. Density is presented as ash free dry weight per square meter collected in October 2009. Only know accessible prey items and size classes of macroinvertebrates were included.

Mapping

The smoothed IDW method takes into account the anisotropy present due to the environmental gradients in the site (namely, the increasing water depth extending perpendicular to the shore). All settings were selected in order to minimize the root mean square error evaluated during cross validation. Cross validation compares the predicted value at each sampling point (while omitting that point) with the actual sampled value. However, it is uncertain if high density patches detected at a particular sampling location will cause undue influence for the foraging model (Figure 3). Once biomass data for the rest of the year are available, I will evaluate the impact of outliers on the model results. Further discussion of seasonal patterns in prey availability will be discussed in future updates.

<u>Next Steps…</u>

Foraging Analysis

Once all the prey availability data have been processed, then I can use the functional response to calculate the amount of food and energy a single bird could harvest at that prey density for the duration of exposure for each 100m elevation segment (Fig 1b) between invertebrate sampling locations. I will calculate the total amount of food harvested by a single bird over both tidal cycles (ebb tide only), and sum it over all elevation bins. If the total consumption of observed WESA and DUNL at the Dumbarton Shoals is more than their daily energy expenditure (DEE), then I will conclude that additional shorebirds may be able to forage profitably on this mudflat (Figure 4).

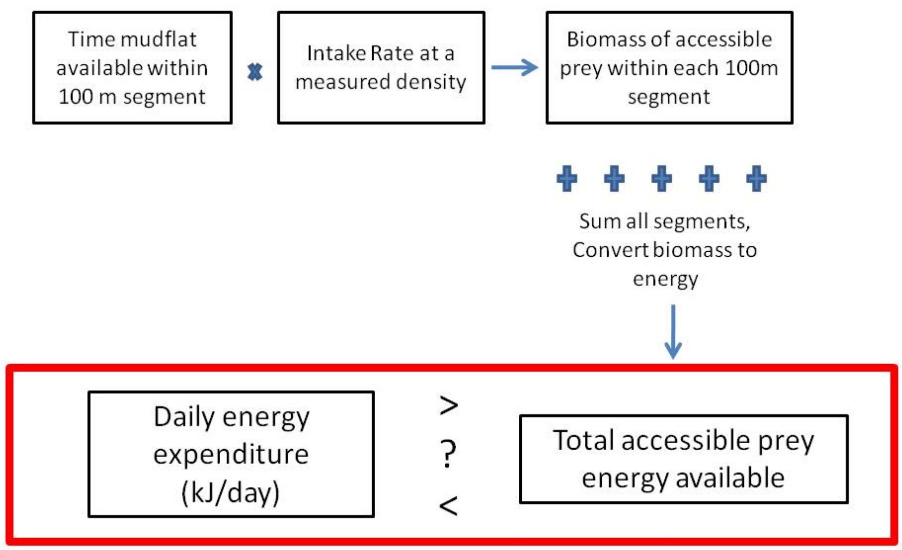

Figure 4. Schematic of foraging analysis that takes into account tidal availability

Availability of intertidal habitat

Assuming that a 2m swathe of mudflat above water's edge during ebb tide contains all the available prey, I will calculate the duration during each diel period that each elevation is available to foraging Western Sandpipers and Dunlin by multiplying the average rate of water level decline by the change in elevation between sampling points.

Calculating energy content

Brey *et al.* (1988) found that the average energetic value of macroinvertebrates in their meta analysis (n=229 species) was 22.99 ± 0.26 J mg^{-1} AFDW. Castro *et al* (1989) found a strong relationship between assimilation efficiency (73.9% ± 2.28 SE for insectivores) and food type regardless of bird taxa.

Functional Response

A bird's functional response describes how the intake rate varies with prey density. Zwarts and Wanink (1993) provide an equation to describe the functional response of wading birds according to their weight:

$$\text{Intake rate} = 0.004W^{0.95}$$

This corresponds to an intake rate of 0.088 mg AFDW/s for Western Sandpiper and 0.164 mg AFDW/s for Dunlin. I will use these intake rates to calculate how much prey biomass a small shorebird is able to consume given the time the intertidal mudflat is available.

Daily energy expenditure (DEE)

Kelly *et al.* (2002) found that daily energy expenditure in aviary Dunlin was 2.85 kJ g d^{-1} or 2.8 x BMR. Basal metabolic rate (BMR) is the energy consumption of a resting bird at thermoneutrality. Kersten and Piersma (1987) calculate basal metabolic rate as:

$$BMR = 5.06 \times LW^{0.729}$$

in which LW = the lean (fat-free) weight of the species in grams. Other studies have used equations from Lasiewski and Dawson (1967) or Aschoff and Pohl (1970), but these result in lower estimates of wader BMR.

Sensitivity analysis

The parameters that will vary within the sensitivity analysis are DEE, functional response, coefficients, constant elevation change of tidal level and mud flat slope change. All the other factors are empirically based. After performing the sensitivity analysis for the existing mudflat, I plan to re-do the calculations for three scenarios of mud flat morphologic change (increased slope, overall loss of elevation, channelization).

Conclusion:

The results of this study will provide the first steps necessary to address a number of key uncertainties regarding shorebird populations and mud flat habitat. Small shorebirds use a combination of habitats in the region, and estimates of relative contributions will help managers maintain existing populations as salt pond habitats are converted and mud flat area declines. The USGS surveys birds and water quality on 53 salt ponds every month and the PRBO organizes an annual bay-wide survey of shorebirds. Benthic macroinvertebrate populations are notoriously difficult to sample and expensive to process, so any modeling effort contributes greatly to the lack of prey availability data. If shorebird numbers in the South Bay fail to the meet pre-restoration baseline for three consecutive years then specific management actions will be triggered. Analysts for the SBSPRP will look at all available monitoring data for South Bay, Bay Area, and entire Pacific Flyway to determine whether declines are likely the result of SBSP Restoration Project, or the result of external factors (South Bay Salt Pond Restoration Project 2007).

Beyond the impacts of salt marsh restoration in the South Bay Salt Ponds, shorebirds will be facing numerous other challenges in the coming decades. Invasive Spartina threatens to reduce the foraging quality of mud flats (Stralberg *et al.* 2004). Mud flat habitat are is expected to decline by 30% in the next 50 years (South Bay Salt Pond Restoration Project 2007) due to sea level rise and sediment flux. Macroinvertebrate communities are notoriously variable and subject to invasion by non-native species (Nichols *et al.* 1990) and changes in regional ecosystem states (Cloern *et al.* 2007).

It will be interesting to see if changes in the shape of the mudflat affect the amount of foraging time that shorebirds will have on the site. It could be that everything depends on how long they are able to stay on high prey dense areas of mudflat, and they may not have enough time to exploit the available food resources if the slope of the mudflat increases. If we know that the slope or the shape alters the results of the model greatly, then this may be an area for focus in future studies.

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Works Cited:

Aschoff, J. and H. Pohl. 1970. Rhythmic variations in energy metabolism. *Federation Proceedings* 29(4): 1541-1552.

Baldwin, J. R. and J.R. Lovvorn. 1994. Habitats and tidal accessibility of the marine foods of dabbling ducks and brant in Boundary Bay, British Columbia. *Marine Biology* 120: 627-638.

Bearman, J.A., C.T. Friedrichs, B.E. Jaffe and A.C. Foxgrover. 2010. Spatial Trends in Tidal Flat Shape and Associated Environmental Parameters in South San Francisco Bay. *Journal of Coastal Research* 26(2): 342-349.

Brey, T., H. Rumohr and S. Ankar. 1988. Energy content of macrobenthic invertebrates: general conversion factors from weight to energy. *J. Exp. Mar. Biol. Ecol.* 117: 271-278.

Castro, G., N. Stoyan and J. P. Myers, 1989. Assimilation efficiency in birds: a function of taxon or food type? *Comp. Biochem. Physiol.* 92A: 271-278 .

Cloern, J.E., A.D. Jassby, J.K. Thompson, and K.A. Hieb. 2007. A cold phase of the east pacific triggers new phytoplankton blooms in San Francisco Bay: Proceedings of the National Academy of Sciences of the United States of America, 104(47): 18561-18565. doi:10.1073/pnas.0706151104.

Davis, C. A., and L. M. Smith. 2001. Foraging strategies and niche dynamics of coexisting shorebirds at stopover sites in the southern Great Plains. *The Auk* 118 (2): 484-495

Dierschke, V., J. Kube, S. Probst and U. Brenning. 1999. Feeding ecology of dunlins Calidris alpine staging in the southern Baltic Sea, 1. Habitat use and food selection. *Journal of Sea Research* 42: 49-64.

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. Open-file Report. U. S. Geological Survey: 30.

Goals Project. 1999. Baylands Ecosystem Habitat Goals. A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. U. S. Environmental Protection Agency, San Francisco, Calif./S.F. Bay Regional Water Quality Control Board, Oakland, Calif.

Goss-Custard, J. D, A. D West, M. G Yates, R. W.G Caldow, R. A Stillman, L. Bardsley, J. Castilla, *et al.* 2006. Intake rates and the functional response in shorebirds (Charadriiformes) eating macro-invertebrates. *Biological Reviews* 81(4): 501–529.
Hicklin P. W. and P. C. Smith. 1984. Selection of foraging sites and invertebrate prey by migrant semipalmated Sandpipers, *Calidris pusilla* (Pallas), in Minas Basin, Bay of Fundy. *Can J Zool* 62: 2201-2210.
Kelly, J. P., N. Warnock, G. W. Page, and W. W. Weathers. 2002. Effects of weather on daily body mass regulation in wintering dunlin. *J Exp Biol* 205 (1): 109-120.
Kersten, M. and T. Piersma, 1987. High levels of energy expenditure in shorebirds; metabolic adaptations to an expensive way of life. *Ardea* 75: 175-187.
Lasiewski, R. C, and W. R Dawson. 1967. A re-examination of the relation between standard metabolic rate and body weight in birds. *Condor* 69(1): 13–23.
Lovvorn, J.R., J.M. Grebmeier, L.W. Cooper, J.K. Bump, and S.E. Richman. 2009. Modeling marine protected areas for threatened eiders in a climatically changing Bering Sea. *Ecological Applications* 19(6): 1596-1613.
Masero, J.A. 2003. Assessing alternative anthropogenic habitats for conserving waterbirds: Salinas as a buffer areas against the impact of natural habitat loss for shorebirds. *Biodiversity and Conservation* 12: 1157-1173.
Nichols, F. H. and M. M. Pamatmat. 1988. The ecology of the soft bottom benthos of San Francisco Bay: a community profile. U.S. Fish & Wildlife Service Biological Report, 85(7.23).
Nichols, F.H., J.K. Thompson, and L.E. Schemel. 1990. Remarkable invasion of the San Francisco Bay (California, USA) by the Asian clam Potamocorbula amurensis. II. Displacement of a former community. *Marine Ecology Progress Series* 66: 95-101.
Page, G.W., L.E. Stenzel, and J.E. Kjelmyr. 1999. Overview of Shorebird Abundance and Distribution in Wetlands of the Pacific Coast of the Contiguous United States. *The Condor* 101 (3): 461-471.
Poulton, V. K., J. R. Lovvorn, and J. Y. Takekawa. 2004. Spatial and overwinter changes in clam populations of San Pablo Bay, a semiarid estuary with highly variable freshwater inflow. Estuarine, Coastal and Shelf Science 59(3): 459-473.
Quammen, M.L. 1982. Influence of subtle substrate differences on feeding by shorebirds on intertidal mud flats. *Marine Biology* 71: 339-343.
Ramer, B.A., G.W. Page, M.M. Yoklavich. 1991. Seasonal abundance, habitat use, and diet of shorebirds in Elkhorn Slough, California. *Western Birds* 22: 157-174.
Ricciardi, A., and E. Bourget. 1998. Weight-to-weight conversion factors for marine benthic macroinvertebrates. *Marine Ecology Progress Series* 163: 245–251.
Santos, C.D., J.P. Granadeiro, J. Palmeirim. 2005. Feeding ecology of Dunlin *Calidris alpina* in a southern European estuary. *Ardeola* 52 (2): 235-252.
Shepherd, P.C.F. and J.S. Boates. 1999. Effects of a commercial baitworm harvest on semipalmated Sandpipers and their prey in the Bay of Fundy Hemispheric Shorebird Reserve. *Conservation Biology* 13 (2): 347-356
South Bay Salt Pond Restoration Project. 2007. Draft Environmental Impact Statement/Report. Section 3.6 Biological Resources. http://www.southbayrestoration.org/pdf_files/SBSP_ EIR_Final/ 3.6%20Biological%20 Resources%20Final%20EIS_R.pdf
Stenzel, L.E., C.M. Hickey, J.E. Kjelmyr and G. Page. 2002. Abundance and distribution of shorebirds in the San Francisco Bay Area. Western Birds 33(2): 69-98.
Stralberg, D., V. Toniolo, G.W. Page, and L.E. Stenzel. 2004. Potential Impacts of Non-Native Spartina Spread on Shorebird Populations in South San Francisco Bay. PRBO Report to California Coastal Conservancy (contract #02-212). PRBO Conservation Science, Stinson Beach, CA.

Stralberg, D., M. Herzog, N. Warnock, N. Nur and S. Valdez. 2006. Habitat-based modeling of wetland bird communities: an evaluation of potential restoration alternatives for South San Francisco Bay. Final report to California Coastal Conservancy, December 2006 PRBO Conservation Science, Petaluma, CA.

Stralberg, D., D.L. Applegate, S.J. Phillips, M.P. Herzog, N. Nur and N. Warnock. 2009. Optimizing wetland restoration and management for avian communities using a mixed integer programming approach. *Biological Conservation* 142: 94-109.

Sutherland, T. F., P. C. F. Shephard and R. W. Elner. 2000. Predation on meiofaunal and macrofaunal invertebrates by Western Sandpipers (*Calidris mauri*): Evidence for dual foraging modes. *Marine Ecology* 137: 983-993.

Takekawa, J. Y., N. D. Athearn, B. J. Hattenbach, and A. K. Schultz. 2006. Bird Monitoring for the South Bay Salt Pond Restoration Project. Data Summary Report, U. S. Geological Survey, Vallejo, CA. 74pp.

Takekawa, J. Y, C. T. Lu and R. T. Pratt. 2001. Avian communities in baylands and artificial salt evaporation ponds of the San Francisco Bay estuary. Hydrobiologia 466:317-328.

Warnock, N., G. W. Page, T. D. Ruhlen, N. Nur, J. Y. Takekawa, J. T. Hanson. 2002. Management and Conservation of San Francisco Bay Salt Ponds: Effects of Pond Salinity, Area, Tide, and Season on Pacific Flyway Waterbirds. *Waterbirds* 25: 79-92.

Wolff W.J., L. de Wolf. 1977. Biomass and production of zoobenthos in the Grevelingen estuary, The Netherlands. *Estuar cstl Shelf Sci* 5:1-24.

Worrall, D.H. 1984. Diet of the Dunlin *Calidris alpina* in the Severn Estuary. *Bird Study* 31(3): 203-212.

Zwarts, L., and J. H Wanink. 1993. How the food supply harvestable by waders in the Wadden Sea depends on the variation in energy density, body weight, biomass, burying depth and behaviour of tidal-flat invertebrates. *Netherlands Journal of Sea Research* 31 (4): 441–476.