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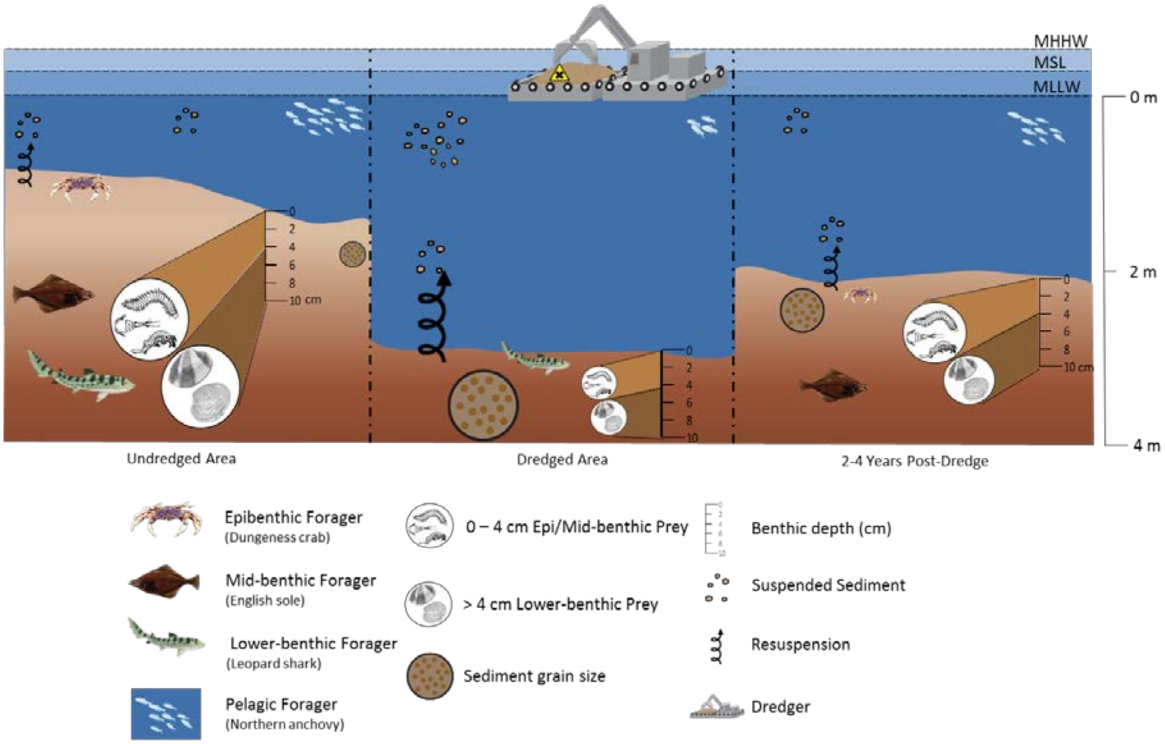
Assessing the Impact of Periodic Dredging on Macroinvertebrate Prey Availability for Benthic Foraging Fishes

Final Study Plan and Preliminary Pilot Study Results



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Cover: Conceptual model of dredge impacts to benthic infauna and their predators. Comparison of undredged benthic habitat (left), with a recently a dredged area (center), and 2-4 years after dredging activity (right). Undredged areas are characterized by an abundant and diverse prey base of benthic infauna of varying size and depths. Turbidity is stable. Sediment is stratified with smaller grains dominating the top 10-cm. Recently dredged areas result in the removal of shallow benthic habitat, resulting in increased suspended sediment. Post-dredging habitat may be partially recovered, with sedimentation dependent on sediment availability and texture. Early macroinvertebrate colonizers are typically smaller, soft-bodied prey items, resulting in the return of some foraging functions for benthic foraging fish.

(Change in size of an object among panes indicates a shift in abundance, size, or magnitude. MHHW = Mean Higher High Water; MSL = Mean Sea Level; MLLW = Mean Lower Low Water. Not to scale.). *Credit: T. Graham.*

Assessing the Impact of Periodic Dredging on Macroinvertebrate-Prey Availability for Benthic Foraging Fishes

Final Study Plan and Preliminary Pilot Study Results

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BACKGROUND

Due to its importance for special status fish, the San Francisco Bay (SFB) estuary has been designated as Essential Fish Habitat (EFH) under the Magnuson-Stevens Fishery Conservation and Management Act ([MSA; 16 U.S.C. 18559b)]. Within this estuary, benthic macroinvertebrate communities provide important prey resources for many economically significant fish species that rely on EFH. Periodic maintenance dredging can impact these infaunal communities; however, there is a lack of scientific information specific to SFB on the degree of benthic community disruption caused by dredging. In addition, rates of benthic community recolonization and recovery following dredging and subsequent effects on foraging fish are unknown. For this reason, it is difficult for regulatory and resource agencies to determine the impacts of maintenance dredging. Thus, the National Marine Fisheries Service (NMFS) and the consortium of agencies (US Environmental Protection Agency (EPA), US Army Corp of Engineers (USACE), San Francisco Regional Water Quality Control Board (SFRWQCB), and San Francisco Bay Conservation and Development Commission (BCDC)) comprising the San Francisco Bay Long Term Management Strategy for Dredging (LTMS) effort identified a study of dredging impacts on SFB fish foraging habitat as one of their highest priorities in their 2011 Programmatic EFH Agreement.

To address this priority, LTMS agencies selected a tiered study approach comprised of three phases: a literature review (Phase I), the design of a full study (Phase II), and a pilot study to refine the full study design (Phase III). Due to challenges associated with locating comparable dredge areas within SFB and to ensure project feasibility, all phases of the study will be focused on shallow (<13 ft. [<3.96 m] MLLW), soft-bottom (silt/clay soil texture) areas in Central SFB. In 2016, the U.S. Geological Survey, Western Ecological Research Center (hereafter USGS) in partnership with University of California, Davis fisheries expert James

Hobbs, completed a draft Phase I literature review centered on evaluating benthic infauna community composition and fish foraging ecology specific to Central SFB. The USGS used information gathered in this review to create a statistically rigorous overall study plan, which was then tested and refined via a Phase III pilot study. In this report, we describe the process used to develop the Phase II full study design aimed at evaluating dredging effects on benthic infauna prey resources for Central SFB foraging fish. We also present results from the Phase III pilot study and identify resulting adjustments to the full study design.

RESEARCH GOAL AND OBJECTIVES

The overarching goal of this study is to assess and compare the quality of benthic habitat for foraging fish in Central SFB areas that are periodically dredged (every 1-3 years) to undredged reference areas. Our study considers the foraging needs of fish species that were identified under the 2011 Programmatic EFH Agreement (Phase I Literature Review, De La Cruz et al., in review). Here, we specifically address Phase II and Phase III.

1) Phase I – Conduct a literature review regarding fish feeding and benthic macroinvertebrate assemblages
2) Phase II – Design a statistically rigorous study to evaluate habitat quality for benthic foraging fish using a functional approach (i.e., based on macroinvertebrate prey availability and biomass) in areas that are dredged at a frequency of annually to every three years compared to those that are undredged.
3) Phase III – Evaluate and finalize the study design using a pilot study and statistical power analysis.

APPROACH

PHASE I: LITERATURE REVIEW

A literature review on benthic foraging fish and macroinvertebrate life histories, distributions, and abundances was conducted in 2015 - 2016 and will be published as a USGS Open File Report. The literature review summarized information regarding fish foraging ecology and benthic macroinvertebrate assemblages in Central SFB to characterize when and how demersal and pelagic fish are using shallow, soft-bottom habitats in this region including what they are eating during different seasons and life stages. Literature relevant to the impact of frequent dredging on benthic community recolonization and prey availability was also examined. Information from the literature review was used to inform the study design and pilot sampling. We hypothesized that immediately following dredge activities, benthic infauna and foraging fishes are greatly diminished in the dredged area as suitable habitat has been removed. Post-dredging habitat may partially recover, with the rate of recolonization depending on sedimentation. Early macroinvertebrate colonizers are typically smaller, soft-bodied prey items, resulting in the return of some foraging functions for benthic foraging fish (Figure 1).

PHASE II: STUDY DESIGN

Design Overview

We have employed an iterative approach to develop the final study design. Our preliminary effort involved a power analysis using previously collected USGS macroinvertebrate datasets from south SFB to estimate the variability that might be expected among macroinvertebrate taxa in the estuary. We used the initial power analysis results to determine the sampling design (i.e, the number of marinas, transects, cores, and replicates) necessary to detect differences between dredged areas and undredged reference areas. The sample processing methodology is based on a modification of an established benthic assessment technique to evaluate functional habitat recovery for fish post-dredging.

This sampling design was implemented and tested during the pilot study. Macroinvertebrate taxa in samples from the pilot study were processed and identified to a broad taxonomic level. We then used site-specific data generated from the pilot study for a second power analysis to modify the study design.

Initial Power Analysis

After an extensive search during our Phase I literature review, we were unable to locate an appropriate existing macroinvertebrate dataset from the Central SFB to use in a power analysis to inform the study design. Therefore, we used a comprehensive USGS macroinvertebrate dataset collected monthly from October 2008 to April 2010 on mudflat and subtidal shoals southwest of the Dumbarton Bridge (Woo et al., unpublished data). The pilot study dataset was used in a simulation-based power analysis to estimate the variability we may expect in Central SFB macroinvertebrates. The study site (Figure 2) is located in the Dumbarton shoals adjacent to pond RSF2 in the Ravenswood complex of the South Bay Salt Pond Restoration Project. The site is bounded by the Dumbarton Bridge to the north and a Southern Pacific Railroad Bridge to the south, the RSF2 levee to the west and a deep channel to the east. The mud flat ranges in elevation from –0.80 m to 0.97 m NAVD88 (North American Vertical Datum 1988). Water column salinity during flood tides at the site ranged from 18 ppt in March and April to 32 ppt in late August and September.

Benthic macroinvertebrates were sampled monthly by taking cores along three transects (Figure 2). At each of 9 stations spaced at 100 m intervals along each transect, we took triplicate sediment cores 10 cm deep and 10 cm in diameter (n = 81 cores for each sampling date). Cores were immediately transported to SFBE on ice and refrigerated until processed. Within 1-2 days cores were rinsed through a 0.5 mm mesh sieve, and fauna retained by the sieve were preserved in a 70% ethanol with 1% rose bengal dye. Identification of benthic macroinvertebrates was completed at the SFBE Macroinvertebrate Ecology Laboratory. All taxa within cores were sorted, identified to lowest practical taxonomic level and enumerated. Dominant macroinvertebrates were grouped by taxa including Bivalvia, Cumacea, Oligochaeta, Ostracoda, Polychaeta (sedentary and errant), and Amphipoda. These broad taxa were used in the power analysis for the pilot study design.

We used a data-derived, simulation-based power analysis that was designed to consider variation within replicates and transects. In the initial step of our power analysis we used an information-theoretic model selection framework (Akaike's Information Criterion (AIC); Burnham & Anderson 2002) to identify the most parsimonious model for each taxa. We separately modeled abundances of each broad taxa group using mixed linear models (PROC Mixed, SAS 9.3, SAS Institute Inc., Cary NC, USA). We used normal approximation models where the dependent variable was the log-transformed count (x + 0.5) for each taxa. We combined the year and month data to make a single unique variable called "monyear" (ex: October of 2009 becomes OCT09). We built the same candidate set of models for each taxa that included all possible combinations of monyear, elevation and the interaction of these terms as fixed effects, as well as the number of transects and cores as random effects.

For each taxa, we identified the top model as that with the lowest AIC score and used the parameter estimates for the fixed and random effects from that model as input parameters for simulation models. Datasets were simulated for eight different sample sizes (Figure 3) representing different combinations of sites, transects, cores locations and core replicates. Since the Dumbarton dataset represents an undredged site with no equivalent paired dredged site, we used scenarios to simulate hypothesized macroinvertebrate reductions of 0, 25, 50, and 75% due to dredging. For each taxa group we ran 1000 simulations per sample size and reduction scenario and calculated power as the proportion of simulations in which a significant effect (α=0.05) was detected.

We used 80% power (Steidl et al 1997, Quinn and Keough 2002, Di Stefano 2003) as the minimum acceptable value for identifying a difference in macroinvertebrate abundance between dredged and undredged areas. We found that power generally increased for all taxa as the sample number increased (Figure 3). Power to determine a 50% reduction in individuals reached >80% under the scenario containing 200 cores for all taxa except errant polychaetes, which did not reach 80% power until the sample size was 320 cores (Figure 3, Table 1). Power to determine a 25% or less difference between dredge and undredged sites was low for several taxa and did not reach 80% power for most taxa even at a sample size of 400 cores (Figure 3). Given the scope and budget of the study, we determined that a design to detect a 50% reduction in individuals between dredged and undredged areas was most feasible. Thus, our design uses the 200 core scenario from the power analysis (Table 1). This scenario includes sampling across 5 marinas, each containing both dredged and undredged areas that are bisected by 2 transects with 5 core locations per transect and 2 replicate cores taken at each core location.

Site Selection and Sampling Design

SFB is a shallow estuary (median depth of 6 ft below MLLW; Conomos et al. 1985) with four major sub-bays: Suisun Bay, North SFB (San Pablo Bay), Central SFB and South SFB. To ensure that significant differences, if present, detected in benthic habitat quality between the dredged and undredged reference areas examined in this study were due to the impacts of dredging (as opposed to differences in environmental conditions such as salinity and sediment texture), we restricted our site selection to areas within Central SFB since this region consists of relatively homogeneous environmental conditions. Central SFB is predominantly polyhaline (1-30 ppt; Figure 4; Thompson et al. 2007, Thompson et al. 2013, Gillet et al. 2014), and is generally characterized by fine-grained (silt and clay) to coarser sediments (sand and shell fragments; Goals 1999, Subtidal Goals Project 2010, Barnard et al. 2013, Greene et al. 2013). Selected study site marinas were mostly silt/clay (Table 2).

To meet the objective of assessing benthic habitat quality for foraging fishes in “areas that are dredged” compared to “those that are undredged.” set forth by the LTMS agencies, we carefully selected recently dredged marinas that had adjacent corresponding undredged reference areas. Here we used the term “reference” to refer to an area that is undredged, rather than a pristine site. It is important to note that the reference areas we selected are not “undisturbed”. Rather, selected undredged reference areas included similar localized environmental characteristics (salinity, depth, sediment texture, etc.) to the associated dredged marina, as well as ambient levels of disturbance to the sediment, including those associated with boat traffic, that are expected to occur in an undredged area of an urbanized estuary.

We compiled site characterization information for each marina from BCDC's database to inform decisions about sampling design elements (Table 2). The primary site selection criteria included: 1) location within the polyhaline region of Central SFB (Figure 4), 2) post-dredging depth of <13 ft. [3.96 m] MLLW; 3) predominantly soft-bottom sediments; 4) a dredging date falling within one of three time periods: 1 year before present, 2 to 3 years before present, and >3 years before present, and 5) an adjacent undredged reference site. Undredged reference sites were considered areas in close proximity to the study marina with no record of dredging that had similar environmental conditions to their corresponding dredged area. Time since dredging categories were chosen to meet the study objective of evaluating differences in areas "that are dredged at a frequency of annually to every three years compared to those that are undredged." For our initial study design, we selected 5 sites (Table 2, Figure 5) that met the criteria above. These sites were evaluated in our pilot study and later modified for the full study design based on pilot results (see Phase III below). Our study site selection will allow for a robust, quantitative assessment of whether the macroinvertebrate prey availability for fish differ between dredged and undredged reference areas.

We used the results of the Dumbarton dataset power analysis to inform the total number of transects and cores needed to determine a 50% difference in benthic infauna abundance between dredged and paired undredged sites. Within each marina we placed, 3) three to six transects in each dredged and undredged location, 4) a minimum of 6 core locations on each transect, 5) two replicate samples taken at each core location (Figures 6-10). This design meets or exceeds the sample size identified in our power analysis as robust for each taxa group except errant polychaetes.

To determine the timing of sample collection, we took factors identified in the Phase I literature review (De La Cruz et al, in review) into consideration, including seasonal and annual patterns of benthic foraging fish and their macroinvertebrate prey in central SFB. The full study will have four sample collection periods, including two summer and two early to mid-winter collections. The pilot study will account for one of the early winter sampling periods. Including multiple collection periods will enable us to compare macroinvertebrate abundance and community composition during wet and dry seasons and across a range of seasonal salinities, one of the major driver of macroinvertebrate community composition (Nichols and Pamatmat 1988, Thompson et al. 2013, De La Cruz et al. in review). The summer sampling periods will overlap with the period of peak fish abundance in central SFB, and will provide information on macroinvertebrate abundance when most focal fish species are present (De La Cruz et al., in review). To further evaluate how benthic macroinvertebrates recolonize dredged sites over time, we added a repeated measures component, in which we sample the same marina over four sampling periods to evaluate macroinvertebrate recolonization.

Sample Processing

Assessment techniques

To develop a sample processing scheme that assesses post-dredging habitat quality for benthic foraging fish, we considered metrics that are tied to the foraging ecology of focal fish species. In the Phase I literature review, we identified several published techniques for habitat quality evaluation that involved measuring structural (e.g. species richness, evenness, biomass, diversity) and functional (e.g. energy content, proportion of sensitive to opportunistic species) features of macroinvertebrate communities. While each technique contained useful elements for determining the quality of foraging habitat for fish, the Benthic Resources Assessment Technique (BRAT; Figure 11; Lunz and Kendal 1982) was most applicable to our study. Below we describe this technique and discuss the modifications we made to some elements to fit our objectives.

Modified Benthic Resources Assessment Technique (MBRAT)

The BRAT has traditionally been used to determine suitable locations to dispose of dredge material in a manner that does not impact trophic support for bottom feeding fishes (Clarke 1986, Lunz and Kendal 1982). It has also been applied as a general measure of habitat quality for benthic foraging fish (Rhoads and Germano 1986). This technique integrates information on fish foraging ecology and prey profitability to estimate the energy that is available to particular fish feeding guilds (Figure 11). Prey profitability is a measurement that has been used to evaluate habitat quality for many benthic foraging predators (Richman and Lovvorn 2004, Goss-Custard 2006, Lovvorn et al. 2013), including fish (e.g. Crowder and Cooper 1984, Godin and Keenleyside 1984). Energetic content, size, and accessibility (visibility, vertical distribution in the benthos, predator defense and escape capabilities) of invertebrates are integral to determining their profitability to benthic foraging fish (Lunz and Kendall 1982, Piet et al. 1998, van Denderen et al. 2013).

The steps in BRAT methodology are as follows:

1. Conduct a diet study to classify fish species present at a site into foraging guilds based on their feeding strategy, including size and burial depth of prey
2. Take benthic core samples from the same site
3. Divide cores into 2 cm depth increments
4. Sort macroinvertebrate taxa by species and size in each core depth increment
5. Measure biomass of macroinvertebrates in each species, size class, and depth increment
6. Compare fish diet (step 1) and macroinvertebrate community (step 5) data to estimate prey biomass and energy available to each fish foraging guild

The BRAT sampling framework is applicable to our study objectives as it yields relevant information on prey profitability and therefore habitat quality for benthic foraging fish. We will tailor the BRAT framework (Figure 11) to address our study objectives and scope by: 1) Substituting a literature review and consultation with fish experts on fish diets, rather than the direct collection of fish for diet analyses; 2) Incorporating the differences in fish foraging ecology for life history stage (juvenile, adult); 3) Dividing sediment cores into two sections, top 0 - 4 cm and bottom, rather than 5 2-cm sections: 4) Identifying invertebrates to broad taxonomic groups (Table 5), rather than identifying to species. For a random subset of core samples taken at each marina we will identify invertebrates to species or lowest taxonomic unit possible to enable comparison of taxa across marina sites.

This modified BRAT (MBRAT) approach will use benthic fish foraging ecology and diet information identified in our literature review and by local expert opinion (Table 3, Figure 12), in lieu of conducting a fish diet study. For each focal fish species, we will consider the following factors for juveniles and adults: common prey taxa, foraging mode, foraging depth in the benthic subsurface, and maximum prey size (Tables 5 and 6). We will adjust the MBRAT to include sorting and identifying invertebrates into broad taxonomic categories (e.g. Table 3) instead of identifying to lowest taxonomic unit possible. Clarke (1986) found that similar modifications to broad levels of taxonomic identification were sufficient for BRAT in previous studies. However, for a random subset of core samples taken at each marina we will identify invertebrates to species or lowest taxonomic unit possible to enable comparison of taxa across marina sites.

We also will simplify cores division into 2 depths: shallow (0 - 4cm) and deep (4 - 10 cm), given the lack of fine-scale information on focal fish foraging depths (Figure 12, Table 5). While the literature on this and other factors is incomplete for several focal fish species, expert opinion suggests there is adequate existing data to measure the prey available to them (J. Hobbs, University of California Davis, pers. comm. 4/10/2017, 2/13/2017).

Maximum macroinvertebrate prey sizes are largely unknown for the focal fish species in this study, especially for certain life stages (juveniles versus adults). For instance, many if not most, fish will consume different prey as juveniles versus adults (e.g., green/white sturgeon and California halibut; Haaker 1975; Plummer et al. 1983; Muir et al. 1986), and spatiotemporal patterns in prey availability can induce prey switching in certain fishes (e.g. Blaxter and Hunter 1982, Toole). Thus, after extensive literature review (De La Cruz et al., in review) and expert consultation with Dr. James Hobbs (University of California Davis, pers. comm. 2/3/2017, 2/1/2017, 8/10/2014, 7/22/2014), Dr. Scott Hamilton (Moss Landing Marine Laboratory, pers. comm. 6/13/2017), and Fred Feyrer (USGS CA Water Science Center pers. comm. 6/13/2017) we established five macroinvertebrate size classes (Table 6; 0 - 4 cm, 4 - 12 cm, 12 - 24 cm, 24 - 50 cm, and 50 - 100 cm). Invertebrates will be sorted into size classes based on overall body length for most taxa, and head width for polychaetes and oligochaetes. Biomass will then be determined for each taxa group and size class in each depth increment. Diet and foraging information (prey taxa, foraging depth in sediment, and maximum prey size) for adult and juvenile focal fish species gathered during the literature review will be used to evaluate macroinvertebrate prey availability for each species and life stage (Table 3). This method will allow us to assess taxa abundance, biomass, vertical distribution for each taxa group and size class, and determine prey availability for each focal fish species (Figure 12, Tables 5 and 6).

Statistical Analyses

The effects of the following factors on macroinvertebrate prey abundance and biomass will be considered in statistical analyses for the full study:

- Water quality: salinity, pH, dissolved oxygen and turbidity
- Season: effects of winter freshwater flow compared to dry summer, recruitment of different taxa
- Presence of physical barriers: specifically, barriers to water flow between undredged reference and dredged areas such as docks and jetties
- Soil composition: texture/grain size and organic matter content
- Dredging history: dredge vs. undredged, distance from dredged areas along transects perpendicular to dredge transect, and time since dredging
- Core depth and macroinvertebrate size classes
- Interactive effects among the above factors
- Random effects: core location within transect, transect location within marina

Statistical analyses will be carried out using two methods. In the first, relationships between biomass and measured environmental variables will be examined for each taxa separately using generalized linear mixed models (GLMMs) to help identify physical drivers. In the second step, will compare variation in prey communities (i.e., broad macroinvertebrate taxa) between dredged and undredged reference areas, and test for macroinvertebrate-environment relationships using macroinvertebrate data (MBRAT taxa group abundance or biomass) as dependent variables and measured environmental factors as independent, explanatory variables. The analysis will be conducted using ordination (redundancy or canonical correspondence analysis), which will allow us to identify the environmental drivers that have the greatest influence on macroinvertebrate prey community composition. Datasets from dredged and undredged areas will be analyzed separately and differences in the macroinvertebrate-environment relationships between the two compared.

For both types of analyses we will use an information-theoretic (Akaike's Information Criterion, AIC) framework to evaluate candidate sets of multiple models (Burnham & Anderson 2002). We will model-average parameter estimates across all models and assess variable importance (the sum of the weights of all models containing that variable; Burnham & Anderson 2002) to determine the impact of each parameter on macroinvertebrate abundance and biomass.

PHASE III: PILOT STUDY

To evaluate and finalize the study design developed in Phase II, we conducted a pilot study during November 2015. The goal of the pilot study was to identify potential sites for a full study, understand variability in benthic community composition among the study sites, and determine if the study sample size identified using data from a South Bay site (Dumbarton) would provide adequate power for a Central Bay study. We present the methods and preliminary results of the pilot study below and discuss how they were used to guide refinements to our final study design.

Methods

Sample Collection

We used the results of the Dumbarton dataset power analysis to inform the total number of sites (5), transects (2 per dredged and undredged area), and cores (5 locations per transect, 2 replicate cores) needed to determine a 50% difference in benthic infauna abundance between dredged and paired undredged sites. We identified five shallow-water (<13 ft. [3.7 m] MLLW) marinas (Table 2, Figure 5, Figures 6-10) that fit the site selection criteria outlined in the study design. Three of these marinas were dredged in 2013 (Pier 32, Mooring Road, and Richardson

Bay Marina) and two were dredged in 2014 (Paradise Cay HOA, Strawberry Channel; Figure 5, Table 2). The number of transects and associated coring locations varied with respect to the size of the dredged and undredged reference areas within each marina (Figures 6-10); however, it always met or exceeded the number identified in the power analysis. When possible, additional reference transects were placed perpendicular to transects running through dredged areas to evaluate the effects of distance from dredging on macroinvertebrate density and community composition as well as to estimate the total area impacted by dredging (Figures 6, 7, 9). In one marina (Richardson Bay Marina, Figure 8), we were able to sample an area that had been dredged in 1994, in addition to an area dredged in 2013. This site was the only site meeting our selection criteria that had been dredged across multiple time scales. Comparison of benthic communities between the two sites will provide additional insight into benthic macroinvertebrate recolonization post-dredging.

At each site there was a minimum of 6 core locations per transect and 3-7 transects per marina. Two replicate core samples were collected at core locations set 20 m apart along each transect. Each core was 10 cm in diameter and 10 cm deep. At two of the five marinas (Pier 32 and Mooring Road), cores were systematically separated into 2 cm increments from top to bottom to measure prey distribution at different depths in the sediment and evaluate how to divide cores to facilitate use of the MBRAT method in the full study. Water quality (temperature, salinity, dissolved oxygen, and pH) was recorded within each marina dredged and undredged area upon arrival and departure during a sampling session using a multi-parameter sonde (YSI Professional Plus, YSI, Inc. Yellow Springs, OH) at the water surface and just above the benthic surface. The water depth at each individual core location along each transect was recorded using a ReefNet© Sensus Ultra Depth Recorder (ReefNet, Inc., Niagra Falls, NY) attached to the coring device and corrected for MLLW tide height at the time of recording. Sediment cores were collected at each transect to determine sediment grain size and chemical composition (e.g., organic matter, soil texture, soil pH).

Cores were immediately transported to SFBE on ice and refrigerated until processed. Within 1-2 days cores were rinsed through a 0.5 mm mesh sieve, and fauna retained by the sieve were preserved in a 70% ethanol with 1% rose bengal dye. Identification of benthic macroinvertebrates was completed at the SFBE Invertebrate Ecology Laboratory. All taxa within cores were sorted, identified and enumerated. Taxa from all samples were identified to a broad taxonomic level (class, order, Table 5), with a subset identified to the lowest taxonomic level possible (family, genus, species, Table 5). For two cores from each marina, sorted taxa were identified to the lowest taxonomic level possible by an external laboratory (EcoAnalysts, Inc., Moscow, ID). This was done both as a quality assurance measure to verify our in-house identification, as well as to build a reference collection for more rapid and precise identification of future samples. For our preliminary evaluation of the pilot data, we computed summary statistics and qualitatively examined differences between macroinvertebrate taxa in dredeged and undredged areas. We used t-tests to compare total macroinvertebrate densities between dredged and undredged areas. Once the full study is complete, data from sites that are sampled in both the pilot and full study will be used in multivariate and generalized linear mixed modeling described above to evaluate the influence of dredging over time on macroinvertebrate abundance and biomass.

Power Analysis to Inform Full Study Design

Using the data collected in our pilot study, we conducted a second power analysis to determine if the number of samples originally identified based on South Bay macroinvertebrate data were appropriate for a Central Bay study given the potential differences in taxa between the two areas. We used the methods described for the power analysis in Phase II above. Briefly, for each broad taxa category, we separately modeled abundances using mixed linear models (PROC Mixed, SAS, SAS Institute, Cary, NC) in an information-theoretic (AIC) framework. For each taxa, we used the parameter estimates from the top ranked AIC model as input parameters for simulation models. We used the same simulation scenarios representing eight different sample sizes (Table 1), each with different combinations of sites, transects, core locations and core replicates. For each taxa group we ran 1000 simulations per sample size and calculated power as the proportion of simulations in which a significant effect (α=0.05) was detected (Figure 13).

Preliminary Results

Macroinvertebrate Community Composition in Dredged and Undredged Areas

We collected a total of 288 benthic cores during the pilot sampling effort. Overall, mean macroinvertebrate density was greater in undredged reference areas than in dredged areas at four of our five study sites (Figure 16; Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel), but only significantly so at the Richardson Bay site (Table 4). Macroinvertebrate community structure appeared to vary across study locations (Table 3); however, polychaetes were consistently among the most dominant taxa overall. Within sites, community structure varied between dredged and undredged reference areas (Tables 3 and 4, Figure 17). In addition, macroinvertebrate density consistently decreased with increasing sediment depth (as determined by 2-cm core sections) at Mooring Road and Pier 32 dredged and undredged reference areas (Figure 15).

Across all sites, macroinvertebrate density was lowest at Mooring Road for both dredged and undredged reference areas (Table 4). Density was 14% higher in reference areas than dredged areas at this site. Dominant taxa in dredged areas included bivalves (52% of the total density), polychaetes (24%), and oligochaetes (17%). At reference areas, the community was predominantly bivalves (52%), and had a larger number polychaetes (39%) and a lower number of oligochaetes (6%) relative to dredged areas.

Pier 32 was the only site where macroinvertebrate density was lower (by 17%) in the reference than in dredged area, although this difference was not significant (Table 4). Dredged and reference areas at Pier 32 were numerically dominated by polychaetes, and contained more polychaetes than any other site. Polychaetes comprised 96% of the community in dredged areas and 86% in reference areas, which also contained 10% bivalves.

The difference in total macroinvertebrate density between undredged reference and dredged areas at Richardson Bay far exceeded that of any other site. Density was 167% higher in reference areas (7,521 individuals m^{-2}) than in dredged areas (2,819 individuals m^{-2}). Dredged areas were dominated by polychaetes (58%) followed by oligochaetes (26%). Macroinvertebrate communities in reference areas were also dominated by polychaetes (54%), but contained larger numbers of oligochaetes (19%), nematodes (13%), and amphipods (10%).

At Paradise Cay, macroinvertebrate density was 58% higher in undredged reference areas (8,135 individuals m^{-2}) than in dredged areas (5,146 individuals m^{-2}). Polychaetes were dominant in dredged areas (88%), which also contained amphipods (9%). This is in contrast to the reference area at this site, which was dominated by amphipods (83%) and had notably fewer polychaetes (13%). Macroinvertebrate communities at Paradise Cay had the highest density and percentage of amphipods relative to other sites.

Strawberry Channel macroinvertebrate densities for dredged (1,502 individuals m^{-2}) and undredged reference areas (1,757 individuals m^{-2}) were similar to those observed at Mooring Road, which had the lowest densities of all study sites. Overall, density was 17% higher in reference areas than in dredged areas at Strawberry Channel. Communities within the dredged and reference areas at this site primarily consisted of oligochaetes (42% dredged; 33% reference), polychaetes (37% dredged; 30% reference), and amphipods (6% dredged; 25% reference). Strawberry Channel macroinvertebrate communities had the highest percentage of oligochaetes at dredged and reference areas relative to other sites.

Macroinvertebrate Accessibility

At pilot study sites where 10 cm core samples were sectioned into 2 cm depth increments (Mooring Road and Pier 32), macroinvertebrate density decreased with increasing core depth in both dredged and undredged reference areas (Figure 15). The top 0-2 cm depth increment contained the majority of macroinvertebrates in both dredged and undredged reference areas, ranging from 51% of total core macroinvertebrates at Mooring Road dredged areas to 75% of total core macroinvertebrates at Pier 32 dredged areas. The next lowest depth increment (2-4 cm) contained substantially fewer invertebrates, ranging from 11 to 18% of the total number of macroinvertebrates counted in the cores.   Macroinvertebrate density was consistently lowest, at 5 to 18% of the total core, in the bottom 3 depth increments combined representing the lower 4 to 10 cm of the core.

Power Analysis

We found that 80% power to detect a 50% difference between dredged and undredged areas was reached in simulations using the pilot dataset at scenarios as low as 100 samples (Figure 13, Table 1). This was true for all taxa except polychaetes and amphipods, which reached 80% power at a sample size of 200 cores. In fact, for bivalves, cumacea, and nematoda, we were able to detect a 25% difference in dredged and undredged areas at 80% power with just 100 samples. The results of this power analysis reinforced those of our initial analysis using the Dumbarton dataset and suggest that using a sample size of just over 200 full cores would be most conservative to capture differences between dredged and undredged areas for all broad taxa groups.

MODIFICATIONS TO FULL STUDY DESIGN

Based on our preliminary findings in the pilot study, we have made only one significant modification to our full study design. This change involves removing the Pier 32 site from the study and adding two more suitable sites. Pilot study samples from both the undredged reference and dredge areas at Pier 32 were dominated by polychaetes and thus the taxa from this site differed greatly from the other sampling sites. This site is the furthest south of the five pilot sites, and while still in the polyhaline region of the Bay may have environmental conditions that differ from sites to the north. During site selection for the 2015 pilot study only five locations, including Pier 32, fit our selection criteria (Table 2); however, since that time new sites in our study area have been dredged creating the opportunity to have a more balanced design. We again worked with the BCDC to select two additional sampling sites that were dredged in 2015 (Loch Lomond Marina, Figure 17 and Paradise Cay Yacht Harbor, Figure 18) using our selection criteria (Table 2). Both new sites are located within central SFB (Figure 16) with similar depth (< 13 ft. [3.7 m] MLLW), salinity (polyhaline), and sediment (i.e., soft-bottom) characteristics as the sites selected for the pilot study, and have an available nearby undredged reference site. Four (Mooring Road, Paradise Cay, Richardson Bay Marina, and Strawberry Channel) of the five pilot study sites were retained for the full study. Among all six marinas chosen for the full study, there are two marinas in each of three dredging time periods: 2013, 2014, and 2015. These sites are evenly divided among three embayments within the central SFB polyhaline region (Figure 16).

Results of our efforts to split benthic cores into 2 cm increments at two pilot study sites further validated our planned modification to the BRAT in which we split cores into 2 sections (0 - 4 cm and 4 - 10 cm) to be implement in the full study. We found that the majority of invertebrates in cores from both of these sites were located in the upper 4 cm of the core (Figure 15), corresponding to the prey available to shallow foragers, while lower densities of prey were found in the 4 - 10 cm section available to deep benthic foragers. Thus, it appears we will not lose resolution on prey distribution across depth by selecting this simplified method. Furthermore, in studies of fish prey, the best sample unit depth should approximately match the predator's foraging depth (Ferraro and Cole 2004). While skate, sturgeon, leopard sharks, and crabs can forage relatively deep within the sediment, many invertebrate prey studies have found that most fish are primarily near surface feeders (e.g., Gotshall 1977, Holland et al. 1980, Bottom and Jones 1990; Table 5). Thus, it has been suggested that shallow benthic samples (≤ 5 cm deep) should be sufficient for fish prey studies (Ferraro and Cole 2004), which corresponds to the 0 - 4 cm foraging depth category defined in our simplified scheme for evaluating prey accessibility (Tables 5 and 6, Figure 12).

Based on the pilot power analysis results, we kept the same locations and number of transects for the four marinas we sampled during for the pilot study, and followed the same protocol in designing transects for the two additional marinas. This scheme will result in the collection of 452 whole cores during each sampling period. Each core will be divided into two sections (shallow 0 - 4 cm and deep 4 – 10 cm), yielding 904 samples per collection (Table 6). This represents more samples than the power analysis indicated were required to determine a 50% change in abundance between dredged and undredged areas; however, these additional cores will be collected as a conservative measure and to allow for a balanced design as indicated above.

Results from the full study design detailed in this plan are expected to provide insight into the amount of time after dredging that it takes for macroinvertebrate communities to recover to a state that is functionally equivalent (in terms of prey availability for fish) to macroinvertebrate communities in undredged areas. Potential new insights about species-specific prey accessibility for certain fish species and life stages will help enhance subsequent efforts to understand dredging impacts on macroinvertebrates and corresponding effects on benthic fishes.

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TABLES

Table 1. Sampling scenarios used in simulation power analysis to determine project sample size. Scenarios have a variable number of sites (marinas) and each marina has one dredged and one undredged area. Within each of these areas we have varied the number of transects, cores, and core replicates.

Site (marina)	Areas (dredged and non-dredged)	Transects (per area)	Cores (per transect)	Replicates (per core)	Total number of core samples
2	2	2	2	2	32
3	2	1	5	3	90
5	2	2	5	1	100
5	2	1	5	3	150
5	2	2	5	2	200
5	2	1	8	3	240
5	2	2	5	3	300
5	2	2	8	2	320
10	2	2	5	2	400
5	2	2	10	2	400

Table 2. Central Bay site selection table indicating all sites considered for the pilot and full study.

Study Area	Location	Embayment	Salinity Regime†	Habitat Type	Sediment Texture	Dredge Depth MLLW (ft/m)	Last Dredged	Est. Dredging Frequency (years)
Selected sites								
Pier 32*	San Francisco	Central SFB	Polyhaline	Shallow Subtidal	Sand/silt/clay	12/3.7	2013	2-3
Mooring Road**	San Rafael	San Rafael Bay	Poly/Mesohaline	Marina	Silt/clay	6/1.8	2013	infrequent
Richardson Bay Marina**	Sausalito	Richardson Bay	Polyhaline	Marina	Silt/clay	10.5/3.2	2013	3
Paradise Cay HOA**	Paradise Cay	Corte Madera Bay	Polyhaline	Channel	Silt	8/2.4	2014	4
Strawberry Channel**	Strawberry	Richardson Bay	Polyhaline	Channel	Silt/clay	7/2.1	2014	7
Loch Lomond Marina***	San Rafael	San Rafael Bay	Poly/Mesohaline	Marina	Silt/clay	9/2.7	2015	12
Paradise Cay Yacht Harbor***	Paradise Cay	Corte Madera Bay	Polyhaline	Marina	Silt	10/3.0	2015	4
Sites considered, not selected								
Aeolian Yacht Club	Alameda	San Leandro Bay	Polyhaline	Marina	Clay	10/3.0	2010, 2014	4
Larkspur Marina	Larkspur	Corte Madera Bay	Polyhaline	Marina	Silt/clay	6/1.8	2010, 2015	4-5
Marina Vista HOA	San Rafael	San Rafael Bay	Poly/Mesohaline	Channel	Silt/clay	7/2.1	2011, 2015	4
Marin Yacht Club	San Rafael	San Rafael Bay	Poly/Mesohaline	Marina	Silt/clay	9/2.7	2011, 2016	5
SF Marina West Basin	San Francisco	Central SFB	Polyhaline	Shallow Subtidal	Sand/silt/clay	13/4	2014	2-3
Clipper Yacht Harbor	Sausalito	Richardson Bay	Polyhaline	Marina	Silt/clay	9/2.7	2015	3-4
Corinthian Yacht Club	Tiburon	Belvedere Cove	Polyhaline	Marina	Silt/clay	13/4.0	2015	4
Larkspur Ferry Terminal	Larkspur	Corte Madera Bay	Polyhaline	Channel	Silt/clay	17/5.2	2015	4

†Thompson et al. 2012

*Sites sampled for Pilot Study only

**Sites sampled for Pilot Study and Full Study

***Sites sampled for Full Study only

Table 3. List of invertebrates identified to lowest taxonomic ID level within broad taxonomic groups at each site. The number of samples identified to lowest taxonomic level compared to the total number collected is indicated under each site name. Presence of each taxa within dredged, undredged reference areas, or at both is also shown.

Site	Broad Taxonomic Group	Lowest Taxonomic ID	Taxonomic Rank	Present in		
				Only Dredge	Only Reference	Dredge and Reference
Mooring Road Dredge n=7 (7 dredge samples total) Reference n=12 (12 reference samples total)	Oligochaeta	Oligochaeta	Subclass			x
		Tubificoides	Genus			x
	Polychaeta	Unidentified species A	Class	x		
	Polychaeta (Errant)	Exogone lourei	Species			x
	Polychaeta (Sedentary)	Capitellidae	Family	x		
		Barantolla	Genus			x
		Capitella capitata	Species		x	
		Decamastus	Genus		x	
		Heteromastus filiformis	Species			x
		Mediomastus	Genus		x	
		Cossura	Genus		x	
		Sabaco elongatus	Species			x
		Euchone limnicola	Species		x	
		Spionidae	Family			x
		Streblospio benedicti	Species			x
		Cirratulidae	Family			x
	Amphipoda	Grandidierella japonica	Species	x		
	Cumacea	Nippoleucon hinumensis	Species	x		
	Isopoda	Paranthura japonica	Species	x		
	Ostracoda	Myodocopida	Order			x
	Bryozoa	Bryozoa	Phylum	x		
	Bivalvia	Gemma gemma	Genus			x
		Arcuatula senhousia	Species			x
	Gastropoda	Volvulella	Genus		x	
Mooring Road Total				6	6	12
Paradise Cay Dredge n=7 (24 dredge samples total) Reference n=4 (21 reference samples total)	Oligochaeta	Oligochaeta	Subclass			x
	Polychaeta	Unidentified species B	Class			x
		Unidentified species C	Class		x	
		Unidentified species D	Class		x	
	Polychaeta (Errant)	Dorvillea	Genus	x		
	Polychaeta (Sedentary)	Platynereis bicanaliculata	Species		x	
		Exogone lourei	Species			x
		Capitellidae	Family	x		
		Heteromastus filiformis	Species		x	
		Cossuridae	Family		x	
		Cossura	Genus			x

		Sabaco elongatus	Species			x
		Armandia brevis	Species		x	
		Sabellidae	Family		x	
		Euchone limnicola	Species			x
		Cirratulidae	Family	x		
	Arthropoda	Arthropoda	Phylum		x	
	Hemiptera	Corixidae	Family	x		
	Amphipoda	Caprella	Genus			x
		Caprella drepanochir	Species		x	
		Caprella natalensis	Species	x		
		Metacaprella anomala	Species		x	
		Ampelisca abdita	Species			x
		Grandidierella japonica	Species		x	
		Monocorophium	Genus			x
		Monocorophium acherusicum	Species		x	
		Monocorophium insidiosum	Species		x	
		Paradexamine	Genus		x	
	Cumacea	Nippoleucon hinumensis	Species	x		
		Cumella vulgaris	Species		x	
	Isopoda	Isopoda	Order			x
		Paranthura japonica	Species		x	
	Copepoda	Copepoda	Subclass		x	
	Ostracoda	Ostracoda	Class	x		
	Bryozoa	Bryozoa	Phylum	x		
	Ascidiacea	Ascidiidae	Family	x		
	Bivalvia	Bivalvia	Class			x
		Theora lubrica	Species		x	
		Arcuatula senhousia	Species		x	
	Gastropoda	Gastropoda	Class			x
		Philine	Genus		x	
	Nematoda	Nematoda	Phylum			x
	Porifera	Porifera	Phylum	x		
Paradise Cay Total				10	20	13
Pier 32 Dredge n=11 (12 dredge samples total) Reference n=13 (18 reference samples total)	Oligochaeta	Oligochaeta	Subclass			x
	Polychaeta	Unidentified species E	Class	x		
		Unidentified species F	Class	x		
		Unidentified species G	Class			x
	Polychaeta (Errant)	Dorvillea	Genus	x		
		Glycera sp.	Genus	x		
		Glycera americana	Species		x	
		Glycera nana	Species		x	
		Lepidasthenia	Genus	x		
	Polychaeta (Sedentary)	Capitellidae	Family			x
		Heteromastus filiformis	Species			x
		Mediomastus	Genus			x
		Cossura	Genus			x
		Maldanidae	Subfamily	x		
		Sabaco elongatus	Species		x	

		Armandia brevis	Species			x
		Sabellidae	Family	x		
		Euchone limnicola	Species			x
		Leitoscoloplos pugettensis	Species	x		
		Spionidae	Family	x		
		Ampharetidae	Family	x		
		Cirratulidae	Family	x		
	Brachyura	Brachyura	Infraorder		x	
	Amphipoda	Ampeliscidae	Family		x	
		Ampelisca abdita	Species	x		
		Grandidierella japonica	Species	x		
	Cumacea	Cumacea	Order		x	
		Lampros sp.	Genus	x		
	Copepoda	Copepoda	Subclass		x	
	Bryozoa	Walkeriidae	Superfamily		x	
	Ascidiacea	Ascidiacea	Class			x
	Tunicata	Tunicata	Subphylum		x	
	Anthozoa	Anthozoa	Class		x	
	Bivalvia	Macoma	Genus			x
		Mya arenaria	Species		x	
	Gastropoda	Gastropoda	Class		x	
	Nematoda	Nematoda	Phylum			x
	Nemertea	Nemertea	Phylum		x	
	Sipuncula	Sipuncula	Phylum			x
Pier 32 Total				14	13	12
Richardson Bay Dredge n=5 (20 dredge samples total) Reference n=5 (13 reference samples total)	Oligochaeta	Oligochaeta	Subclass			x
		Tubificoides	Genus			x
	Polychaeta	Unidentified species H	Class		x	
		Unidentified species I	Class		x	
		Unidentified species J	Class	x		
		Unidentified species K	Class	x		
	Polychaeta (Errant)	Dorvilleidae	Family		x	
		Pettiboneia pugettensis	Species		x	
	Polychaeta (Sedentary)	Capitellidae	Family			x
		Capitella capitata	Species		x	
		Heteromastus filiformis	Species		x	
		Mediomastus	Genus	x		
		Cossura	Genus			x
		Ophellidae	Family	x		
		Orbiniidae	Family		x	
		Sabellidae	Family		x	
		Chone gracilis	Species		x	
		Euchone limnicola	Species		x	
		Spionidae	Family			x
		Cirratulidae	Family			x
		Cirriformia moorei	Species			x
	Collembola	Collembola	Subclass	x		
	Crustacea	Crustacea	Subphylum		x	
	Amphipoda	Caprellidae	Family		x	

		Caprella drepanochir	Species	x		
		Ampelisca abdita	Species	x		
		Monocorophium	Genus	x		
		Paradexamine	Genus		x	
	Cumacea	Cumacea	Order			x
	Isopoda	Isopoda	Order			x
		Paranthura japonica	Species		x	
	Tanaidacea	Tanaidacea	Order			x
		Leptochelia dubia	Species	x		
	Leptostraca	Leptostraca	Order			x
		Nebalia kensleyi	Species	x		
	Copepoda	Copepoda	Subclass		x	
		Harpacticoida	Order	x		
	Ostracoda	Ostracoda	Class	x		
	Bryozoa	Bryozoa	Phylum			x
		Bugulidae	Family	x		
	Tunicata	Styelidae	Family	x		
	Anthozoa	Anthozoa	Class			x
	Bivalvia	Bivalvia	Class			x
		Macoma	Genus		x	
		Theora lubrica	Species		x	
	Gastropoda	Gastropoda	Class			x
	Nematoda	Nematoda	Phylum			x
Richardson Bay Total				14	17	16
Strawberry Channel Dredge n=8 (17 dredge samples total) Reference n=6 (22 reference samples total)	Oligochaeta	Oligochaeta	Subclass			x
		Tectidrilus	Genus		x	
		Tubificoides	Genus		x	
	Polychaeta (Errant)	Phyllodocidae	Family		x	
		Syllidae	Family		x	
		Exogone lourei	Species	x		
	Polychaeta (Sedentary)	Capitellidae	Family	x		
		Capitella capitata	Species		x	
		Sabaco elongatus	Species			x
		Owenia collaris	Species		x	
		Sabellidae	Family	x		
		Euchone limnicola	Species		x	
		Leitoscoloplos pugettensis	Species		x	
		Ampharetidae	Family		x	
		Cirriformia moorei	Species	x		
	Coleoptera	Coleoptera	Order		x	
	Neoptera	Lepidoptera	Order		x	
	Amphipoda	Caprellidae	Family		x	
		Caprella	Genus		x	
		Grandidierella japonica	Species			x
		Paradexamine	Genus		x	
		Gammaroidae	Superfamily		x	
		Ampithoe	Genus		x	
	Cumacea	Nippoleucon hinumensis	Species	x		

	Isopoda	Isopoda	Order			x
		Paranthura japonica	Species		x	
		Gnorimosphaeroma oregonensis	Species		x	
	Leptostraca	Leptostraca	Order			x
		Nebalia gerkenae	Species	x		
		Nebalia kensleyi	Species		x	
	Copepoda	Copepoda	Subclass		x	
	Ostracoda	Ostracoda	Class			x
		Myodocopida	Order	x		
	Bryozoa	Bryozoa	Phylum			x
	Ascidiacea	Ascidiidae	Family		x	
	Osteichthyes	Osteichthyes	Superclass		x	
	Anthozoa	Anthozoa	Class			x
	Bivalvia	Venerupis philippinarum	Species		x	
		Arcuatula senhousia	Species			x
	Nematoda	Nematoda	Phylum			x
	Sipuncula	Sipuncula	Phylum			x
Strawberry Channel Total				7	23	11

Table 4. Comparison of macroinvertebrate density in dredged and undredged reference areas during the pilot study in each site and overall. Significant differences between dredged and reference areas are indicated in bold font. P value indicates result of t-test.

	Dredge		**Undredged Reference**			
Site	**Mean individuals/m^2**	**SE**	**Mean individuals/m^2**	**SE**	***t*-test**	**P value**
Mooring Road	1164.7	389.6	1321.7	451.6	2.11	0.80
Paradise Cay	5146.0	1235.7	8135.3	901.9	2.02	0.06
Pier 32	6247.4	1331.4	5208.8	881.6	2.09	0.52
Richardson Bay	2818.5	559.6	7520.9	1903.7	2.14	**0.03**
Strawberry Channel	1502.5	497.7	1757.4	356.2	2.04	0.68
All sites	3606.7	493.6	4728.8	512.2	1.97	0.12

Table 5. Foraging depth, common macroinvertebrate prey, foraging mode, and prey size class for focal fish species juveniles and adults. Information was obtained during the Phase I Literature Review and from local expert opinion (J. Hobbs, UC Davis).

Foraging Depth	Fish Species	Life Stage	Common Prey Taxa	Foraging Mode	Max. Prey Size Class	Reference
Shallow (0-4 cm)	Pacific Sardine	Juvenile	Euphausids, copepods, diatoms, Oikopluera, fish eggs	picker, filter*	4 mm	Emmett et al. 2005 MacFarlane et al. 2010
		Adult	phytoplankton, copepods, euphasids, diatoms, pelagic fish eggs	particle, filter*	24 mm	Espinoza et al. 2009 Fernandez and Gonzalez-Quiros 2006
	Longfin Smelt	Juvenile	copepods (*Eurytemora affinis*), crustaceans,	picker*	4 mm	Baxter 2009 Hobbs et al. 2006 Moyle and Davis 2000
		Adult	mysid shrimp, copepods, zooplankton, and crustaceans	picker*	24 mm	Boubee and Ward 1997 Chigbu et al. 1998 Feyer et al. 2003 Hobbs et al. 2006
	Northern Anchovy	Juvenile	copepod nauplii, phytoplankton	filter (particulates)*	4 mm	Hunter 1977 Miller and Brodeur 2007 Parish 1985
		Adult	small crustaceans, copepods, phytoplankton	filter (particulates)	100 mm	Blaxter and Hunter 1982 Longhurst 1971 Leong and O'Connell 1969 Miller and Brodeur 2007
	English Sole	Juvenile	polychaetes, bivalves, amphipods, cumaceans, copepods	picker*	12 mm	Ambrose 1976 Gadomski and Boehlert 1984 Hogue and Carey 1982 Lassuy 1989 Toole 1980
		Adult	gammarid amphipods (summer), polychaetes (fall)	picker*	50 mm	Ambrose 1976 Buechner et al. 1981 Clark 1986
	Starry Flounder	Juvenile	mysid shrimp, copepods, amphipods, insect larvae (in freshwater)	picker*	12 mm	Ambrose 1976 McCall 1992 Moore and Moore 1976 Moyle 2000
		Adult	Crabs, polychaetes, molluscs, amphipods, isopods, copepods, mysid shrimp	picker*	100 mm	Ambrose 1976 Herbold 1987 Miller 1967 Moore and Moore 1976 Orcutt 1950
	Brown Rockfish	Juvenile	crustaceans, amphipods, isopods, eelgrass epifauna	picker*	Unknown	Bizzarro et al. 2016 Love et al. 2002
		Adult	fish	picker*	100 mm	Washington 1978
	California Halibut	Juvenile	caridean shrimp, crabs, small fishes	ambush*	50 mm	Allen 1988 Madon 2002
		Adult	fish	visual, ambush*	100 mm	Allen 1988 Haugen 1990

Deep (0-10 cm)	Dungeness Crab	Juvenile	clams, crustaceans, fish	opportunistic, scavenger, grazer*	100 mm	Jensen 1998 Stevens et al. 1982
		Adult	clams, crustaceans, fish	omnivore, opportunistic, scavengers grazer*	100 mm	Jensen 1998 Stevens et al. 1982
	Big Skate	Juvenile	fish, shrimp, euphausiids	opportunistic generalist, inertial suction	100 mm	Bizzarro et al. 2007 Motta and Wilga 2001 Yang 2007
		Adult	crabs, cephalopods, demersal teleosts, shrimps, polychaetes, clams, sculpin, pelagic skate	opportunistic generalist	100 mm	Ackerman 1971 Bizzaro et al. 2007 Kao 2000 Reecht et al. 2013 Robinson et al. 2007 Russo 1975 Talent 1976 Yang 2007
	Green Sturgeon	Juvenile	drifting and benthic insects (seasonally), oligochaetes, amphipods, small fish, fish eggs , mysid shrimp	generalists, opportunist*	100 mm	Dumbauld et al. 2008 Gessner et al. 2007 Radtke 1966
		Adult	shrimp, molluscs, amphipods, small fish	opportunist, suction	100 mm	Adams et al. 2002 Dumbauld et al. 2008 Moyle 2002
	White Sturgeon	Juvenile	amphipods (Corophium), mysid shrimp	suction	100 mm	Bogacka-Kapusta et al. 2011 Dumbauld et al. 2008 McCabe et al. 1993 Moyle and Davis 2000 Muir et al. 1988 Radtke 1966
		Adult	shrimp, crabs, clams, herring, anchovy, striped bass, starry flounder, smelt; herring eggs	suction	100 mm	Dumbauld et al. 2008 McKechnie and Fenner 1971 Miller 2004
	Leopard Shark	Juvenile	crabs (*Hemigrapsus oregonensis*), fish <0cm TL 4	opportunistic generalists, disturb mud, inertial suction	100 mm	Barry 1983 Barry et al. 1996 Ferry-Graham 1998 Motta and Wilga 2001 Talent 1976
		Adult	fishes, crabs, clam siphons, innkeeper worms (*Urechis caupo*), fish eggs (*Atherinopsis californiensis*), isopods, amphipods, zooplankton, shrimp, teleosts, small elasmobranch	opportunistic generalists, disturb mud, inertial suction	100 mm	Barry 1983 Barry et al. 1996 Ebert and Ebert 2005 Motta and Wilga 2001 Stewart et al. 2004 Talent 1976

*Expert opinion, James Hobbs, University of California, Davis

Table 6. Simplified foraging table for focal fish species showing the depth increments and prey class sizes that will be used in the MBRAT assessment. Depth and size class categories were derived based on information discussed in the Phase I Literature Review and summarized in Table 3.

			Prey Size Class (mm)				
Foraging Depth in Sediment	Fish Species	Life Stage	0-4	4-12	12-24	24-50	50-100
Shallow 0-4 cm	Pacific Sardine	Juvenile	x				
		Adult	x	x	x		
	Longfin Smelt	Juvenile	x				
		Adult	x	x	x		
	Northern Anchovy	Juvenile	x				
		Adult	x	x	x	x	x
	English Sole	Juvenile	x	x			
		Adult	x	x	x	x	
	Starry Flounder	Juvenile	x	x			
		Adult	x	x	x	x	x
	Brown Rockfish	Juvenile*	x				
		Adult	x	x	x	x	x
	California Halibut	Juvenile	x	x	x	x	
		Adult	x	x	x	x	x
Deep 0-10 cm	Dungeness Crab	Juvenile	x	x	x	x	x
		Adult	x	x	x	x	x
	Big Skate	Juvenile	x	x	x	x	x
		Adult	x	x	x	x	x
	Green Sturgeon	Juvenile	x	x	x	x	x
		Adult	x	x	x	x	x
	White Sturgeon	Juvenile	x	x	x	x	x
		Adult	x	x	x	x	x
	Leopard Shark	Juvenile	x	x	x	x	x
		Adult	x	x	x	x	x

*Maximum prey size class available to juvenile Brown Rockfish unknown.

FIGURES

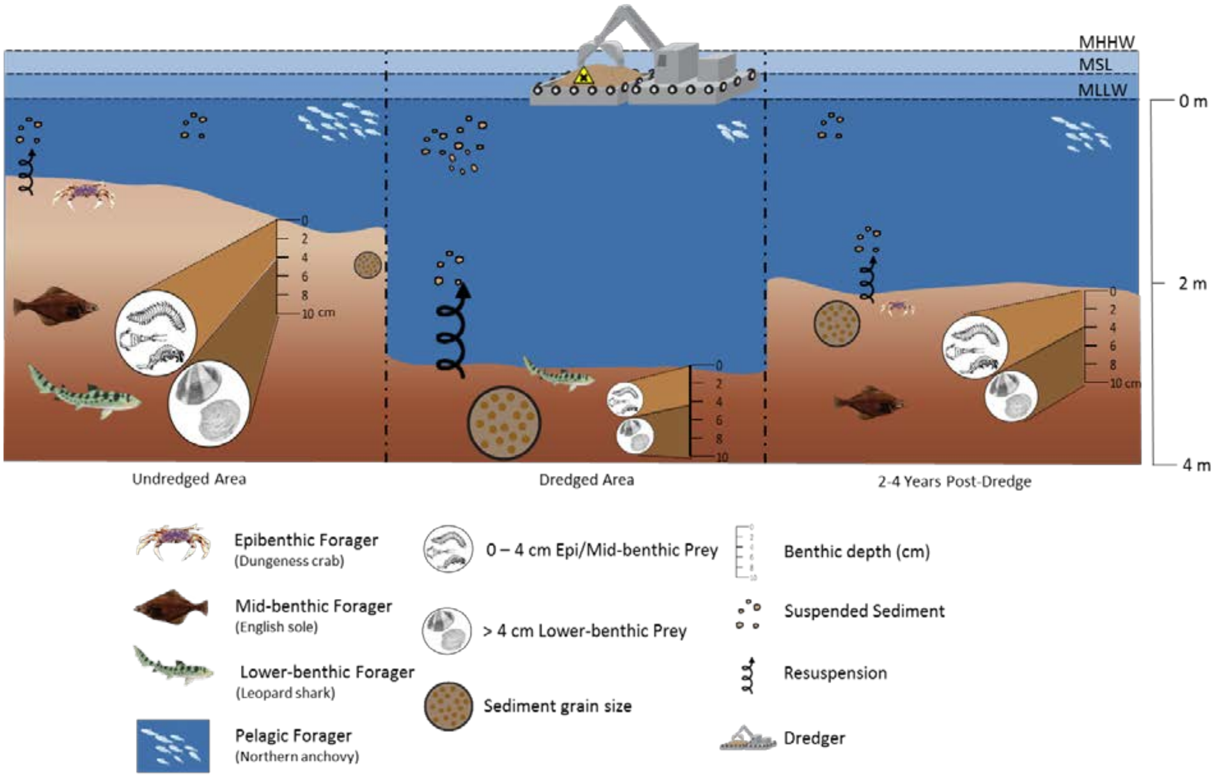

Figure 1. Conceptual diagram illustrating the comparison between an undredged benthic habitat (left), a recently a dredged area (center), and 2-4 years after dredging activity (right). Undredged areas are characterized by an abundant and diverse prey base of benthic infauna of varying size and depths. Turbidity is stable and sediment is stratified with smaller grains dominating the top 10-cm. Recently dredged areas result in the direct removal of shallow benthic habitat, resulting in increased suspended sediment. Post-dredging habitat is partially recovered, with medium sediment grain size providing habitat for smaller soft-bodied prey items. (Change in size of an object among panes indicates a conceptual shift in abundance, size, or magnitude. MHHW = Mean Higher High Water; MSL = Mean Sea Level; MLLW = Mean Lower Low Water. Not to scale.)

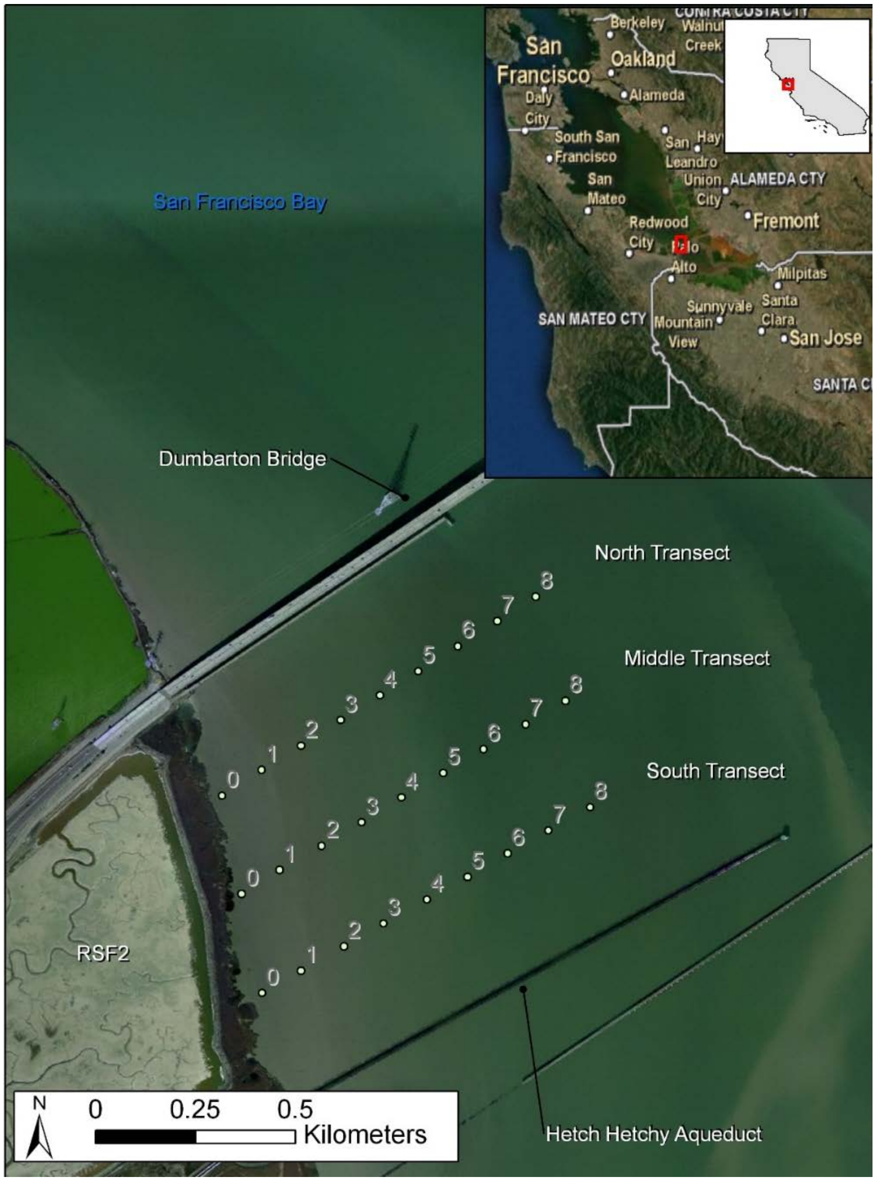

Figure 2. Map of sampling locations in the Dumbarton Shoals mudflat adjacent to pond RSF2 in the Ravenswood complex of the South Bay Salt Pond Restoration Project. Benthic macroinvertebrates were sampled monthly from 2008—2010 by taking cores along three transects. Nine stations were spaced at 100 m intervals along each transect. The site has a surface area of about 8.48 ha and is bounded by the Dumbarton Bridge to the north and the Southern Pacific Railroad Bridge to the south

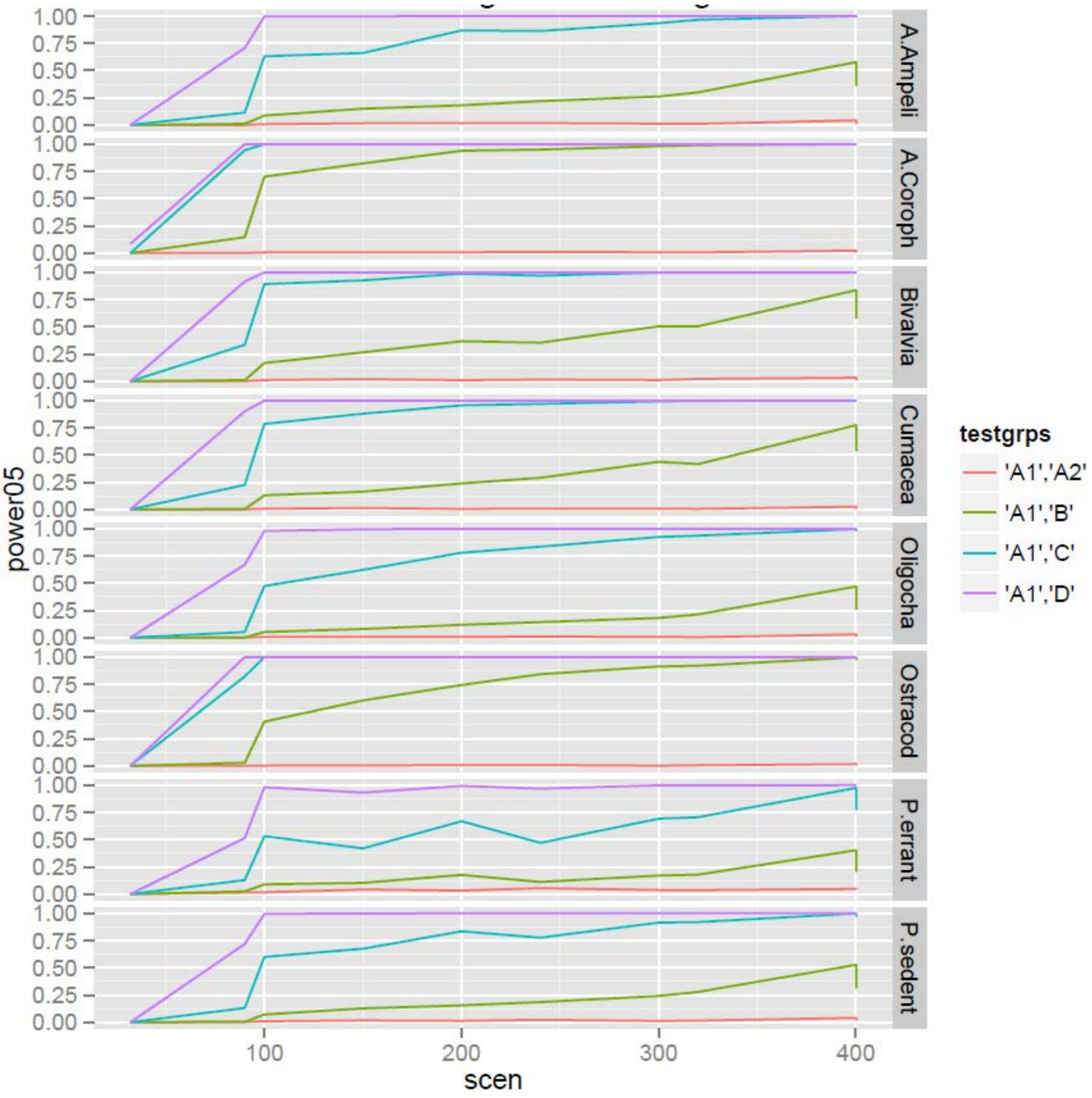

Figure 3. Power analysis curves for individual taxa groups based on the comprehensive USGS Dumbarton macroinvertebrate dataset. Scenarios depicted on the x-axis are for eight simulated datasets (listed in Table 1) representing different combinations of sites, transects and replicate cores. The y-axis indicates the percent power to determine the difference between dredged and undredged areas. Colored lines represent macroinvertebrate reductions of 0 (red), 25 (green), 50 (blue), and 75% (purple) due to dredging.

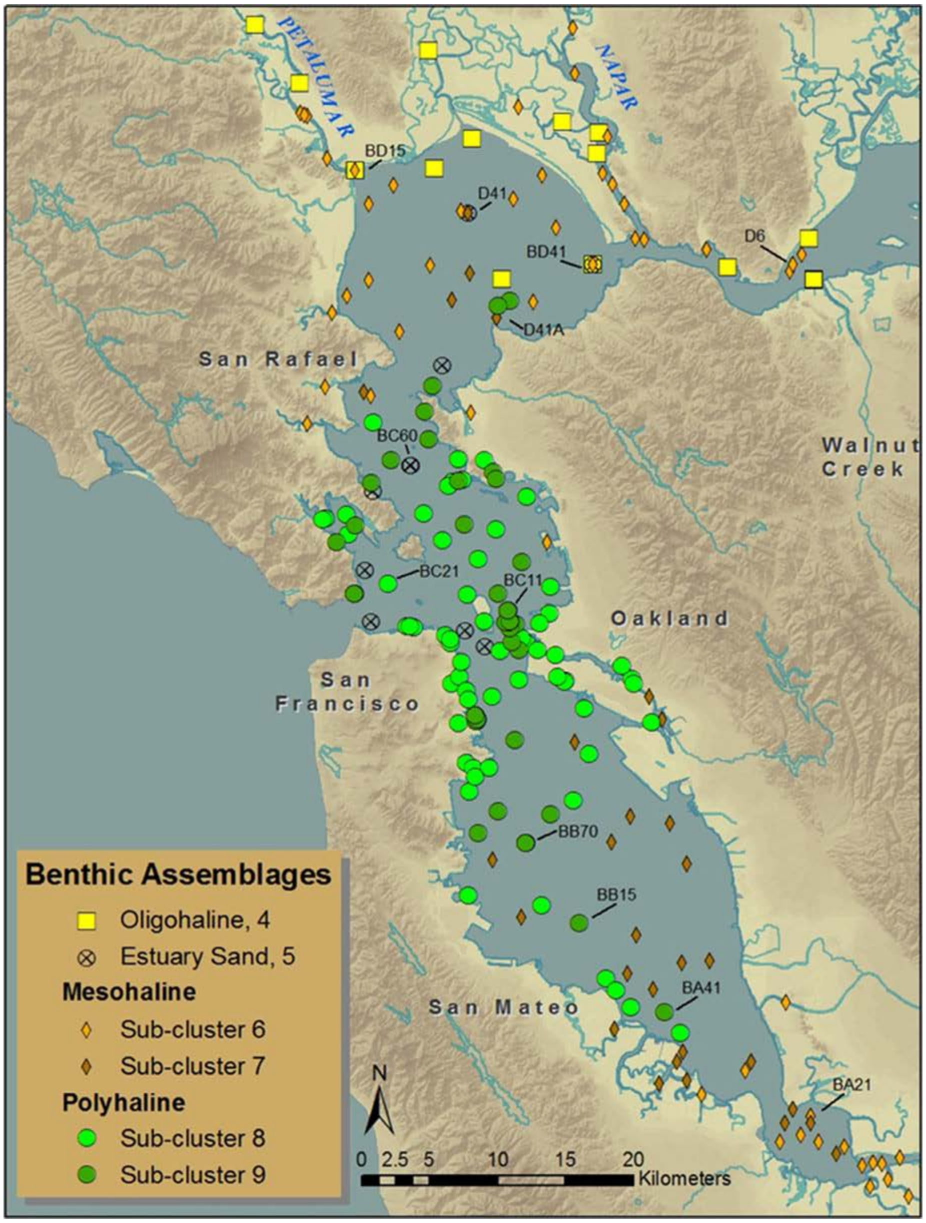

Figure 4. Map from SFB benthic assemblages (Thompson et al. 2013). We focused on the polyhaline benthic assemblage in Central Bay. The average salinity in this assemblage is 30.4 ppt. Subcluster 8 and 9 are dominated by the amphipods*, Ampelisca abdita* and *Monocorophium acheruscium*, while sub-cluster 8 has high abundances of polychaetes, *Mediomastus* spp. and *Dorvillea (Schistomeringos) annulata*.

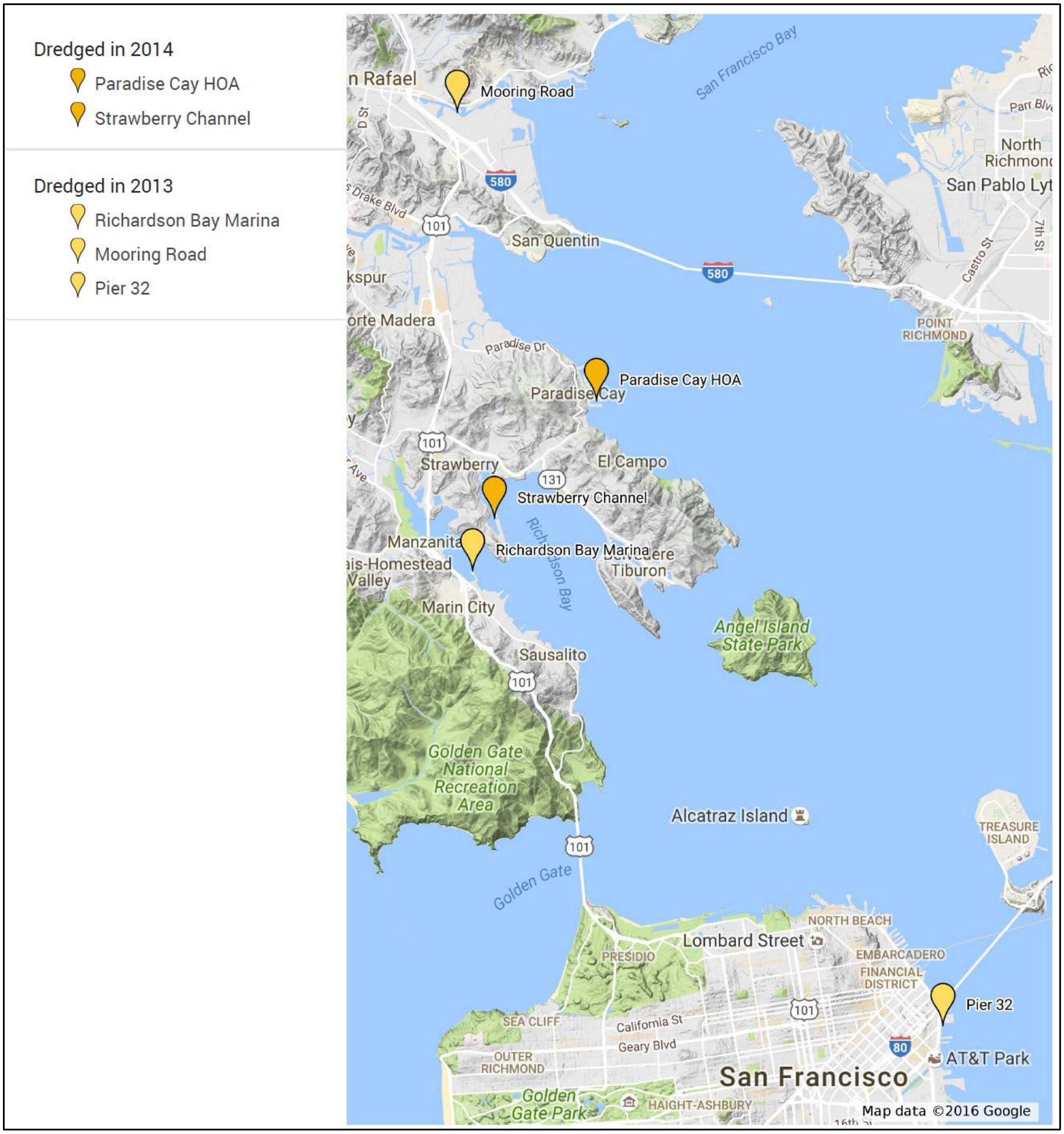

Figure 5. Pilot study sampling locations. Sites sampled in November 2015.

Figure 6. Paradise Cay HOA study site composed of residential docks and berths in western SFB. Sampled as part of pilot and full study. White outlined area dredged to 8 ft MLLW in 2014. Site contains 24 core locations in dredged area, 21 undredged reference core locations; three transects of six core locations in dredged marina, one transect of six core locations in dredged entrance channel, one reference transect of six core locations with three transects of five core locations extending from reference transect to dredged entrance channel transect.

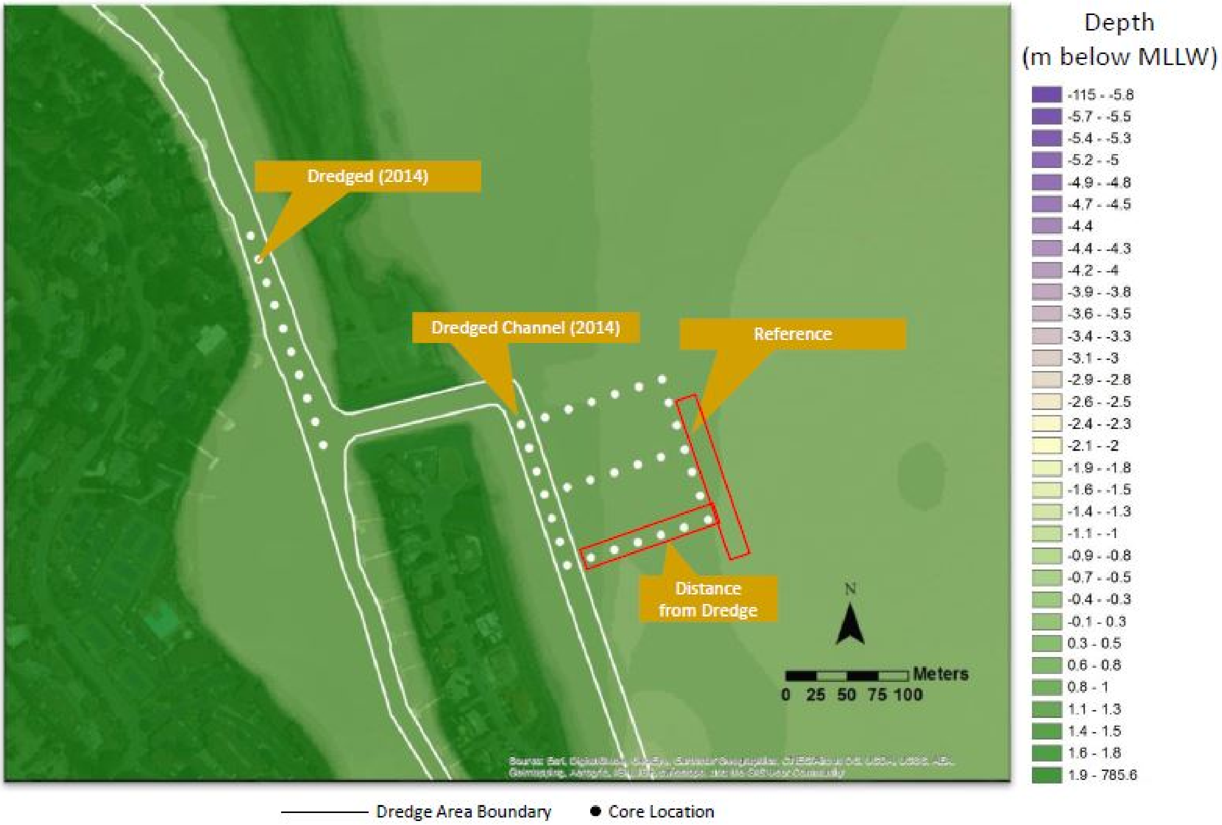

Figure 7. Strawberry Channel study site composed of residential docks and berths in dredged channel through residential area and Aramburu Island in Richardson Bay. Sampled as part of pilot and full study. White outlined area dredged to 7 ft MLLW in 2014. Site contains 10 core locations in dredged area, 12 undredged reference core locations; one transect of ten core locations and one transect of seven core locations in dredged marina/channel, one reference transect of seven core locations with three transects of five core locations extending from reference transect to dredged entrance channel transect.

Figure 8. Richardson Bay Marina study site composed of marina docks and undredged reference area northeast of marina. Sampled as part of pilot and full study. White outlined area dredged to 10.5 ft MLLW in 2013. Site contains one transect of 10 core locations taken in area between docks that was dredged to 10.5 ft MLLW in 2013, another transect of 10 core locations in area between docks that was dredged in 1994. Two reference transects of six core locations each extend from the marina.

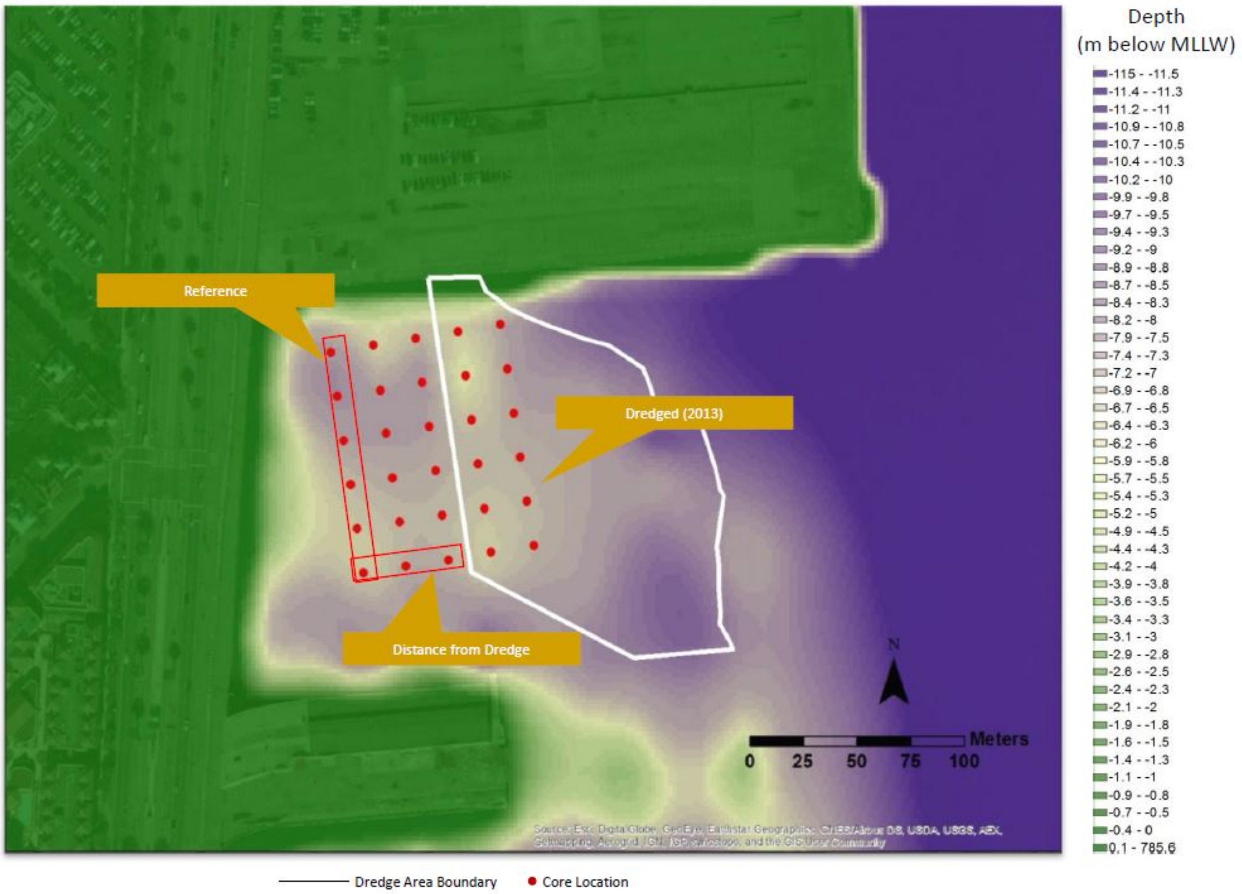

Figure 9. Port of San Francisco Piers 32-36 study site composed of area between piers in San Francisco. Sampled only as part of pilot study. White outlined area dredged to 12 ft MLLW in 2013. Site contains 12 core locations in dredged area, 18 undredged reference core locations; two transect of six core locations in dredged marina/channel, and three parallel transects of six core locations in reference area in between dredge and shore.

Figure 10. Mooring Road study site composed of dredged areas around residential docks in tidally influenced San Rafael Creek. Sampled as part of pilot and full study. White outlined area dredged to 6 ft MLLW in 2013. Site contains 7 core locations in dredged area, 12 undredged reference core locations; one transect of seven core locations in dredged areas, and one transect of twelve reference core locations that runs parallel to dredge transect for seven core locations, and continues downstream from dredging for five core locations.

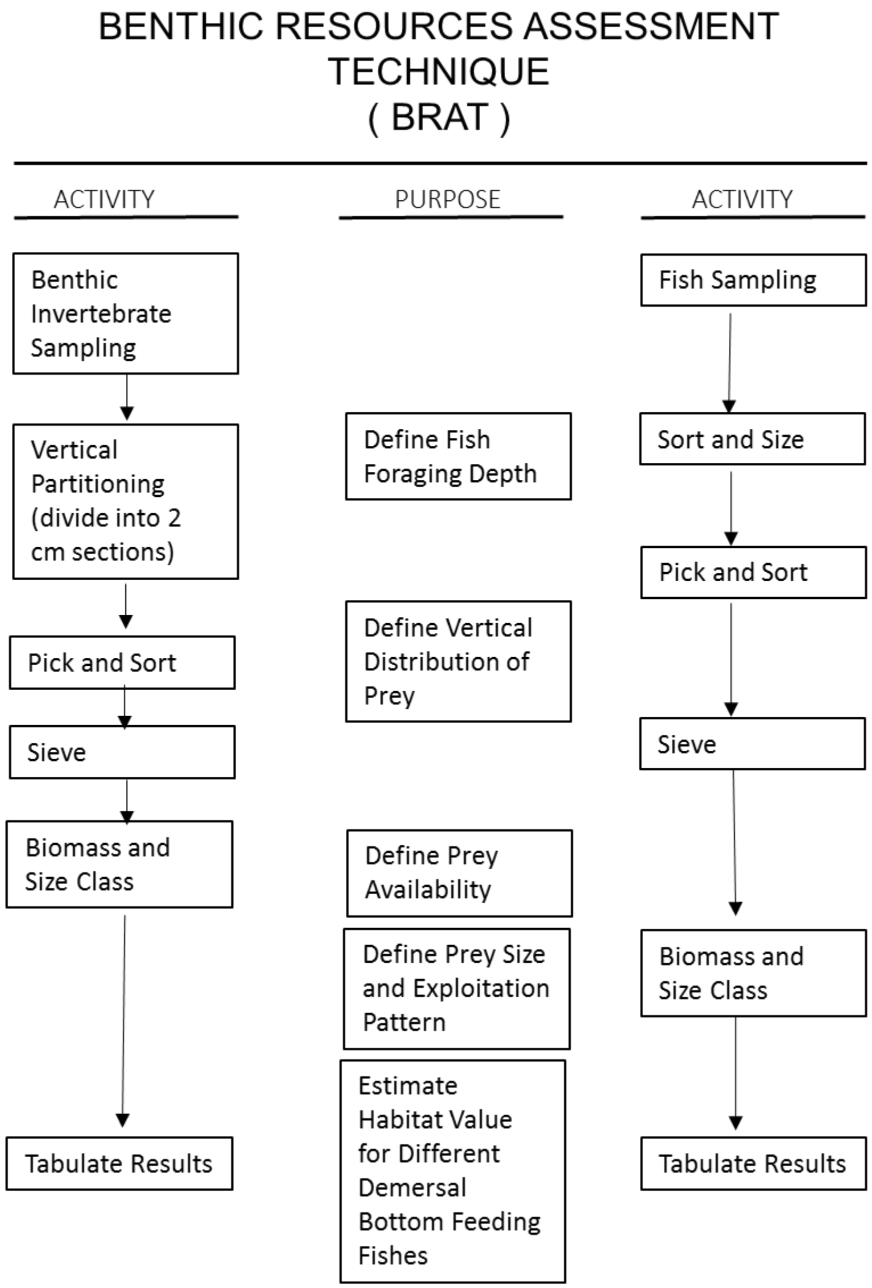

Figure 11. The Benthic Resource Assessment Technique (BRAT) outlines the activities to relate the resource value of benthic invertebrates to fish predators (modified from Rhoads and Germano 1986).

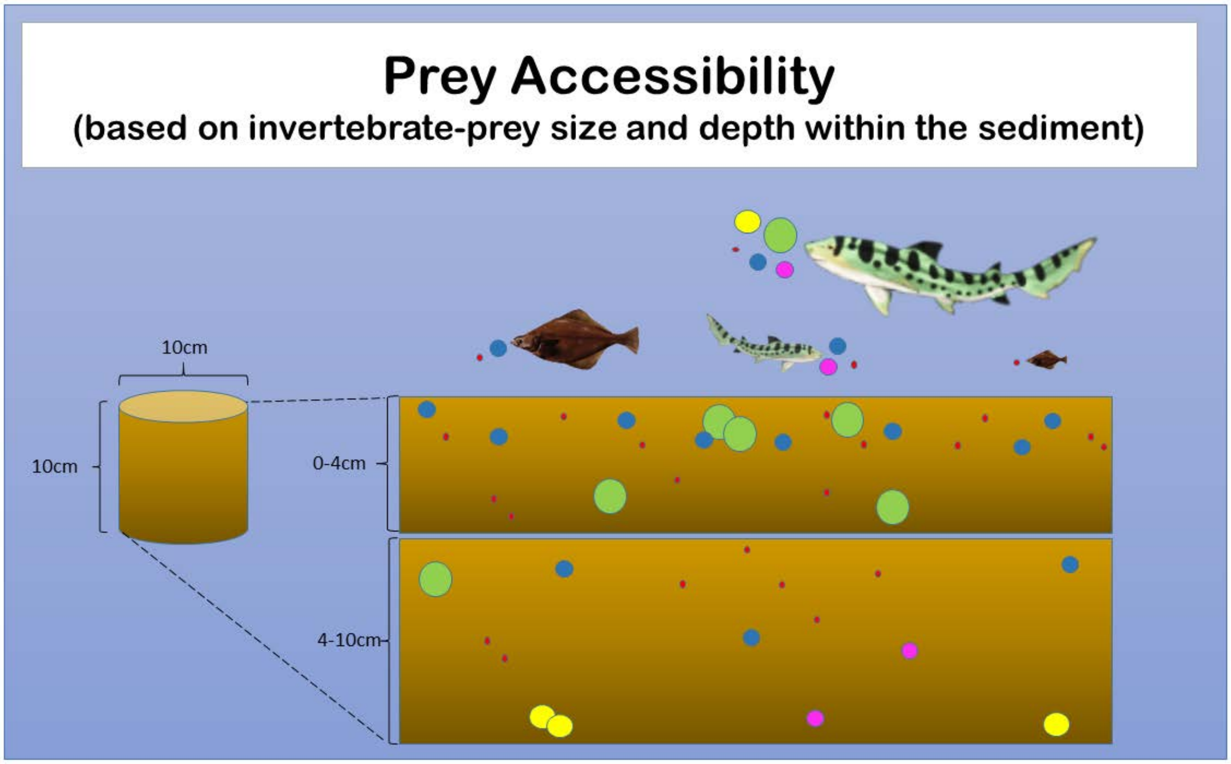

Figure 12. Conceptual diagram illustrating differences in prey consumption for focal foraging fish species, and between juvenile and adult fish (e.g., English sole vs. a Leopard shark). Expected prey accessibility is based on depth within the sediment and macroinvertebrate size. A 10 cm sediment core is partitioned into 2 depth strata (0 - 4 cm and 4 - 10 cm), and different size classes of macroinvertebrates are represented by colored circles of variable dimensions.

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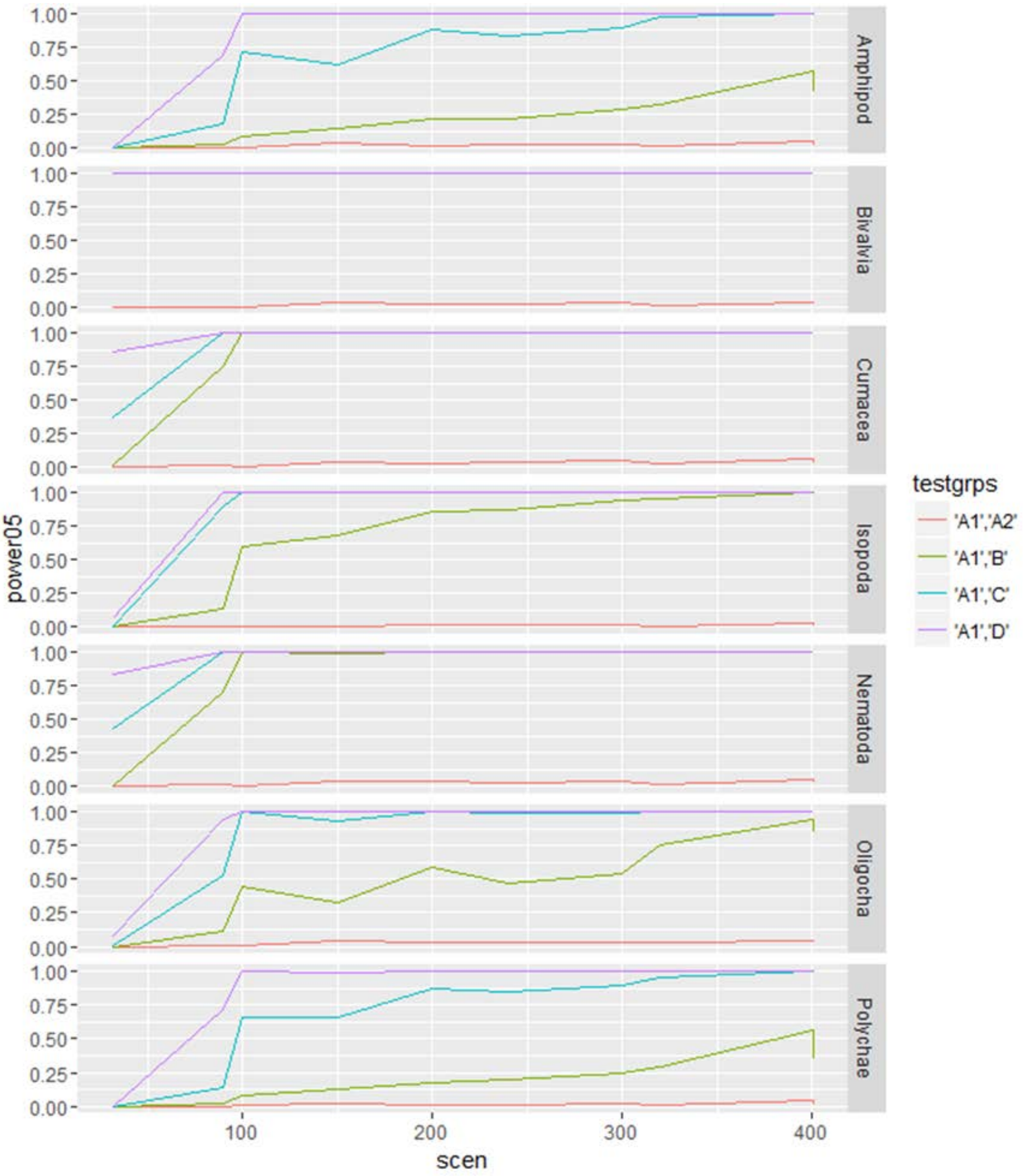

Figure 13. Power analysis curves for individual taxonomic groups based on pilot study data collected in November 2015 from 5 Central Bay marinas. Scenarios depicted on the x-axis are for eight simulated datasets (listed in Table 1) representing different combinations of sites, transects and replicate cores. The y-axis indicates the percent power to determine the difference between dredged and undredged areas. Colored lines represent differences in macroinvertebrate abundances of 0 (red), 25 (green), 50 (blue), and 75% (purple) between dredged and undredged areas.

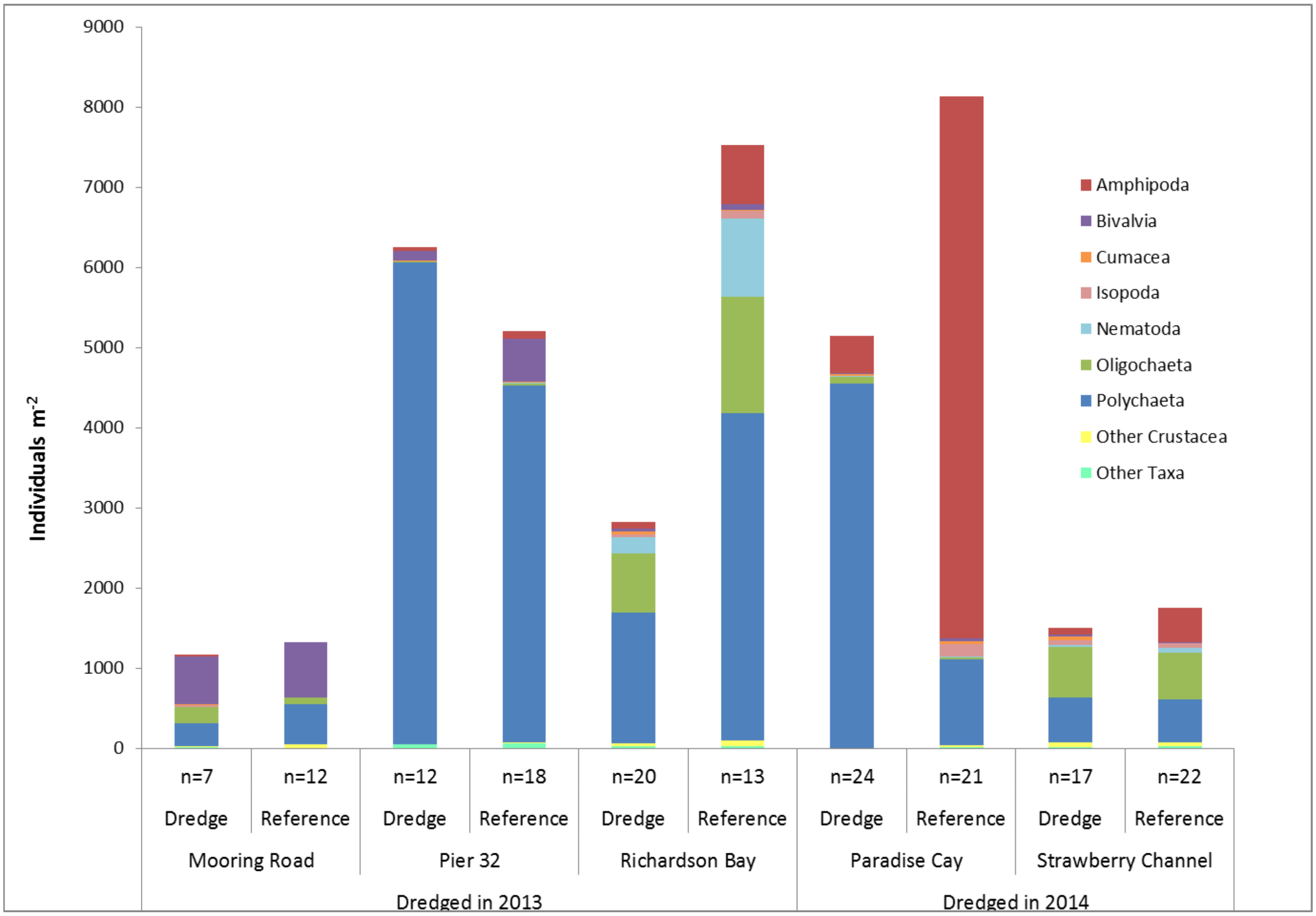

Figure 14. Density of benthic invertebrates within dredged and undredged reference areas by site.

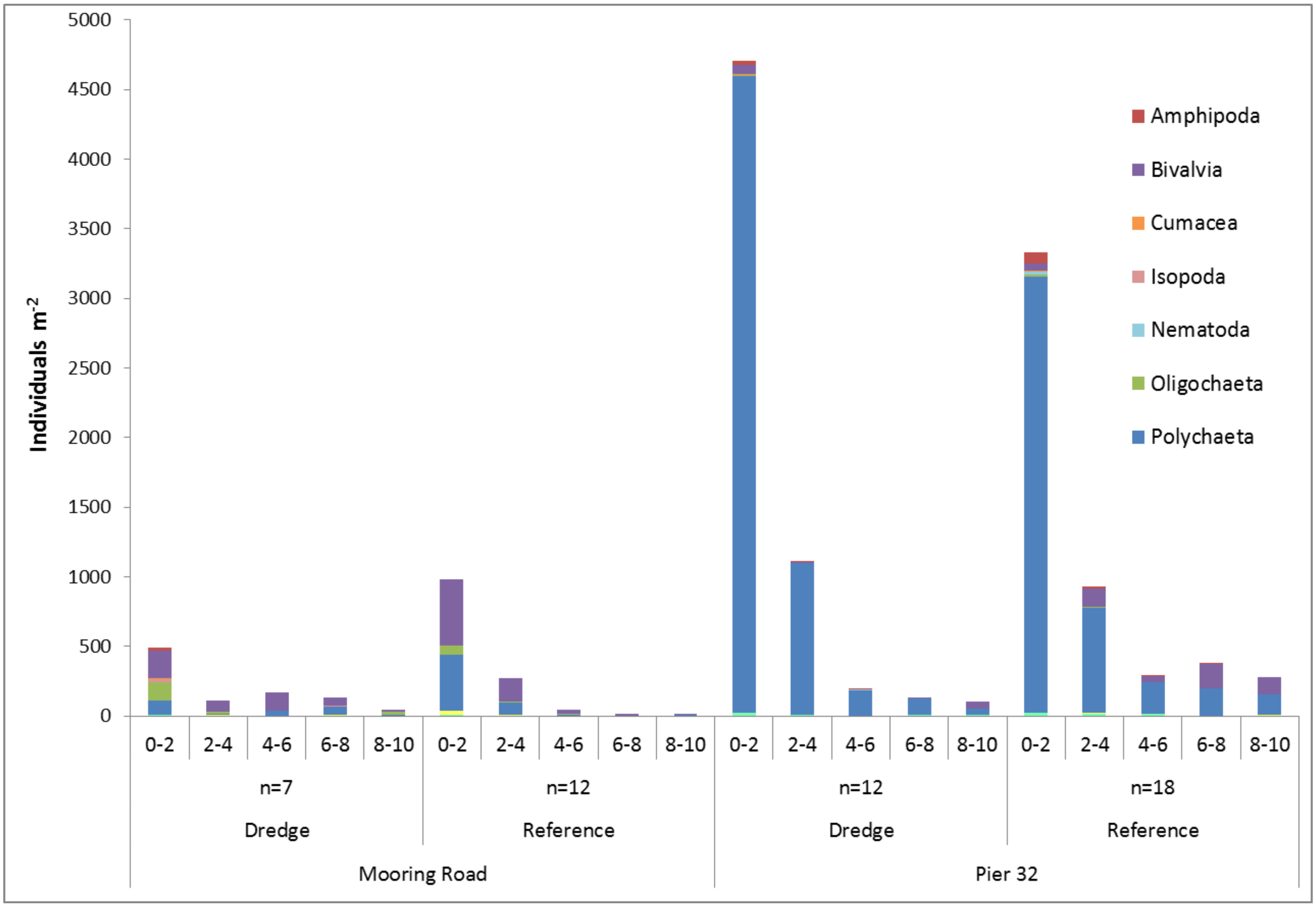

Figure 15. Density of benthic invertebrates by depth at dredged and undredged reference areas at Mooring Road and Pier 32.

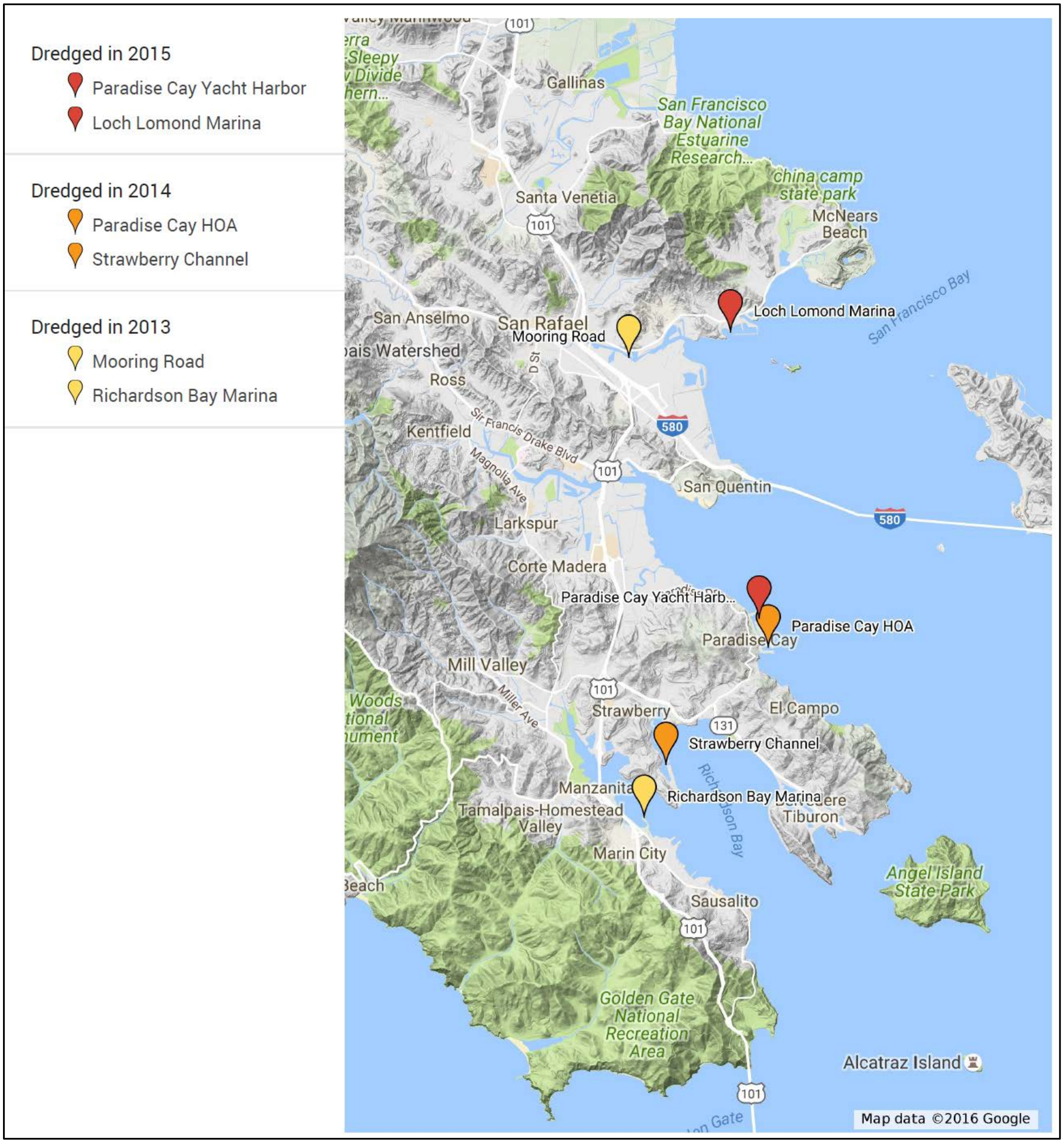

Figure 16. Full study sampling locations. Sites sampled in August/September 2016 and January 2017. Will be sampled again in August 2017.

Figure 17. Loch Lomond Marina study site composed of marina and entrance channel in San Rafael Bay. Sampled as part of full study. White outlined area dredged to 9 ft MLLW in 2015. Site contains 28 core locations in dredged area, 20 undredged reference core locations; four transects of four to seven core locations in dredged marina, one transect of six core locations in dredged entrance channel, one reference transect of five core locations with three transects of five core locations extending from reference transect to dredged entrance channel transect.

Figure 18. Paradise Cay Yacht Harbor study site composed of marina and entrance channel in western SFB. Sampled as part of full study. White outlined area dredged to 10 ft MLLW in 2015. Site contains 22 core locations in dredged area, 21 undredged reference core locations; three transects of five to six core locations in dredged marina, one transect of six core locations in dredged entrance channel, one reference transect of six core locations with three transects of five core locations extending from reference transect to dredged entrance channel transect.