

Impacts of Periodic Dredging on Macroinvertebrate Prey Availability for Benthic Foraging Fishes in Central San Francisco Bay, California



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Cover Photo: Dredge operating in a shallow subtidal region of San Francisco Bay, California.
Photo by Hannah Mittelstaedt, U.S. Geological Survey, May 4, 2017.

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By Susan E. W. De La Cruz, Isa Woo, Laurie Hall, Alison Flanagan, and
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
micrometer (μm)	0.0004279515	inch (in)
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Area		
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
Energy		
joule (J)	0.2388459	calorie (cal)
kilojoules (kJ)	238.8459	Calorie (cal)

Temperature in degrees Celsius ($^{\circ}\text{C}$) may be converted to degrees Fahrenheit ($^{\circ}\text{F}$) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AFDM	ash-free dry mass
AIC	Akaike's Information Criterion
BACI	Before After Control Impact
BRAT	Benthic Resources Assessment Technique
°C	degree Celsius
dw	dry weight
EFH	Essential Fish Habitat
EPA	Environmental Protection Agency
ESA	Endangered Species Act
FMP	Fishery Management Plan
GLM	General Linear Models
GLMM	Generalized Linear Mixed Models
HEP	Habitat Evaluation Program
HOA	Homeowners Association
LDF	Linear Discriminant Function
LTMS	Long Term Management Strategy
MBRAT	Modified Benthic Resources Assessment Technique
MLLW	mean lower low water
MSA	Magnuson-Stevens Fishery Conservation and Management Act
NMFS	National Marine Fisheries Service
ppt	parts per thousand
psu	practical salinity units
SFB	San Francisco Bay
SFRWQCB	San Francisco Regional Water Quality Control Board
U.S.A.	United States of America
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

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Background

Because of its importance for species covered under Federal Fishery Management Plans (FMPs), 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 United States Code §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 benthic communities; however, there is a lack of scientific information specific to SFB regarding dredging effects on macroinvertebrates in fish foraging areas. 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 (U.S. Environmental Protection Agency [EPA], U.S. Army Corp of Engineers [USACE], San Francisco Regional Water Quality Control Board [SFRWQCB], and San Francisco Bay Conservation and Development Commission [BCDC]) that make up the San Francisco Bay Long Term Management Strategy for Dredging (LTMS) identified a study of dredging impacts on SFB fish foraging habitat as one of their highest priorities in their 2011 Programmatic EFH Agreement (U.S. Army Corp of Engineers and U.S. Environmental Protection Agency, 2011).

The LTMS agencies identified the region of interest as shallow (<13 feet [<4 meters (m)] mean lower low water [MLLW]), soft-bottom (silt/clay soil texture) areas in the Central Bay of SFB that were periodically dredged (every 1–3 years). Fish species of interest were compiled by NMFS and included those managed by the Pacific Groundfish, Pacific Salmon, and Coastal Pelagic FMPs (pursuant to the MSA) as well as those listed under the California State or Federal

Endangered Species Act (ESA; 16 U.S.C. §1531–1544) as threatened or endangered. Target species included leopard shark (*Triakis semifasciata*), big skate (*Raja binoculata*), English sole (*Parophrys vetulus*), starry flounder (*Platichthys stellatus*), brown rockfish (*Sebastes auriculatus*), green sturgeon (*Acipenser medirostris*; threatened species under Federal ESA), northern anchovy (*Engraulis mordax*), longfin smelt (*Spirinchus thaleichthys*, threatened under California ESA), and Pacific sardine (*Sardinops sagax*). In addition, Dungeness crab (*Cancer magister*), California halibut (*Paralichthys californicus*), and white sturgeon (*Acipenser transmontanus*) also were included because they are substantial contributors to the California State fishery.

To address LTMS priorities, U.S. Geological Survey, Western Ecological Research Center, San Francisco Bay Estuary Field Station (hereafter USGS) conducted a multi-phased project including an initial literature review, study design, pilot study, and implementation of a full study. The overarching goal was to assess the effects of periodic dredge operations (every 1–3 years) on benthic habitat for foraging fish in the Central Bay, with emphasis on the foraging requirements of target fish species and analyses of benthic macroinvertebrates in dredged areas compared to adjacent undredged reference areas. The USGS partnered with University of California, Davis, fisheries expert James Hobbs to synthesize existing knowledge of fish foraging ecology and review benthic infauna community composition in SFB with a focus on the Central Bay. The literature review (Phase I; De La Cruz and others, 2016) addressed key questions identified by the LTMS on benthic foraging fish in the study area, including the following: (1) What are target fish eating? (2) What are the seasonal differences in prey items and macroinvertebrate assemblages? (3) What are the annual differences in prey items and macroinvertebrate assemblages? (4) What are the predominant macroinvertebrate functional groups from the perspective of fish foraging? Phase II consisted of creating a framework for a functional assessment of maintenance dredging effects on foraging fish and drafting a full study design (De La Cruz and others, 2017), which was then tested in the Phase III pilot study. The Phase IV full study incorporated lessons learned from the pilot study. Here we focus on the results of the full study and implications for benthic foraging fishes.

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Introduction

San Francisco Bay, the largest estuary on the Pacific coast of North America, has been greatly modified by human development for commercial, residential, and recreational purposes (Nichols and others, 1986; Cohen and Carlton, 1998). Despite this urban estuary's extensive history of habitat alteration, SFB remains home to myriad wildlife and continues to provide essential ecosystem functions through its role as a nursery, maturation area, and foraging habitat for many fishes including several state and Federal ESA-listed species (for example, longfin smelt, winter and spring-run Chinook salmon [*Oncorhynchus tshawytscha*], and green sturgeon) and species of economic importance (Dungeness crab, California halibut, and white sturgeon). Furthermore, SFB has been designated as EFH in the Pacific Groundfish, Pacific Salmon, and Coastal Pelagic FMPs pursuant to the MSA.

In urbanized estuaries, dredging (the action of removing benthic sediment) is often necessary at varying intervals and intensities to maintain access to shallow-water facilities such as marinas, harbors, and navigational channels. Though periodic and recurring dredge activities may be necessary to maintain waterway access, the impacts of maintenance dredging on fish habitat are largely unknown. Dredging is a localized disturbance that can adversely impact benthic communities either directly by the removal of organisms (via mortality or injury by entrainment, impingement, or burial; Hirsch and others, 1978; Nightingale and Simenstad, 2001) or indirectly by reducing habitat quality (for example, releasing buried organic matter, nutrients, or contaminants, and increasing suspended sediment concentrations; Reilly and others, 1992; Newell and others, 1998; Ray, 2005). Maintenance dredging may also indirectly impact benthic communities by increasing predation risk and (or) facilitating the colonization of opportunistic non-native or invasive species (Hanson and others, 2004). These physical changes can have cascading impacts on benthic communities (for example, altered composition and species abundance) and subsequently on fishes that forage on benthic infauna (Hirsch and others, 1978; LaSalle, 1990; Clarke and others, 2000; Dernie and others, 2003; Lebednik, 2004; Ray and others, 2005; Rich, 2010).

Fish Foraging Ecology

Shallow subtidal and intertidal benthos are key foraging areas for many fish species. Knowledge of fish diets and prey accessibility (including, prey burial depth, prey size class) are fundamental to understanding the foraging value of the benthos for demersal fishes. Specific data about diets and prey sizes of fishes are generally lacking for SFB (De La Cruz and others, 2016), and much of the limited existing information on macroinvertebrate prey is at a broad taxonomic level (for example, crustaceans). Many of the target fish species for this study are considered generalist foragers that consume

a wide variety of organisms depending on species-specific physiological constraints (such as, gape size, maximum foraging depth) and life history traits that can often change from juvenile to adult life (ontogenetic) stages (De La Cruz and others, 2016; table 1). For example, leopard sharks and big skates are opportunistic generalists known to forage on benthic macroinvertebrates (such as, crabs, molluscs, shrimp, polychaetes), and as they grow, they tend to consume other fish (Hart, 1973; Talent, 1976; Motta and Wilga, 2001; Ebert and Ebert, 2005; Yang, 2007). Whereas juvenile green and white sturgeon consume opossum shrimp and amphipods (Radtke, 1966; Muir and others, 1988), adults consume a wider range of macroinvertebrates and fishes (Adams and others, 2002). Within estuaries, smaller California halibut use shallow habitats and have a predominantly macroinvertebrate-based diet but switch to a more fish-based diet as they grow and inhabit deeper channels (Allen, 1988). Pelagic fishes, including northern anchovy and Pacific sardine, exhibit two distinct modes of feeding: particulate feeding (individual prey items are attacked and consumed) and filter feeding (small food particles are collected and strained through the fine filaments in the gill rakers; Blaxter and Hunter, 1982). In some species, adults will actively switch between particulate and filter feeding modes depending on prey availability. Larval and young juvenile smelt primarily feed on calanoid copepods, including *Eurytemora affinis* (Baxter and others, 1999) and other crustaceans, and mature juveniles and adult fish feed predominantly on opossum shrimp (*Neomysis mercedis*, *Acanthomysis* sp.) and copepods (Feyrer and others, 2003; Hobbs and others, 2006).

The relative abundance of adult and juvenile fish in the Central Bay varies seasonally and by species (De La Cruz and others, 2016). For instance, juvenile northern anchovy are present year-round, but adults are absent during winter. Juvenile Pacific herring (*Clupea pallasii*) are abundant throughout SFB in spring and summer, whereas adult herring are more abundant in winter when they spawn on substrates such as eelgrass and wharf pilings (Skinner, 1962). California halibut of varying age classes are abundant throughout winter, spring, early summer, and fall, with fewer individuals collected in mid-summer months (California Department of Fish and Wildlife, 2013). Young leopard sharks are abundant year-round in SFB and spend many years maturing in SFB before migrating offshore to reproduce (Ebert and Ebert, 2005).

The foraging value of the shallow benthos for generalist fishes can be evaluated using the metric of prey profitability, which compares the energy gained to the energy expended to capture and ingest prey. Prey profitability has been used to evaluate habitat quality and carrying capacity for many benthic foraging predators (Godin and Keenleyside, 1984). The energy content and accessibility (prey size in relation to fish gape size, and the vertical distribution in the sediment) of macroinvertebrates are integral to determining their availability to benthic foraging fishes (Piet and others, 1998; van Denderen and others, 2013).

Table 1. 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 opinion¹. **Abbreviations:** mm, millimeter; <, less than; cm, centimeter]

Fish species	Life stage	Common prey taxa	Foraging mode	Maximum prey size class (mm)	References
Foraging depth: shallow (0–4 cm)					
Pacific sardine	Juvenile	Euphausiids, copepods, diatoms, <i>Oikoplura</i> spp., fish eggs	Picker, filter ¹	4	Emmett and others, 2005; McFarlane and others, 2010
	Adult	Phytoplankton, copepods, euphausiids, diatoms, pelagic fish eggs	Particle, filter ¹	24	Munuera Fernandez and Gonzalez-Quiros, 2006; Espinoza and others, 2009
Longfin smelt	Juvenile	Copepods (e.g. <i>Eurytemora affinis</i>), crustaceans	Picker ¹	4	Moyle and Davis, 2000; Hobbs and others, 2006; Baxter, 2009
	Adult	Mysid shrimp, copepods, zooplankton, crustaceans	Picker ¹	24	Boubee and Ward, 1997; Chigbu and others, 1998; Feyrer and others, 2003; Hobbs and others, 2006
Northern anchovy	Juvenile	Copepod nauplii, phytoplankton	Filter (particulates) ¹	4	Hunter, 1977; Parrish and others, 1985; Miller and Brodeur, 2007
	Adult	small crustaceans, copepods, phytoplankton	Filter (particulates)	100	Leong and O'Connell, 1969; Longhurst, 1971; Blaxter and Hunter, 1982; Miller and Brodeur, 2007
English sole	Juvenile	Polychaetes, bivalves, amphipods, cumaceans, copepods	Picker ¹	12	Ambrose, 1976; Toole, 1980; Hogue and Carey, Jr., 1982; Gadomski and Boehlert, 1984; Lassuy, 1989
	Adult	Gammarid amphipods (summer), polychaetes (fall)	Picker ¹	50	Ambrose, 1976; Buechner and others, 1981; Clarke, 1986
Starry flounder	Juvenile	Mysid shrimp, copepods, amphipods, insect larvae (in freshwater)	Picker ¹	12	Ambrose, 1976; Moore and Moore, 1976; McCall, 1992; Moyle and Davis, 2000
	Adult	Crabs, polychaetes, molluscs, amphipods, isopods, copepods, mysid shrimp	Picker ¹	100	Orcutt, 1950; Miller, 1967; Ambrose, 1976; Moore and Moore, 1976; Herbold, 1987
Brown rockfish	Juvenile	Crustaceans, amphipods, isopods, eelgrass epifauna	Picker ¹	Unknown	Bizzarro and others, 2017; Love and others, 2002
	Adult	Fish	Picker ¹	100	Washington and others, 1978
California halibut	Juvenile	Caridean shrimp, crabs, small fishes	Ambush ¹	50	Allen, 1988; Madon, 2002
	Adult	Fish	Visual, ambush ¹	100	Allen, 1988; Haugen, 1990
Foraging depth: deep (0–10 cm)					
Dungeness crab	Juvenile	Clams, crustaceans, fish	Opportunistic, scavenger, grazer ¹	100	Stevens and others, 1982; Jensen and Asplen, 1998
	Adult	Clams, crustaceans, fish	Omnivore, opportunistic, scavenger, grazer ¹	100	Stevens and others, 1982; Jensen and Asplen, 1998
Big skate	Juvenile	Fish, shrimp, euphausiids	Opportunistic generalist, inertial suction	100	Motta and Wilga, 2001; Yang, 2007; Bizzarro and others, 2007

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Table 1. Foraging depth, common macroinvertebrate prey, foraging mode, and prey size class for focal fish species juveniles and adults.—Continued

[Information was obtained during the Phase I Literature Review and from local expert opinion¹. **Abbreviations:** mm, millimeter; <, less than; cm, centimeter]

Fish species	Life stage	Common prey taxa	Foraging mode	Maximum prey size class (mm)	References
	Adult	Crabs, cephalopods, demersal teleosts, shrimps, polychaetes, clams, sculpin, pelagic skate	Opportunistic generalist	100	Ackerman, 1971; Russo, 1975; Talent, 1976; Kao, 2000; Robinson and others, 2007; Yang, 2007; Bizzarro and others, 2007; Reece and others, 2013
Green sturgeon	Juvenile	Drifting and benthic insects (seasonally), oligochaetes, amphipods, small fish, fish eggs, mysid shrimp	Opportunistic generalist ¹	100	Radtke, 1966; Gessner and others, 2007; Dumbauld and others, 2008
	Adult	Shrimp, molluscs, amphipods, small fish	Opportunistic, suction	100	Adams and others, 2002; Moyle, 2002; Dumbauld and others, 2008
White sturgeon	Juvenile	Amphipods (e.g. <i>Corophium</i> spp.), mysid shrimp	Suction	100	Radtke, 1966; Muir and others, 1988; McCabe and others, 1993; Moyle and Davis, 2000; Dumbauld and others, 2008; Bogacka-Kapusta and others, 2011
	Adult	Shrimp, crabs, clams, herring, anchovy, striped bass, starry flounder, smelt, herring eggs	Suction	100	McKechnie and Fenner, 1971; Miller, 2004; Dumbauld and others, 2008
Leopard shark	Juvenile	Crabs (e.g. <i>Hemigrapsus oregonensis</i>)	Opportunistic generalist, disturb mud, inertial suction	100	Talent, 1976; Barry, 1983; Barry and others, 1996; Ferry-Graham, 1998; Motta and Wilga, 2001
	Adult	Fishes, crabs, clam siphons, innkeeper worms (e.g. <i>Urechis caupo</i>), fish eggs (e.g. <i>Atherinopsis californiensis</i>), isopods, amphipods, zooplankton, shrimp, teleosts, small elasmobranch	Opportunistic generalist, disturb mud, inertial suction	100	Talent, 1976; Barry, 1983; Barry and others, 1996; Motta and Wilga, 2001; Stewart and others, 2004; Ebert and Ebert, 2005

¹Expert opinion, James Hobbs, University of California, Davis.

Macroinvertebrate Prey Availability

Benthic and epibenthic macroinvertebrates are important prey resources for fish, birds, and other predators. Benthic infauna also form an interface between sediment properties and the aquatic food web by facilitating nutrient flux through their burrowing and feeding activities within the sediment (Nichols and Pamatmat, 1988; Thompson and others, 2000; Weigelhofer and Waringer, 2003; Cardoso and others, 2010). Benthic macroinvertebrate communities in SFB commonly include gastropods, bivalves, polychaetes, oligochaetes, and several crustaceans (such as, amphipods, isopods, copepods, crabs, mysids and shrimp; Thompson and others, 2007, 2013).

The distribution and community composition of benthic infauna is largely controlled by salinity (Nichols and Pamatmat, 1988). In winter months, during periods of high freshwater input, the surface salinity in the Central Bay can rapidly decline from 30 to 10 parts per thousand (ppt); however, salinity values in the demersal waters tend to be more stable owing to stratification of the less dense surface freshwater (Cloern and others, 2000). Because salinity in the Central Bay is more stable than in the northern reaches of SFB, it sustains a more diverse community across seasons (Thompson and others, 2000). Still, large freshwater influx in the Central Bay can affect the benthos in shallow shoal areas (Thompson and others, 2007).

Although benthic macroinvertebrate communities are most influenced by salinity gradients within SFB, macroinvertebrate abundance, taxonomic richness, and spatial distributions are also influenced by other physical factors such as temperature, flow velocities, and substrate characteristics (for example, texture and particle size; Thompson and others, 2000). In shallow shoals, sediment composition and particle size are largely influenced by physical processes such as wave action and water flow velocity (Krone, 1979; van Duren and Middelburg, 2001). Benthic habitats with greater proportions of fine particles such as silt and clay contain different macroinvertebrate species than coarser sediments such as sand and shell fragments, resulting in distinct benthic community assemblages.

Much of the benthic substrate throughout the Central Bay consists of a mixture of sand, silt, clay, and shell fragments (Goals Project, 1999; California State Coastal Conservancy, 2010; Barnard and others, 2013; Greene and others, 2013); however, the shallow benthic regions that are the focus of this study are characterized predominately by muddy, fine-grained sediment substrates, which are dominated by amphipods (primarily *Ampelisca abdita* as well as *Monocorophium acherusicum*) and mobile errant polychaetes (primarily *Euchone limnicola*; Thompson and others, 2000; Lee II and others, 2003). Benthic macroinvertebrate density and taxonomic richness are frequently greater in these low-flow habitats with fine sediments, whereas sandy substrates with swift-moving currents are typically dominated by polychaete species (*Heteropodarke heteromorpha* and *E. limnicola*; Thompson and others, 2000, 2007; Lee II and others, 2003).

Assessing Benthic Recovery After Maintenance Dredging

In urbanized estuaries, maintenance dredging and resulting localized disturbances often occur at regular or periodic intervals to maintain access to harbors, marinas, and waterways. Benthic recovery post-dredging is complicated by the fact that repopulation may occur at different rates for different taxa. In general, large, hard-bodied macroinvertebrates with greater longevity have longer recovery times and are disproportionately affected by disturbance. Smaller species are often associated with high fecundity and shorter generation times and thus are conceivably more resilient to disturbance (McCall, 1977; Newell and others, 1998; van Denderen and others, 2013). Recolonization is primarily driven by the lateral movement of organisms, larval settlement, and appropriate conditions for larval settlement and growth. Initial colonizers are generally opportunistic species that may differ from those that were present prior to sediment removal (Oliver and others, 1977; Newell and others, 1998; Applied Marine Sciences Inc., 2009; Cohen, 2010). Following disturbance, a transitional community with lower peak abundances than the initial colonizers will appear, but it may take several years for larger and longer-lived taxa to recolonize and grow (McCall, 1977;

Van Der Veer and others, 1985; Rhoads and Germano, 1986; Newell and others, 1998). Thus, chronic disturbance may change a community of large, hard-bodied macroinvertebrates to one that is dominated by smaller, soft-bodied species (such as, polychaetes) with low species diversity (Rhoads and Germano, 1986; Rees and Dare, 1993; Newell and others, 1998; van Denderen and others, 2013). On the other hand, some studies indicate that with enough time, the re-established biotic community might recover and resemble the pre-dredged community (Oliver and others, 1977; Newell and others, 1998; Applied Marine Sciences Inc., 2009; Cohen, 2010).

Defining benthic recovery remains a major challenge, despite the post-dredging impact studies that have been conducted over the past several decades. Several methods have been suggested for evaluating recovery, but there is little consensus concerning the appropriate metrics (such as, macroinvertebrate density, biomass, species richness, evenness, and diversity) or statistical techniques to assess post-disturbance recovery (Rhoads and Germano, 1986; Bolam and Rees, 2003; Wilber and Clarke, 2007; Wilber and others, 2008). As a result, recovery estimates are variable (Bolam and others, 2006; Wilber and Clarke, 2007). Recovery is often defined as a return to a baseline (pre-impact) or reference (unimpacted) condition and tested for using a BACI (Before-After Control-Impact; Currie and Parry, 1996; Wilber and others, 2008) or Beyond BACI (an asymmetrical BACI design using multiple reference sites to assess impacts; Underwood, 1994; Roberts and others, 1998a, 1998b) design. The combination of natural and anthropogenic disturbances is common in estuaries such that the baseline macroinvertebrate community (in other words, pre-dredging) may not be representative of a natural, “healthy” community, and instead may be dominated by a few small, opportunistic taxa commonly found in areas that are frequently or chronically disturbed. Newell and others (1998) examined 17 studies and reported that recovery rates were faster in disturbed and channel mud habitat communities that originally comprised small opportunistic taxa. They noted that habitats that were originally dominated by larger, long-lived taxa had much slower recovery times (up to 12 years).

Structural metrics such as the density and taxonomic composition of benthic organisms at a site are often used to assess benthic recovery; however, they may not be very meaningful if they lack relationships to ecological functions of interest in the impacted habitat (Wilber and Clarke, 2007), such as prey productivity for consumers. Measures of ecological function, such as macroinvertebrate biomass, secondary production (amount of energy generated by a species assemblage; Brey and others, 1988), and functional diversity (for example, presence of multiple foraging guilds) of the community, provide information on the role benthic macroinvertebrates play in the ecosystem and may recover independently from structural metrics (Bolam, 2012, 2014). Thus, there is a growing interest in applying structural and functional metrics to evaluate recovery of habitat quality after a disturbance event (Clarke and others, 1993; Rodil and others, 2013; Bolam, 2014).

Measuring Structural and Functional Recovery

Assessments such as the U.S. Fish and Wildlife Service (USFWS) Habitat Evaluation Procedure (HEP; U.S. Fish and Wildlife Service, 1980), Estuarine Habitat Assessment Protocol (Simenstad and others, 1991), and the Benthic Resources Assessment Technique (BRAT; Lunz and Kendall, 1982; LaSalle, 1990) have been developed and used to evaluate functional recovery of the benthos. The BRAT assessment was specifically developed by the USACE to be used as a quantitative tool for evaluating and comparing dredge impacted sites in terms of trophic support for bottom feeding fishes (Lunz and Kendall, 1982; LaSalle, 1990). The BRAT approach has traditionally been used to determine the most suitable location to dispose of dredge material (Lunz and Kendall, 1982; Clarke, 1986), and it has also been applied to assessments of benthic prey availability for fish (Rhoads and Germano, 1986). Because BRAT integrates information on fish foraging ecology, prey biomass and energy content to estimate trophic (nutritional) support available for fishes in benthic habitats, we applied this framework with modifications to evaluate the impacts of periodic dredging on benthic communities compared to undredged reference areas. Our study considered the foraging needs of target fish species that were identified under the 2011 Programmatic EFH Agreement. In addition, we evaluated benthic macroinvertebrate density and community taxonomic composition between dredged and undredged reference areas as structural measures of habitat. Here we present synthesized results from the full study evaluating habitat quality for SFB benthic foraging fish in relationship to (1) dredged versus undredged locations, (2) distance to dredged site, and (3) years since dredging.

Methods

Study Design

Modified Benthic Resources Assessment Technique (MBRAT) Framework

The BRAT framework (fig. 1) integrates information on fish foraging ecology and prey profitability to estimate the energy that is available to specific fish feeding guilds. Prey profitability is a measurement that has been used to evaluate habitat quality for many benthic foraging predators (Richman and Lovvorn, 2004; Goss-Custard and others, 2006; Lovvorn and others, 2013), including fish (Crowder and Cooper, 1982; Godin and Keenleyside, 1984). Energy

content, size, and accessibility (visibility, vertical distribution in the sediment, predator defense, and escape capabilities) of macroinvertebrates are integral to determining their profitability to benthic foraging fish (Lunz and Kendall, 1982; Piet and others, 1998; van Denderen and others, 2013).

We modified the BRAT framework to address our study objectives, budget, and scope. This modified BRAT (hereafter, MBRAT) approach used benthic fish foraging ecology and diet information identified in our literature review and by local expert opinion (table 1; De La Cruz and others, 2017), in lieu of conducting a fish diet study. For each focal fish species, we considered the following factors for juveniles and adults: common prey taxa, foraging mode, foraging depth in the benthic subsurface, and maximum prey size (tables 1–2). Many benthic-foraging fishes are generalists, and consumption of macroinvertebrate prey items is related to local macroinvertebrate prey density, biomass, and vertical distribution. Therefore, we adjusted the MBRAT to include sorting and identifying macroinvertebrates into broad taxonomic categories 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, we identified macroinvertebrates to species or lowest taxonomic unit in a random subset of core samples from each study site to enable comparison of structural metrics across sites.

Another modification to the traditional BRAT approach was dividing benthic core samples into two depths: shallow (0–4 centimeters [cm]) and deep (4–10 cm), rather than partitioning in 2-cm increments. This modification was based on our pilot study where we found that the majority of macroinvertebrates in cores from two pilot sites were located in the upper 4 cm of the core (fig. 2; De La Cruz and others, 2017). Furthermore, other studies of fish prey have identified the best sample depth as that which approximately matches the predator's foraging depth (Ferraro and Cole, 2004). Although skates, sturgeon, leopard sharks, and crabs can forage relatively deep within the sediment (here represented as the entire core 0–10 cm depth), other target fish in our study (such as, sardine, anchovy, brown rockfish, and others) are primarily epi-benthic and near-surface feeders, which corresponds to the shallow portion of our cores (0–4 cm depth; Gotshall, 1977; Holland and others, 1980; Bottom and Jones, 1990; tables 1–2). Thus, in our simplified scheme for evaluating prey accessibility (table 2), the upper 0–4 cm of the core represents the foraging area of target species such as sardine, anchovy, and brown rockfish, whereas deeper (4–10 cm) portions of the core represent the additional area available to species such as skates, sturgeon, leopard sharks, and crabs (table 2).

BENTHIC RESOURCES ASSESSMENT TECHNIQUE (BRAT)

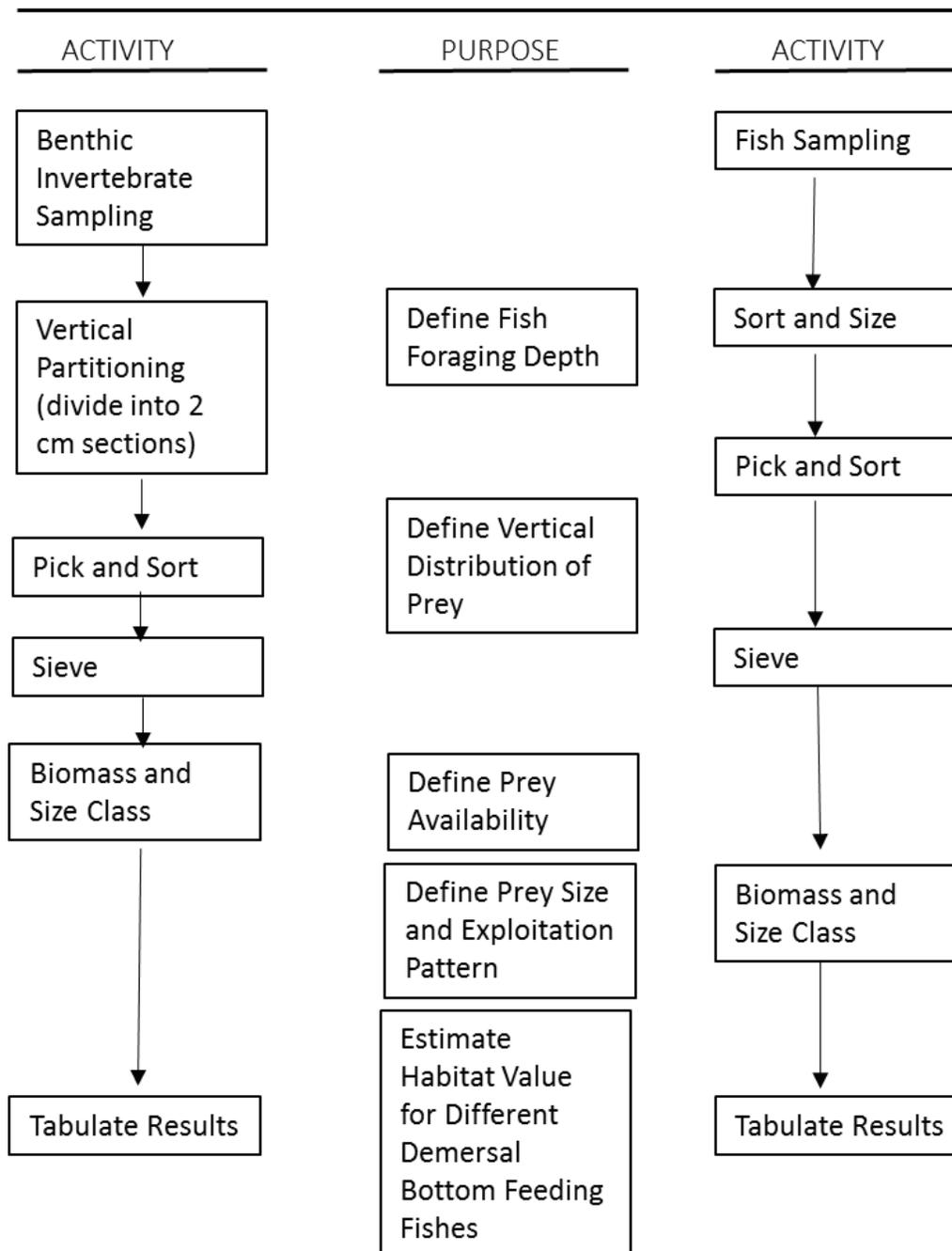


Figure 1. The Benthic Resource Assessment Technique (BRAT) outlines the activities to relate the resource value of benthic macroinvertebrates to fish predators (modified from Rhoads and Germano, 1986).

Table 2. Simplified foraging table for focal fish species showing the depth increments and prey class sizes 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. Estimated available mean biomass (gram per square meter; g/m²) in dry weight (dw) and energy (kilojoule per square meter; kJ/m²) for each fish species and age class were calculated across all study sites and sampling dates for the appropriate depth and prey size class. *The 50–100 millimeter (mm) size class can be consumed by some fish species; however, this study did not detect any macroinvertebrates in the 50–100 mm size class. **Abbreviations:** %, percent; cm, centimeter]

Fish species	Life stage	Prey size class (mm)*	Available prey biomass (g/m ² dw)		% biomass reduction from undredged to dredged	Available prey energy (kJ/m ²)		% energy reduction from undredged to dredged
			Dredged	Undredged		Dredged	Undredged	
Foraging depth in sediment: Shallow (0–4 cm)								
Pacific sardine	Juvenile	0–4	3.04	5.40	44	50.23	89.22	44
	Adult	0–24	26.62	41.02	35	126.96	212.43	40
Longfin smelt	Juvenile	0–4	3.04	5.40	44	50.23	89.22	44
	Adult	0–24	26.62	41.02	35	126.96	212.43	40
Northern anchovy	Juvenile	0–4	3.04	5.40	44	50.23	89.22	44
	Adult	0–100	30.04	48.86	39	137.99	237.46	42
English sole	Juvenile	0–12	5.95	12.05	51	60.02	112.94	47
	Adult	0–50	30.04	48.86	39	126.96	212.43	40
Starry flounder	Juvenile	0–12	5.95	12.05	51	60.02	112.94	47
	Adult	0–100	30.04	48.86	39	137.99	237.46	42
Brown rockfish	Juvenile	0–4	3.04	5.40	44	50.23	89.22	44
	Adult	0–100	30.04	48.86	39	137.99	237.46	42
California halibut	Juvenile	0–50	30.04	48.86	39	126.96	212.43	40
	Adult	0–100	30.04	48.86	39	137.99	237.46	42
Foraging depth in sediment: Deep (0–10 cm)								
Dungeness crab	Juvenile	0–100	33.44	56.97	41	154.66	310.11	50
	Adult	0–100	33.44	56.97	41	154.66	310.11	50
Big skate	Juvenile	0–100	33.44	56.97	41	154.66	310.11	50
	Adult	0–100	33.44	56.97	41	154.66	310.11	50
Green sturgeon	Juvenile	0–100	33.44	56.97	41	154.66	310.11	50
	Adult	0–100	33.44	56.97	41	154.66	310.11	50
White sturgeon	Juvenile	0–100	33.44	56.97	41	154.66	310.11	50
	Adult	0–100	33.44	56.97	41	154.66	310.11	50
Leopard shark	Juvenile	0–100	33.44	56.97	41	154.66	310.11	50
	Adult	0–100	33.44	56.97	41	154.66	310.11	50

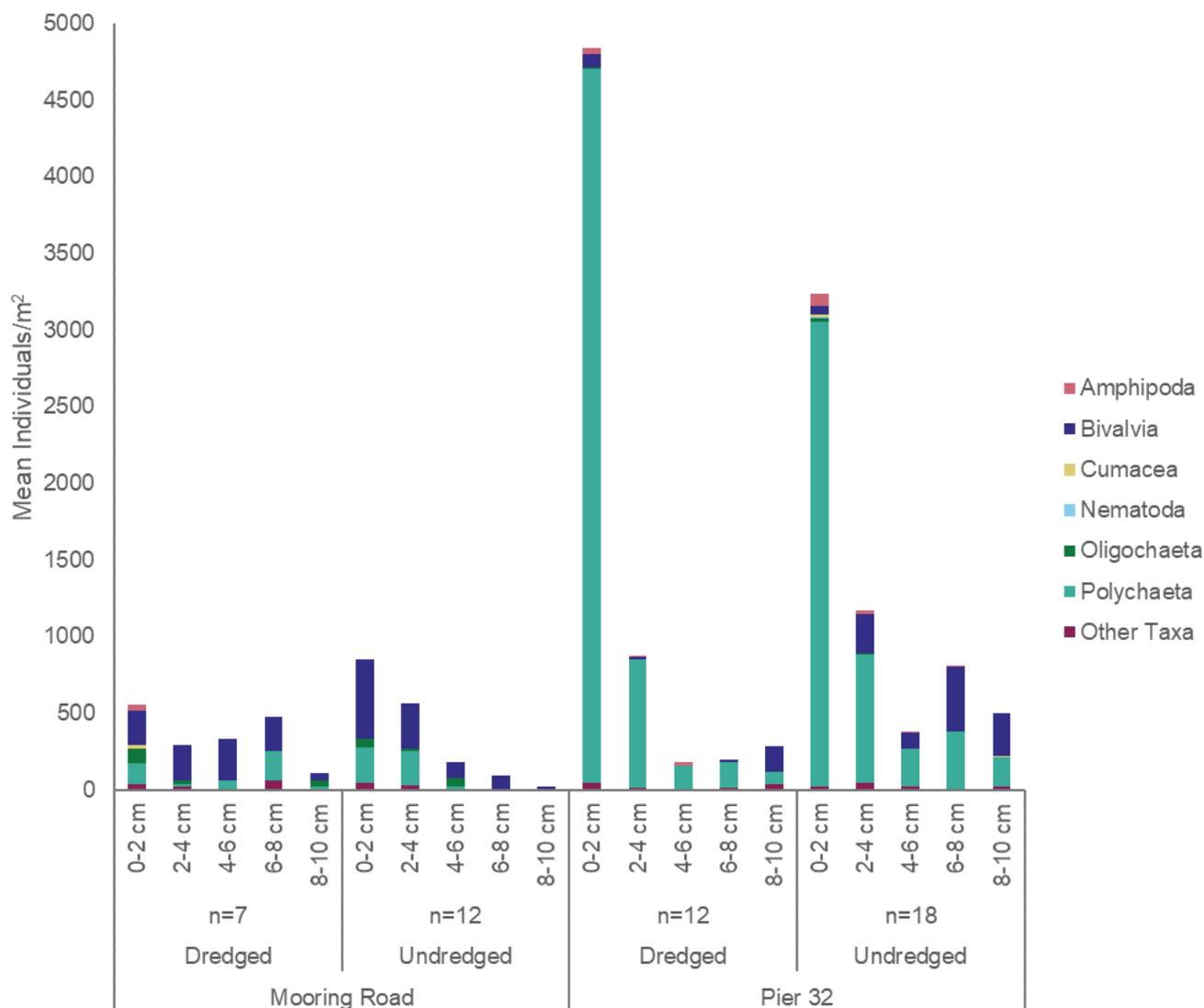


Figure 2. Mean density of benthic macroinvertebrates by 2-centimeter depth increments at dredged and undredged reference areas sampled at Mooring Road and Pier 32 sites during the pilot study.

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, most fish will consume different prey in juvenile compared to adult stages (such as, green and white sturgeon, California halibut; Haaker, 1975; Plummer and others, 1983; Muir and others, 1988), and spatiotemporal patterns in prey availability can induce prey switching in certain fishes (Toole, 1980; Blaxter and Hunter, 1982). While some fish are expected to be able to consume prey as large as 100 millimeters (mm), such prey are likely to be small fishes or other highly mobile taxa, the sampling of which was outside the scope of our study. We did not encounter macroinvertebrates >50 mm in our samples, even though individuals of this size can be detected with our sampling gear. Thus, after extensive literature review (De La Cruz and others, 2016) and expert consultation with Dr. James Hobbs (University of California Davis, oral and

written commun., 2014, 2017), Dr. Scott Hamilton (Moss Landing Marine Laboratory, oral and written commun., 2017), and Dr. Fred Feyrer (USGS California Water Science Center, written commun., 2017), we established four unique macroinvertebrate size classes that encompassed the prey sizes that could be consumed by target fish species in our study: 0 to 4 mm, greater than 4 mm to 12 mm, greater than 12 mm to 24 mm, and greater than 24 mm to 50 mm (table 2). Macroinvertebrates were sorted into size classes based on overall body length for most taxa and head width for polychaetes and oligochaetes. 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 were used to evaluate macroinvertebrate prey availability for each species and life stage at each study site.

Taken together, the components of the MBRAT method create a framework to assess density, biomass, energy content, and vertical distribution for each broad macroinvertebrate taxa group and size class and we used this information to determine prey availability for each focal fish species (fig. 3, table 2). Implicit to this framework is the idea that an increase in biomass and (or) energy content of prey (as in, trophic support) that is the right size and depth to be available for a particular target species means that there is an increase in habitat function for that species.

Study Area and Site Selection

San Francisco Bay is a shallow estuary (median depth 1.83 m below MLLW; Conomos and others, 1985) with four major sub-bays: Suisun Bay, North Bay (San Pablo Bay), Central Bay, and South Bay (fig. 4). We collected data for the initial power analyses conducted in this study from a 1.25 square kilometer (km²) intertidal mudflat located in the South Bay (Dumbarton mudflat, 37°50' N., 122°12' W.; fig. 5). The South Bay is mesohaline (Thompson and others, 2013) with mixed semidiurnal tides ranging up to 3 m (Shellenbarger and others, 2013) such that the mudflat is inundated and exposed

twice daily. The width of the Dumbarton mudflat increases from 200 to 900 m from north to south, and mudflat width is correlated with net deposition and erosion patterns throughout South Bay (van der Wegen and others, 2017). The Dumbarton mudflat extends about 1 km from shore to the channel and ranges in elevation from about -1.21 m to 1.11 m North American Vertical Datum 1988 (NAVD 88). Water column salinity during flood tides at the site ranged from 18 parts per thousand (ppt) in March and April to 32 ppt in late August and September.

Sampling sites for the pilot and full studies were located within and adjacent to marinas in the Central Bay, a predominantly polyhaline zone (1–30 ppt; fig. 6; Thompson and others, 2007, 2013; Gillet and others, 2014), which is generally characterized by fine-grained (silt and clay) to coarser sediments (sand and shell fragments; Goals Project, 1999; Subtidal Goals Project, 2010; Barnard and others, 2013; Greene and others, 2013). Selected study site marinas were all less than 4 m deep, and the substrate consisted mostly of silt and clay (table 3). Sites were also most recently dredged in 2013, 2014, or 2015 with a dredging frequency of 2–4 years, though some sites had a longer span of time between dredging such as Strawberry Channel (7 years), Loch Lomond Marina (12 years), and Mooring Road (infrequent).

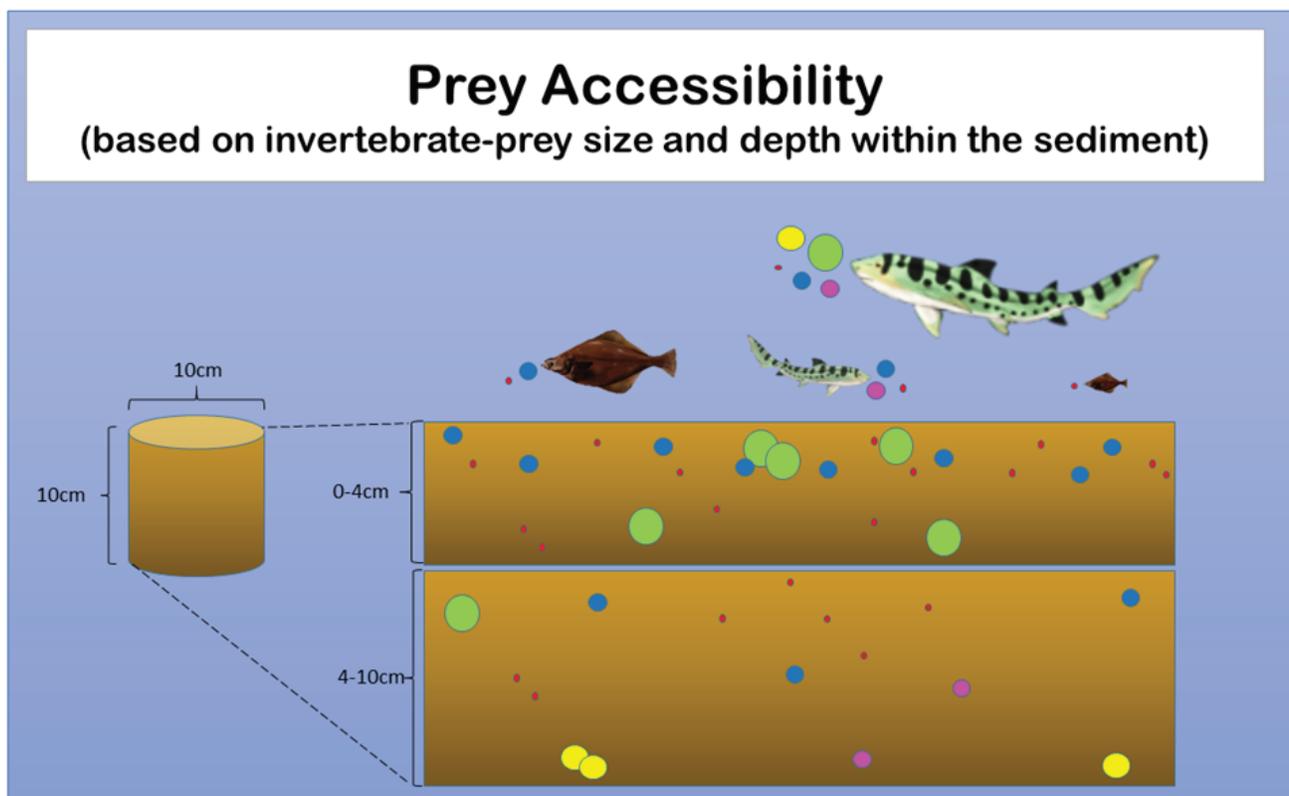


Figure 3. Conceptual diagram illustrating differences in prey consumption for focal foraging fish species and between juvenile and adult fish (for example, English sole versus a leopard shark). Expected prey accessibility is based on depth within the sediment and macroinvertebrate size. A 10-cm sediment core is partitioned into two depth strata (0–4 cm and 4–10 cm), and different size classes of macroinvertebrates are represented by colored circles of variable dimensions.

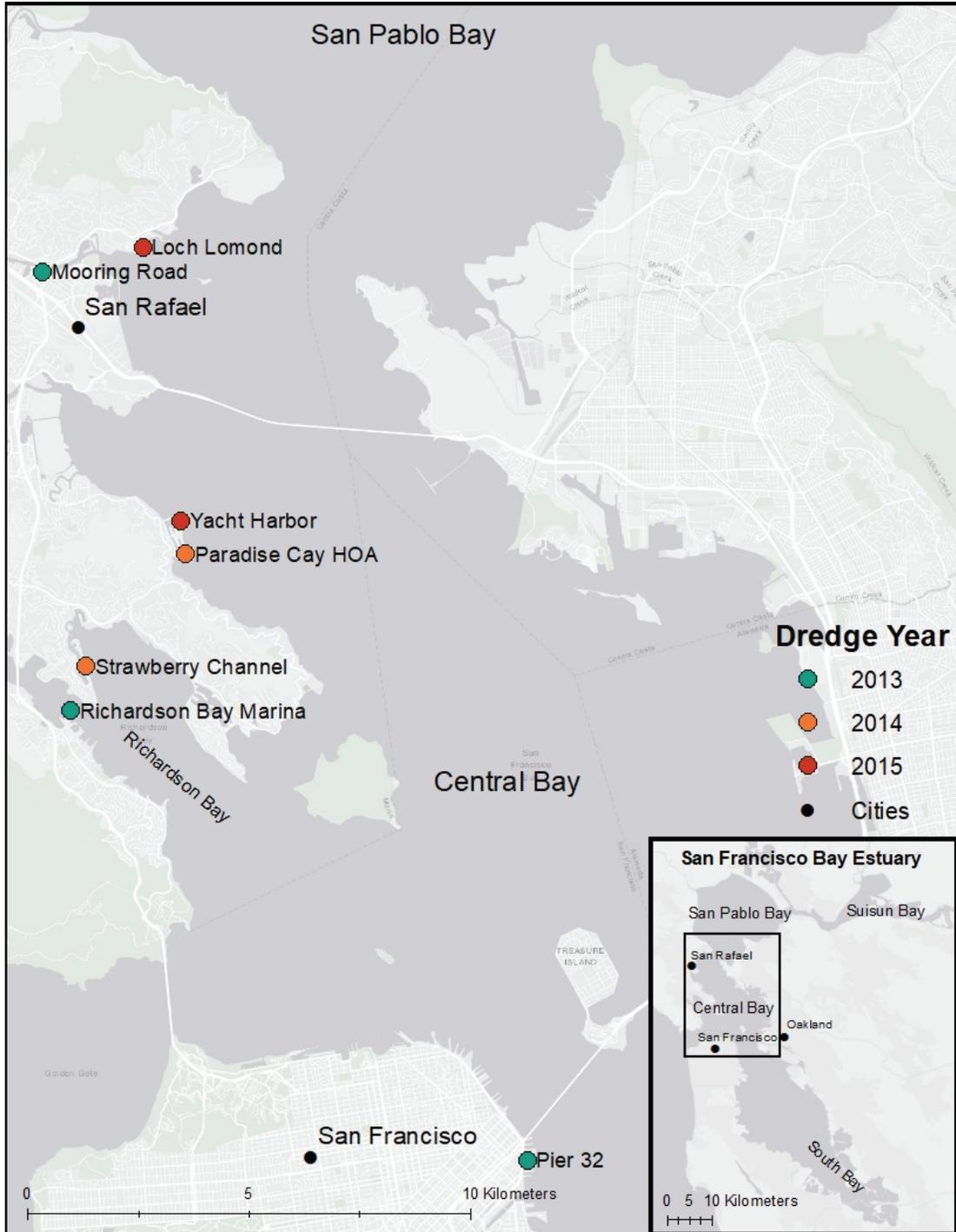


Figure 4. Study sites in central San Francisco Bay. Red sites were dredged in 2015, orange sites were dredged in 2014, and green sites were dredged in 2013.

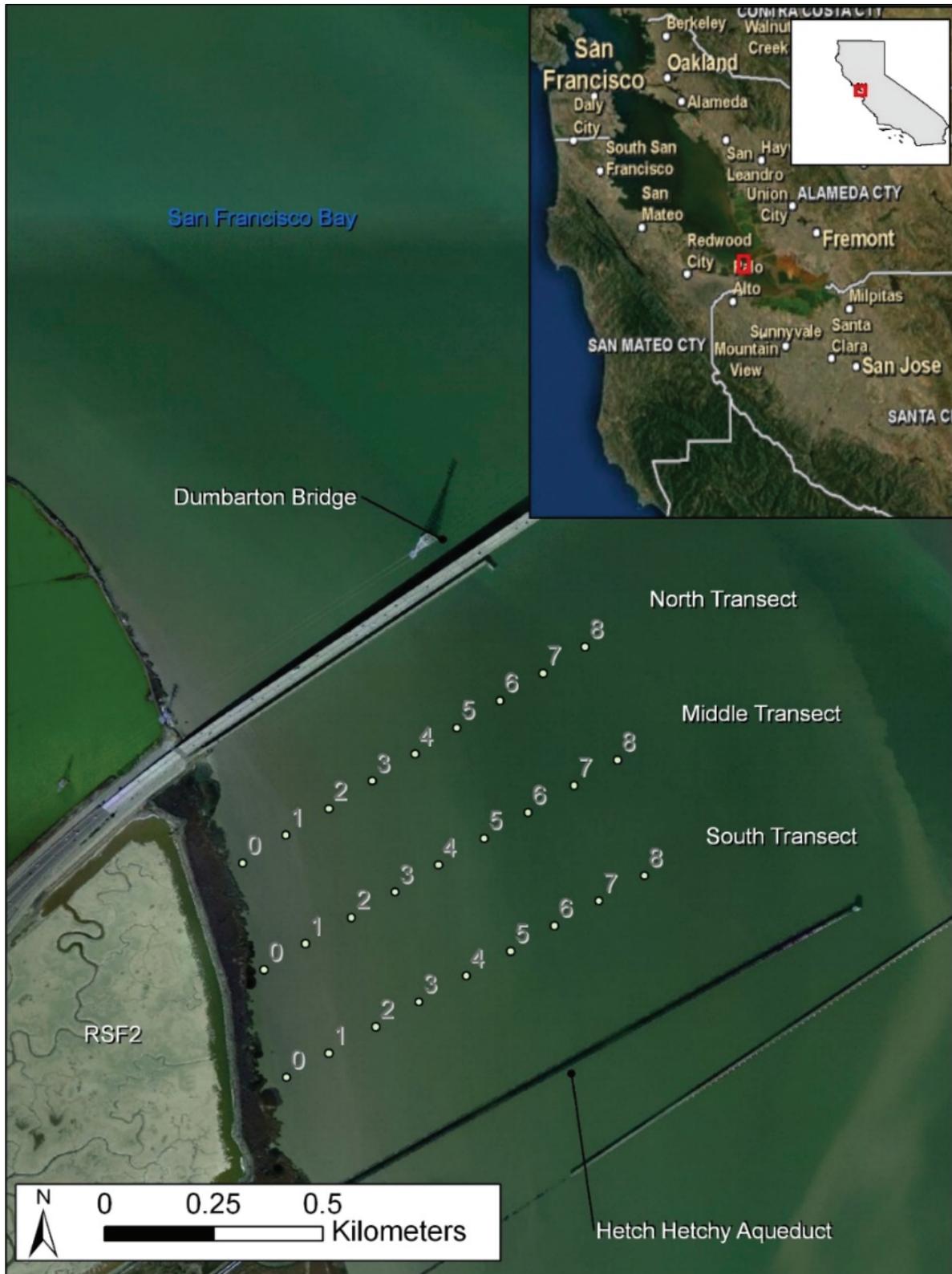


Figure 5. Sampling locations in the Dumbarton Shoals mudflat adjacent to pond RSF2 in the Ravenswood complex of the South Bay Salt Pond Restoration Project.

Table 3. Central Bay site selection table indicating all sites considered for the pilot and full study.

[MLLW, mean lower low water; ft/m, foot per meter; SFB, San Francisco Bay; HOA, Homeowners Association]

Study area	Location	Embayment	Salinity regime ¹	Habitat type	Sediment texture	Dredge depth MLLW (ft/m)	Last dredged	Estimated dredging frequency (years)
Selected sites								
² Pier 32	San Francisco	Central SFB	Polyhaline	Shallow subtidal	Sand/silt/clay	12.0/3.7	2013	2–3
Mooring Road ³	San Rafael	San Rafael Bay	Poly/mesohaline	Marina	Silt/clay	6.0/1.8	2013	Infrequent
Richardson Bay Marina ³	Sausalito	Richardson Bay	Polyhaline	Marina	Silt/clay	10.5/3.2	2013	3
Paradise Cay HOA ³	Paradise Cay	Corte Madera Bay	Polyhaline	Channel	Silt	8.0/2.4	2014	4
Strawberry Channel ³	Strawberry	Richardson Bay	Polyhaline	Channel	Silt/clay	7.0/2.1	2014	7
Loch Lomond Marina ⁴	San Rafael	San Rafael Bay	Poly/mesohaline	Marina	Silt/clay	9.0/2.7	2015	12
Paradise Cay Yacht Harbor ⁴	Paradise Cay	Corte Madera Bay	Polyhaline	Marina	Silt	10.0/3.0	2015	4
Sites considered, but not selected								
Aeolian Yacht Club	Alameda	San Leandro Bay	Polyhaline	Marina	Clay	10.0/3.0	2014	4
Larkspur Marina	Larkspur	Corte Madera Bay	Polyhaline	Marina	Silt/clay	6.0/1.8	2015	4–5
Marina Vista HOA	San Rafael	San Rafael Bay	Poly/mesohaline	Channel	Silt/clay	7.0/2.1	2015	4
Marin Yacht Club	San Rafael	San Rafael Bay	Poly/mesohaline	Marina	Silt/clay	9.0/2.7	2016	5
SF Marina West Basin	San Francisco	Central SFB	Polyhaline	Shallow subtidal	Sand/silt/clay	13.0/4.0	2014	2–3
Clipper Yacht Harbor	Sausalito	Richardson Bay	Polyhaline	Marina	Silt/clay	9.0/2.7	2015	3–4
Corinthian Yacht Harbor	Sausalito	Belvedere Cove	Polyhaline	Marina	Silt/clay	13.0/4.0	2015	4
Larkspur Ferry Terminal	Larkspur	Corte Madera Bay	Polyhaline	Channel	Silt/clay	17.0/5.2	2015	4

¹Thompson and others, 2013.²Sites sampled for pilot study only.³Sites sampled for pilot study and full study.⁴Sites sampled for full study only.

We selected recently dredged marinas that had adjacent corresponding undredged reference areas. Here we used the term “reference” to refer to an area that was undredged, rather than a pristine site. It is important to note that the reference areas we selected are not “undisturbed.” Rather, undredged reference areas included similar localized environmental

characteristics (salinity, depth, sediment texture) 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 undredged areas of an urbanized estuary.

We compiled site characterization information for each marina (Bay Conservation and Development Commission, unpub. data, 2015, 2016) to inform decisions about sampling design elements (table 3). The primary site selection criteria were based on identified project objectives and included (1) location within the polyhaline region of the Central Bay (fig. 6); (2) post-dredging depth of <13 feet (4 m) MLLW; (3) predominantly soft-bottom sediments; (4) a dredging date falling within one of three time periods: 1 year before present, 2 years before present, and 3 years before present;

and (5) presence of an adjacent undredged reference site. Undredged reference sites were considered areas near 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,” which was established by LTMS agencies during the study planning period.

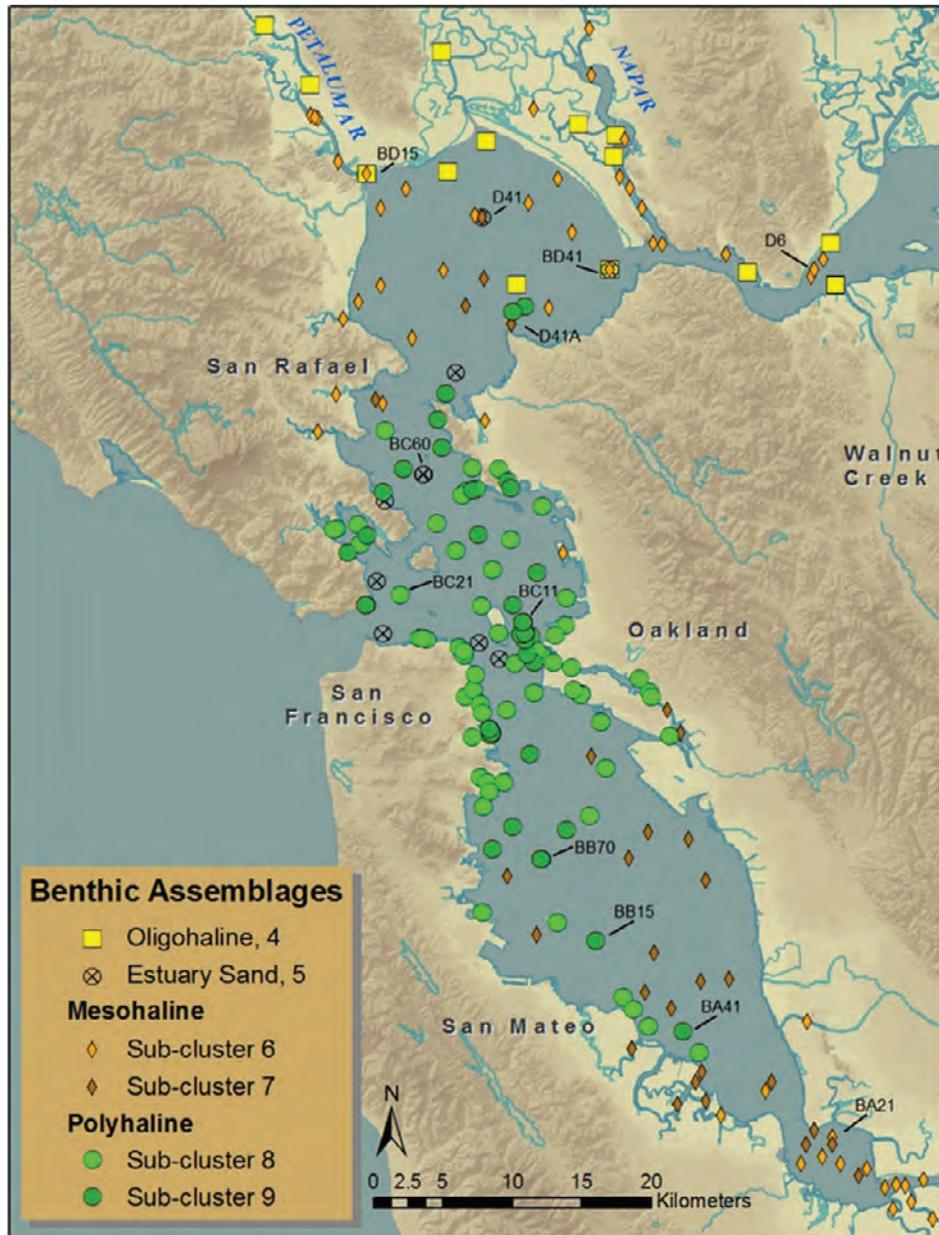


Figure 6. San Francisco Bay benthic assemblages (Thompson and others, 2013). We focused on the polyhaline benthic assemblage in Central Bay. The average salinity in this assemblage is 30.4 parts per thousand. Sub-clusters eight and nine are dominated by the amphipods, *Ampelisca abdita* and *Monocorophium acherusicum*, and sub-cluster eight has high densities of polychaetes, *Mediomastus* spp. and *Dorvillea (Schistomeringos) annulata*.

For our pilot study, we selected sites Pier 32, Mooring Road, Richardson Bay Marina, Paradise Cay HOA, and Strawberry Channel (table 3, figs. 7–11). Pilot study samples from both the undredged and dredged areas at Pier 32 indicated the site was dominated by polychaetes, which differed from the overall community composition at the other sampling sites (De La Cruz and others, 2017). This site was also the farthest south of the five pilot sites, and although still in the polyhaline region of San Francisco Bay, may have environmental conditions that differ from sites to the north. To reduce the variability that could be related to a non-representative study site, we removed Pier 32 from our site list, retained the other pilot study sites, and added two additional sites, Loch Lomond Marina and Paradise Cay Yacht Harbor (hereafter Yacht Harbor; both dredged in 2015; figs. 12–13), for a total of six study sites for the full study. Among the six marinas chosen for the full study, there were two marinas in each of three dredging time periods: 2013, 2014, and 2015. These sites were evenly divided among three embayments within the Central Bay polyhaline region (fig. 6).

Power Analyses

After an extensive search during our Phase I literature review, we were unable to locate an appropriate existing Central Bay macroinvertebrate dataset 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 (fig. 5) as a proxy for the expected variability in the Central Bay.

We used a data-derived, simulation-based power analysis that was designed to consider variation within replicates and transects to inform the total number of transects and cores in our sampling design. In the initial step of our power analysis, we used an information-theoretic model selection framework (Akaike's information criterion [AIC]; Burnham and Anderson, 2002) to identify the most parsimonious model for each taxon. We separately modeled densities of each broad taxa group using linear mixed models (PROC Mixed, SAS 9.3, SAS Institute Inc., Cary, North Carolina, U.S.A.). We used normal approximation models where the dependent variable was the log-transformed count ($x + 0.5$) for each taxon. We built the same candidate set of models for each taxon that included all possible combinations of month and year, elevation, and the interaction of these terms as fixed effects and included site, the number of transects, and the number of cores as random effects.

For each taxon, we identified the top model 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 10 different sample sizes representing different combinations of sites, transects, core locations, and core replicates (table 4). Because 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 percent owing to dredging. For each taxonomic group, we ran 1,000 simulations per sample size and reduction scenario and calculated power as the proportion of simulations in which a significant effect ($\alpha=0.05$) was detected.

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 Dumbarton site macroinvertebrate data were appropriate for a Central Bay study given the potential differences in taxa between the two areas. We used the methods described above for the initial power analysis prior to the pilot study and updated the taxonomic groups detected in the pilot study to include Amphipoda, Bivalvia, Cumacea, Isopoda, Nematoda, Oligochaeta, and Polychaeta. We simulated datasets based on 0, 25, 50, and 75 percent reduction in macroinvertebrate counts between undredged reference and dredged areas using levels of sampling variation in the pilot study.

For both power analyses, we used 80 percent power (Steidl and others, 1997; Quinn and Keough, 2002; Di Stefano, 2003) as the minimum acceptable value for identifying a difference in macroinvertebrate density between dredged and undredged areas. In both analyses, we found that power generally increased for all taxa as the number of samples increased (figs. 14–15). In the initial analysis using the Dumbarton dataset, power to determine a 50 percent reduction in density reached >80 percent under the scenario containing 200 cores for all taxa except errant polychaetes, which did not reach 80 percent power until the sample size was 320 cores (fig. 14). Power to determine a 25 percent or less difference between dredged and undredged sites was low for several taxa and did not reach 80 percent power for most taxa even at a sample size of 400 cores (fig. 14).

In the second power analysis using the pilot study dataset, power to determine a 50 percent reduction in density reached >80 percent under the scenario containing 100 cores for all taxa except for amphipods and polychaetes, which both reached 80 percent power with a sample size of 200 cores (fig. 15). For bivalves, cumaceans, isopods, and nematodes, the power to determine a 25 percent or less difference between dredged and undredged sites reached 80 percent power with a sample size of 200 cores; however, oligochaetes only reached 80 percent under 400-core scenarios, and amphipods and polychaetes did not reach 80 percent at any sample size (fig. 15).



Figure 7. Paradise Cay Homeowners Association (HOA) study site composed of residential docks and berths in western San Francisco Bay. Sampled as part of the pilot and full study. The white outlined area was dredged to 8 feet mean lower low water (MLLW) in 2014. The site contains 24 core locations in the dredged area and 21 undredged reference core locations collected along 3 transects of 6 core locations in dredged marina, 1 transect of 6 core locations in dredged entrance channel, 1 reference transect of 6 core locations with 3 transects of 5 core locations extending from reference transect to dredged entrance channel transect.



Figure 8. 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 the pilot and full study. The white outlined area was dredged to 7 feet mean lower low water (MLLW) in 2014. The site contains 10 core locations in the dredged area and 12 undredged reference core locations collected along 1 transect of 10 core locations and 1 transect of 7 core locations in the dredged marina/channel, 1 reference transect of 7 core locations with 3 transects of 5 core locations extending from reference transect to dredged entrance channel transect.

Sampling Design

Given the scope and budget of the study, we determined that a design to detect a 50 percent reduction in individuals between dredged and undredged areas was most feasible. Thus, we designed the sampling effort to meet or exceed the 200-core sample size identified by the pilot data power analysis as robust for all taxonomic groups. Within each marina, we placed two to six transects in each dredged and undredged location. From each transect, we sampled a minimum of six core locations with two replicate samples taken at each core location (figs. 7–13).

Sampling was conducted seasonally in winter and summer to assess the greatest differences in seasonal variation in macroinvertebrate density and biomass. The inclusion of multiple collection periods enabled us to compare macroinvertebrate density and community composition during

wet and dry seasons and across a range of seasonal salinities—one of the major drivers of macroinvertebrate community composition (Nichols and Pamatmat, 1988; Thompson and others, 2013; De La Cruz and others, 2016). The summer sampling periods overlapped with the period of peak fish densities in the Central Bay and provided information on macroinvertebrate densities when most focal fish species were present (De La Cruz and others, 2016). To evaluate the effect of time-since-dredging on trophic support for fishes, we measured macroinvertebrate density and biomass at marinas that had been dredged 1, 2, and 3 years prior to sampling. To assess the effect of distance to nearest dredge site on macroinvertebrate density and biomass, we evenly spaced sampling locations within each transect 20 m apart from each other and ran transects perpendicular to dredged areas so that distances up to 120 m away from dredged areas could be evaluated.



Figure 9. Richardson Bay Marina study site composed of marina docks and an undredged reference area northeast of the marina. Sampled as part of the pilot and full study. The white outlined area was dredged to 10.5 feet MLLW (mean lower low water) in 2013. The site contains one transect of 10 core locations taken in the dredged area between docks and another transect of 10 core locations in the area between docks that was dredged in 1994. Two reference transects of six core locations each extend from the marina.

Sample Processing

Sample Collection

We conducted sampling during two wet (as in, winter) and two dry (as in, summer) time periods throughout the course of the study: November 2015–December 2015 (pilot sampling), August 2016, January 2017, and August 2017. Based on our sampling design, each site had two to six transects per dredged and undredged site in a marina and a minimum of six core locations per transect. 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. Cores were systematically separated into shallow (0–4 cm) and deep (4–10 cm) increments to measure prey distribution at different depths in the sediment according to MBRAT methodology (figs. 1, 3).

Upon arrival to and departure from sampling sites, water quality (temperature, salinity, dissolved oxygen, and pH) was recorded within dredged and undredged areas of each marina using a multi-parameter sonde (YSI Professional Plus, YSI, Inc., Yellow Springs, Ohio) just above the benthic surface in the demersal zone. The water depth at individual core locations along each transect was recorded using a ReefNet[®] Sensus Ultra Depth Recorder (ReefNet, Inc., Niagra Falls, New York) attached to the coring device and corrected for MLLW tide height at the time of recording. Sediment cores were collected at the mid-point of each transect and sent to an external laboratory (AandL Western Laboratories, Modesto, California) to determine sediment grain size and chemical composition (organic matter, sediment texture, sediment pH).

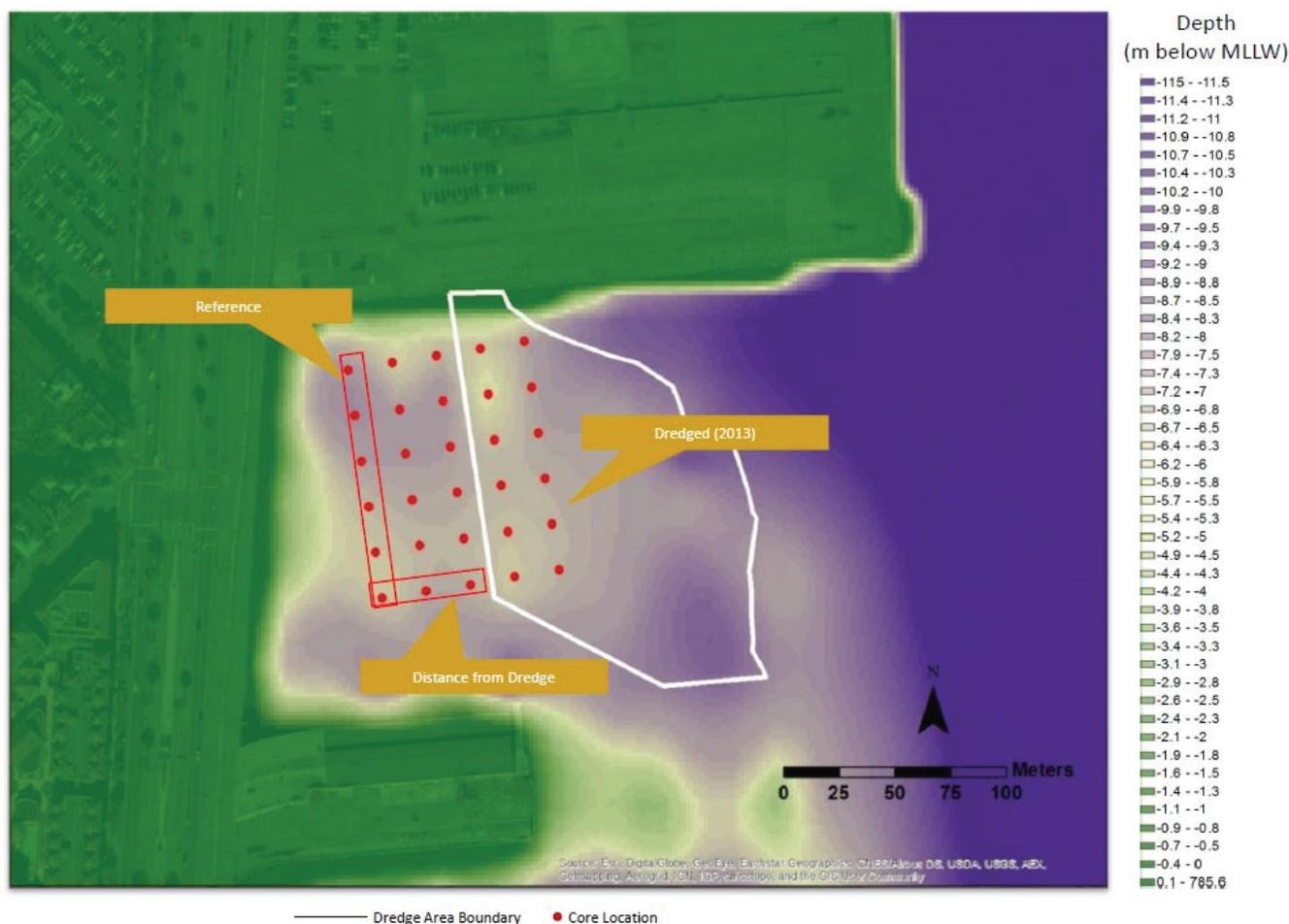


Figure 10. Port of San Francisco Pier 32 study site composed of an area between piers 32 and 36 in San Francisco. This site was only sampled as part of the pilot study. The white outlined area was dredged to 12 feet MLLW (mean lower low water) in 2013. The site contains 12 core locations in the dredged area and 18 undredged reference core locations collected along 2 transects of 6 core locations in the dredged marina/channel and 3 parallel transects of 6 core locations in the reference area between the dredged area and the shore.

Cores were immediately transported to the USGS Invertebrate Ecology Laboratory on ice and refrigerated until processed. Within 1–2 days, cores were rinsed through a 500-micrometer (μm) mesh sieve, and fauna were retained by the sieve were preserved in a 70 percent ethanol with 1 percent rose bengal dye. All taxa within cores were sorted, identified, and enumerated. During all sampling periods except the pilot (November–December 2015), macroinvertebrates were sorted into four size-classes based on target fish foraging ecology: 0–4 mm, 4–12 mm, 12–24 mm, and 24–50 mm. Taxa from all samples were identified to a broad taxonomic level (class, order); however, macroinvertebrates in six cores that were randomly selected from each site (three from dredged locations and three from undredged locations) during each sampling period were identified to the lowest possible taxonomic level (family, genus, species). We determined the

number of cores in which macroinvertebrates were identified to the lowest possible taxonomic level by processing multiple cores from each pilot sampling site until the number of new species found reached an asymptote.

Internal laboratory quality control measures included resorting and identifying a minimum of 10 percent of samples by a technician with equivalent or greater experience compared to the original sorter. This process was repeated until maximum error percentages were less than 10 percent for each sorter. We also sent sorted taxa from two randomly selected cores from each marina and time period to an external laboratory (EcoAnalysts, Inc., Moscow, Idaho) for identification to lowest taxonomic level. This was done both as a quality assurance measure to verify our in-house identification and to build a reference collection for more rapid and precise identification of future samples.



Figure 11. Mooring Road study site composed of dredged areas around residential docks in tidally influenced San Rafael Creek. Sampled as part of the pilot and full study. The white outlined area was dredged to 6 feet MLLW (mean lower low water) in 2013. The site contains 7 core locations in the dredged area and 12 undredged reference core locations collected along 1 transect of 7 core locations in dredged areas and 1 transect of 12 reference core locations that runs parallel to the dredged transect for 7 core locations and continues downstream from dredging for 5 core locations.

Macroinvertebrate Density, Biomass, and Energy Estimations

The density of macroinvertebrates at each core depth from each taxon and size class was calculated by averaging the densities from two replicate cores. Using the six cores from each site and season in which macroinvertebrates were identified to the lowest possible taxonomic level, we calculated the proportion of each lower taxonomic group within each broad taxonomic group for each size class, treatment (dredged or undredged), and site. We multiplied these proportions by the densities of each broad taxonomic group in each size class and treatment observed in the remaining cores at each site to obtain an estimated density for each lower-taxonomic group in each size class and treatment. Next, we multiplied the observed (from the six cores identified to lowest taxonomic level) and estimated (from the remaining cores identified to broad taxonomic level) densities of macroinvertebrates in each taxonomic group and size class by the mean biomass per individual of that taxon and size class.

To determine mean biomass per individual for a given taxon and size class, macroinvertebrates were dried in a precision convection oven at 80 degrees Celsius (°C) for 24 hours and weighed with an A and D Weighing HR-202i

semi microbalance (0.1 mg; Abington, Oxfordshire, United Kingdom). Biomass was estimated for the most abundant taxa (Actiniaria, Amphipoda, Bivalvia, Copepoda, Corixidae, Cumacea, Decapoda, Errantia polychaeta, Gastropoda, Isopoda, Leptostraca, Nemertea, Oligochaeta, Ostracoda, Sedentaria Polychaeta, Tanaidacea, Sipuncula, Tunicata). Because of their limited densities, it was not possible to measure biomass for rare taxa, but the biomass of these taxa was considered negligible. When a broad taxonomic group was not present in any of the cores identified to the lowest possible taxonomic level, we used the average biomass of all possible lower taxonomic groups within that broad taxonomic group. We determined secondary production of each site by calculating the energy available to benthic foraging fishes. We calculated macroinvertebrate energy content (in kilojoules, kJ) using published conversion factors (Cummins and Wuycheck, 1971; Ricciardi and Bourget, 1998; Brey, 2001; Cauffope and Heymans, 2005) to convert dry biomass to ash-free dry biomass (AFDM) and AFDM to energy (kJ). Because biomass is size-dependent and macroinvertebrates were not separated into size classes during the pilot study, we did not calculate biomass or energy content for pilot study samples.

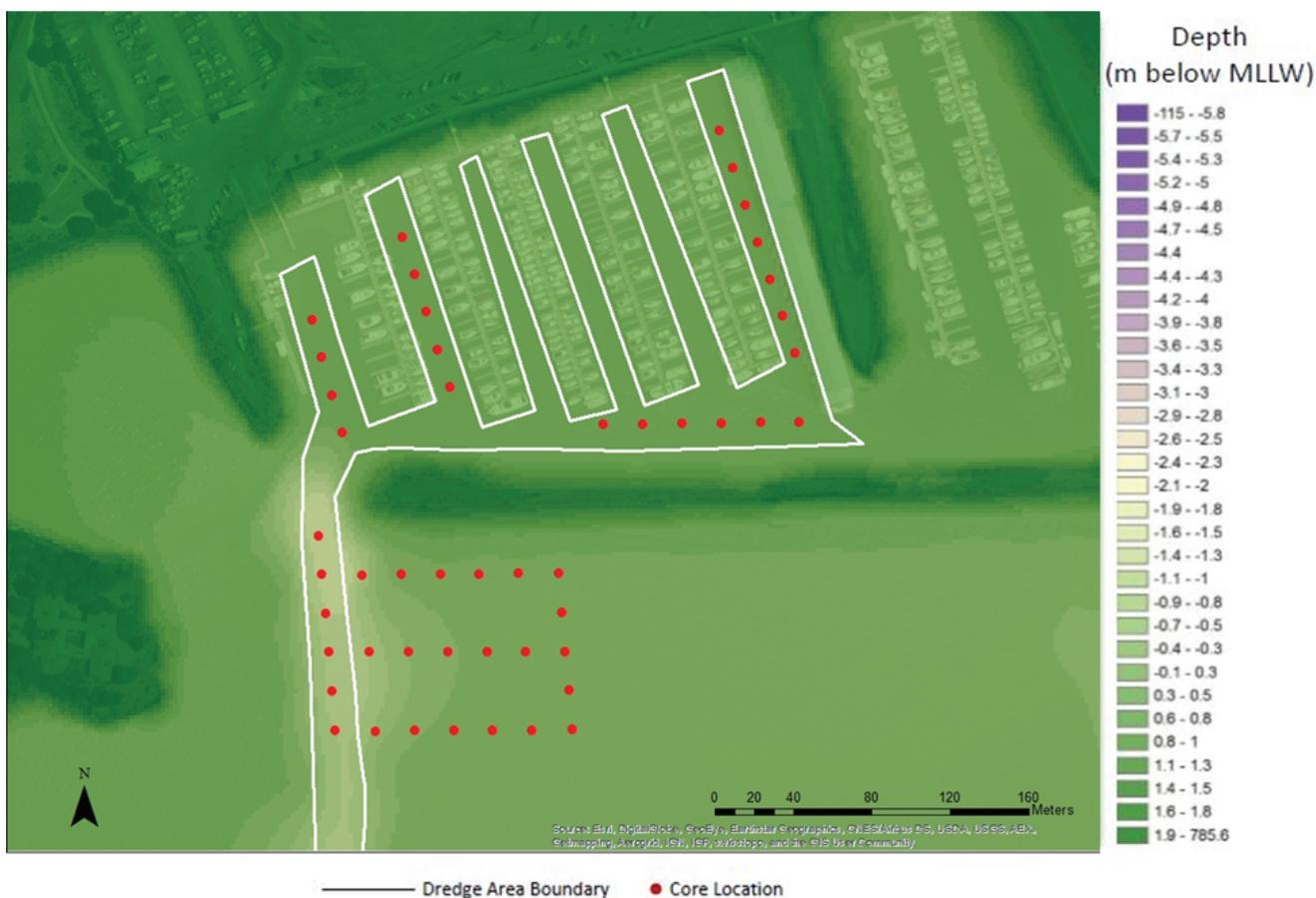


Figure 12. Loch Lomond Marina study site composed of a marina and entrance channel in San Rafael Bay sampled as part of the full study. The white outlined area was dredged to nine feet MLLW in 2015. The site contains 28 core locations in the dredged area and 20 undredged reference core locations collected along 4 transects of 4 to 7 core locations in the dredged marina, 1 transect of 6 core locations in the dredged entrance channel, 1 reference transect of 5 core locations, and 3 transects of 5 core locations extending from the reference transect to the dredged entrance channel transect.

Statistical Analyses

We evaluated differences in salinity, bathymetry, and sediment characteristics that could influence macroinvertebrate density and biomass among sites using general linear models (GLMs) and linear discriminant function (LDF) analysis. We tested differences in the elevations of core locations among sites and differences in average demersal zone salinity among sites and sampling periods using GLMs. Differences in sediment characteristics including pH, percent organic matter, percent sand, and percent silt were tested among sites and

between dredged and undredged areas using LDF analysis with the package `klaR` (Weihs and others, 2005) in R v.3.4.1 (R Development Core Team, 2017). We included percent clay in figures, but not in statistical analyses because percent sand, percent silt, and percent clay for a single sample add up to 100 percent. Thus, they were perfectly correlated so only two of the three variables could be included in analyses. All variables were centered and scaled prior to LDF, and statistical significance of sediment characteristics was determined with forward, stepwise selection using the Wilks' Lambda (λ) criterion.

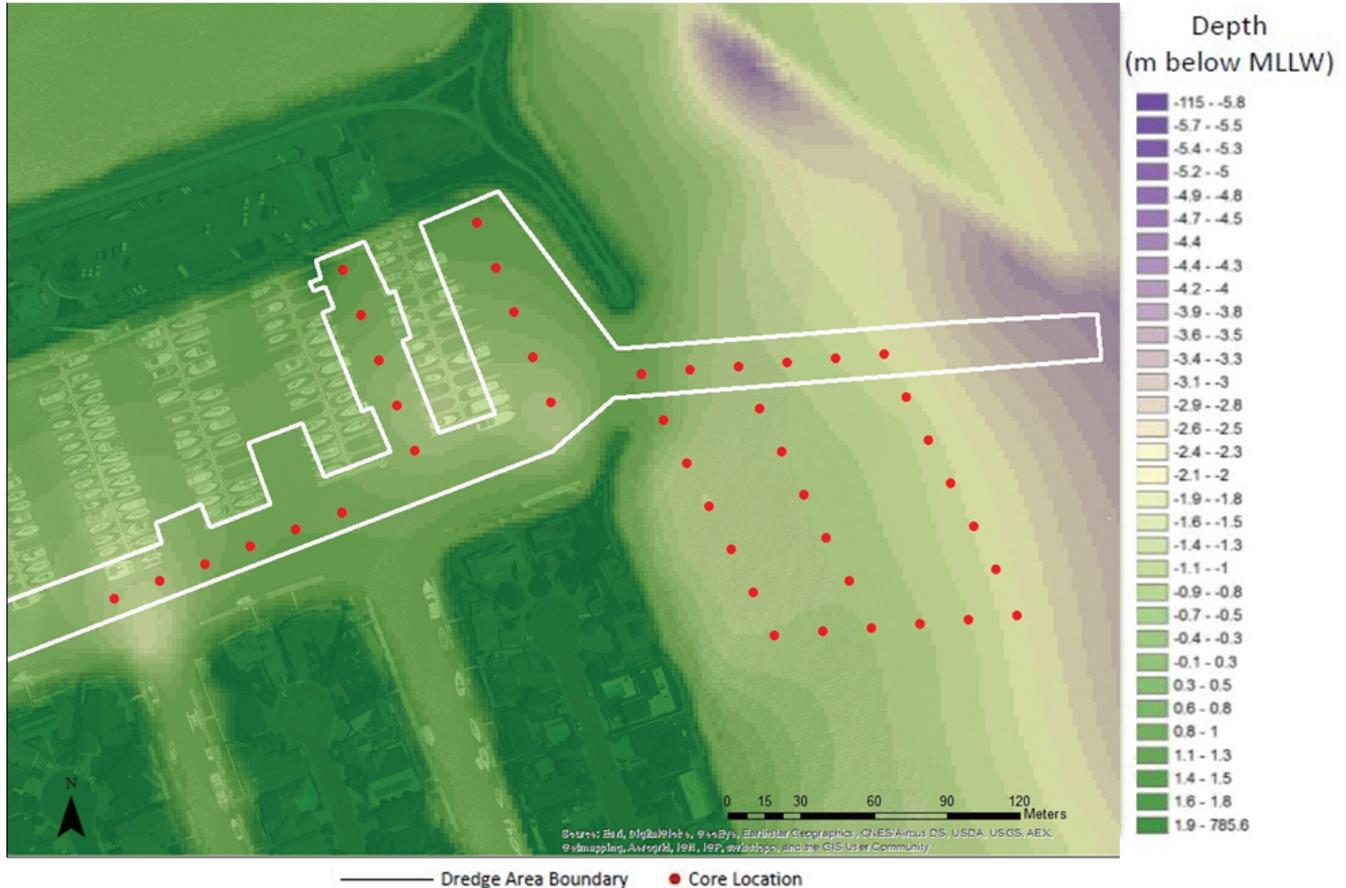


Figure 13. Paradise Cay Yacht Harbor study site composed of a marina and entrance channel in western San Francisco Bay. Sampled as part of the full study. The white outlined area was dredged to 10 feet MLLW (mean lower low water) in 2015. The site contains 22 core locations in the dredged area and 21 undredged reference core locations collected along 3 transects of 5 to 6 core locations in the dredged marina, 1 transect of 6 core locations in the dredged entrance channel, 1 reference transect of 6 core locations, and 3 transects of 5 core locations extending from the reference transect to the dredged entrance channel transect.

We assessed the effects of treatment (dredged versus undredged), time-since-dredging, and distance to the nearest dredged area separately on three response variables: (1) density (individuals per square meter [m^2]), (2) dry biomass (grams per square meter [g/m^2]), and (3) energy content (kilojoules per square meter [kJ/m^2]) of macroinvertebrates using generalized linear mixed models (GLMMs) with the *gamlss* package (Stasinopoulos and Rigby, 2007) in R v.3.4.1 (R Development Core Team, 2017). For each response variable, we ran GLMMs for five different datasets that represented the spectrum of macroinvertebrate prey available to benthic foraging fishes: (1) 0–4 mm macroinvertebrates in surface cores (0–4 cm deep); (2) 4–12 mm macroinvertebrates in surface cores; (3) 12–24 mm macroinvertebrates in surface cores; (4) 24–50 mm macroinvertebrates in surface cores; and (5) 0–50 mm macroinvertebrates in whole cores (0–10 cm deep). For whole cores, macroinvertebrate size classes were combined because fish that could exploit this depth could also consume all prey sizes considered.

The GLMMs that tested the effects of treatment and distance to the nearest dredged area included macroinvertebrate data from cores collected in dredged and undredged areas, but GLMMs that tested the effect of time-since-dredging included data from cores collected in dredged areas only. The effect of distance to the nearest dredged area was tested to evaluate both the effect size of a dredged area, as well as to provide insight on species-specific recolonization of dredged sites from adjacent undredged areas. All GLMMs were run using a zero-adjusted gamma distribution because our macroinvertebrate datasets were zero-inflated. We included season, salinity, and elevation of the core location in all models as fixed effects. We determined the best random effects structure for GLMMs by comparing AIC scores among models with and without each of the random effects. Site and transect were included as random effects in GLMMs that tested the effects of treatment and distance to the nearest dredged area, and site was included as a random effect in GLMMs that tested the effect of time-since-dredging.

Table 4. Sampling scenarios used in simulation power analyses to determine project sample size. Scenarios had a variable number of sites (marinas), and each marina had one dredged and one undredged area.

[Scenarios had a variable number of sites (marinas), and each marina had one dredged and one undredged area. Within each of these areas we varied the number of transects, cores, and core replicates.]

Site (marina)	Areas (dredged and undredged)	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

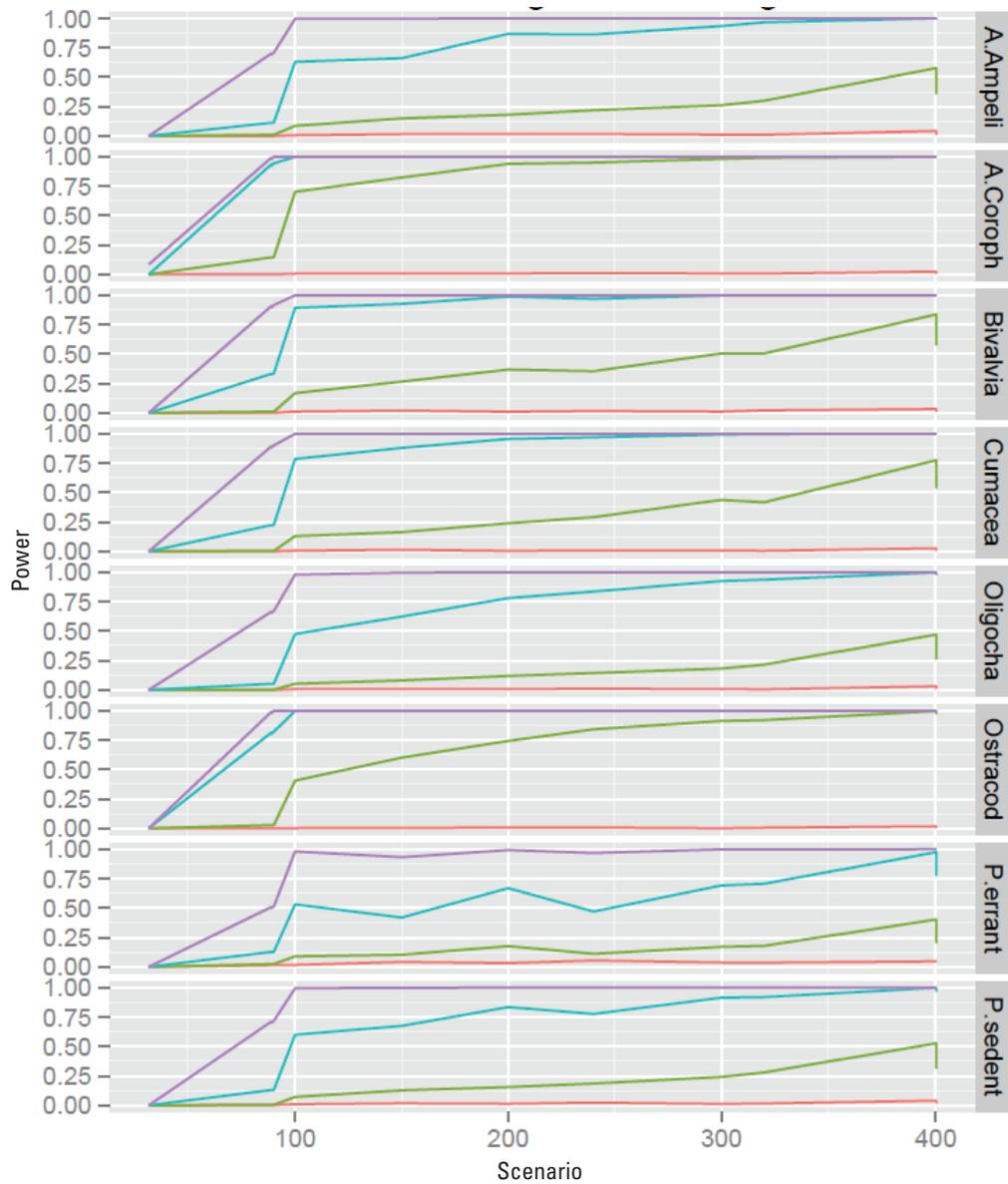


Figure 14. Power analysis curves for individual taxa groups based on the comprehensive U.S. Geological Survey Dumbarton macroinvertebrate dataset. Scenarios depicted on the x-axis are for 10 simulated datasets (listed in table 1) representing different combinations of sites, transects, and replicate cores. The y-axis indicates the percent power to determine the difference between dredged and undredged areas. Colored lines represent macroinvertebrate reductions of 0 percent (red), 25 percent (green), 50 percent (blue), and 75 percent (purple) owing to dredging.

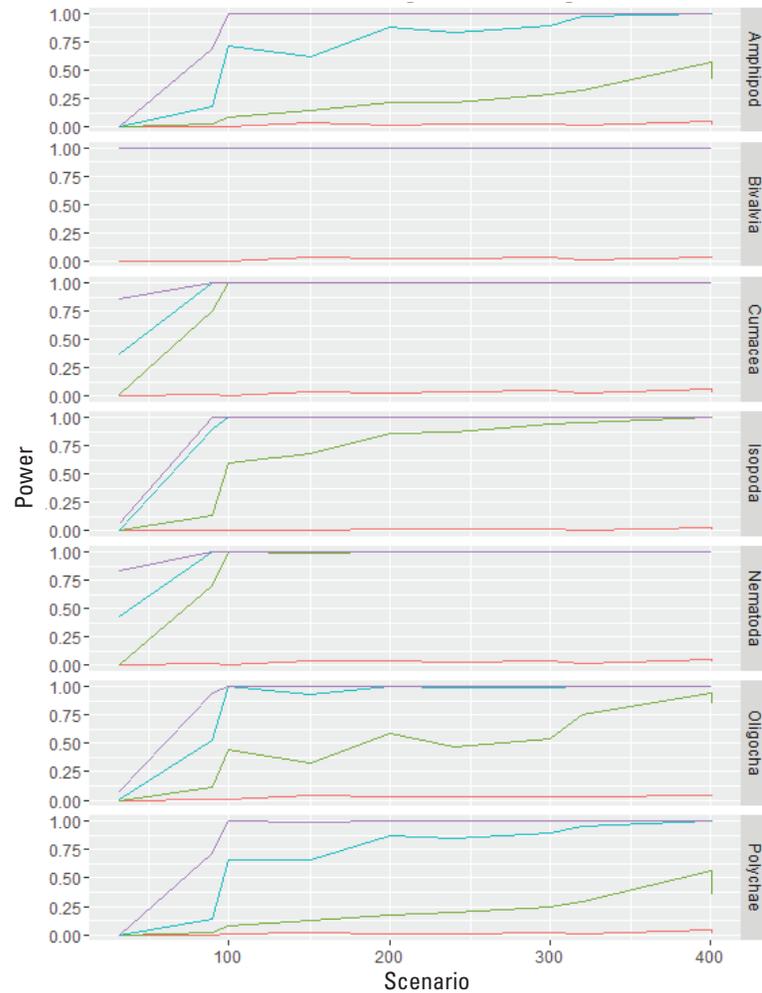


Figure 15. Power analysis curves for individual taxa groups based on the 2015 pilot study macroinvertebrate dataset. Scenarios depicted on the x-axis are for 10 simulated datasets (listed in [table 4](#)) representing different combinations of sites, transects, and replicate cores. The y-axis indicates the percent power to determine the difference between dredged and undredged areas. Colored lines represent macroinvertebrate reductions of 0 percent (red), 25 percent (green), 50 percent (blue), and 75 percent (purple) owing to dredging.

Results

Salinity, Elevation, and Sediment Characteristics Among Sites

Overall, demersal zone salinities measured during the winter sampling period of January 2017 were significantly lower at all sites than salinities measured during the other sampling periods (table 5), reflecting the unusually heavy rainfall from a series of atmospheric rivers during this season. Despite some significant differences in demersal zone salinity among sites (fig. 16; table 5), we observed the same general pattern at each site; salinities were lowest during the unusually wet January 2017 sampling period and were similar among the pilot sampling period (November–December 2015) and the two summer sampling periods (August 2016 and August 2017; fig. 16). Practical Salinity Unit (psu) measurements ranged from 2.37 at Mooring Road in January 2017 to 32.66 psu at Strawberry Channel in August 2016 (fig. 16). Demersal zone salinities at Richardson Bay and Strawberry Channel had the least seasonal variability (fig. 16). In contrast, large differences between summer and winter demersal salinities were observed at Mooring Road and Yacht Harbor (fig. 16).

Among sites, elevation of core locations ranged from –2.2 m to 0.3 m, with both the highest and lowest points at Yacht Harbor. We observed notable differences in core elevations among sites (table 6), but generally, elevations at all

sites fell within a relatively narrow range (fig. 17). In addition, core elevations at dredged and undredged areas were similar within sites (fig. 17).

Sediment characteristics including percent organic matter, pH, percent sand, percent silt, and percent clay were not different between shallow (0–4 cm) and deep (4–10 cm) core segments within each site (figs. 18–23). Three sediment characteristics, percent silt ($\lambda = 0.77$, $p < 0.001$), percent sand ($\lambda = 0.59$, $p < 0.001$), and pH ($\lambda = 0.49$, $p < 0.001$), contributed significantly to an LDF that explained differences in sediments among sites (figs. 18–23). Percent silt ranged from 36.82 ± 1.00 (mean \pm standard error) at Mooring Road to 48.16 ± 1.16 at Yacht Harbor. Percent sand ranged from 14.41 ± 0.92 at Loch Lomond to 24.80 ± 1.28 at Richardson Bay, and mean pH ranged from 6.92 ± 0.07 at Strawberry Channel to 7.27 ± 0.03 at Loch Lomond. In addition, percent organic matter ($\lambda = 0.84$, $p < 0.001$), percent silt ($\lambda = 0.81$, $p = 0.01$), and percent sand ($\lambda = 0.79$, $p = 0.02$), contributed significantly to an LDF that explained differences in sediment between dredged and undredged areas. Percent organic matter and percent sand (2.48 ± 0.05 and 17.51 ± 0.80), whereas percent silt was greater in undredged areas (47.69 ± 0.75) compared to dredged areas (42.58 ± 0.56 ; figs. 18–20). Despite these significant differences, sediment texture based on percent sand, silt, and clay was similar among sites and between dredged and undredged areas, with most sediments classified as loams with high percentages of silt or clay (fig. 23).

Table 5. General Linear Model (GLM) results for demersal salinity as a function of site (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) and sampling period (November 2015, August 2016, January 2017, and August 2017).

[Loch Lomond is the reference site, and November 2015 is the reference sampling period for the analysis. **Abbreviation:** <, less than]

Fixed effect	Estimate	Standard error	Z-value	p
Intercept	28.731	1.850	15.534	<0.001
Site: Mooring Road	–4.205	1.632	–2.577	0.013
Site: Paradise Cay	–0.177	1.600	–0.111	0.912
Site: Richardson Bay	4.669	1.620	2.882	0.006
Site: Strawberry Channel	5.179	1.653	3.132	0.003
Site: Yacht Harbor	–1.408	1.690	–0.833	0.409
Sampling 2016-8	0.919	1.574	0.584	0.562
Sampling 2017-1	–14.736	1.559	–9.454	<0.001
Sampling 2017-8	–0.513	1.574	–0.326	0.746

Table 6. General Linear Model (GLM) results for core elevation as a function of site (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Loch Lomond is the reference site for the analysis. **Abbreviation:** <, less than]

Fixed effect	Estimate	Standard error	Z-value	p
Intercept	–0.412	0.065	–6.368	<0.001
Site: Mooring Road	0.278	0.121	2.290	0.023
Site: Paradise Cay	–0.537	0.093	–5.778	<0.001
Site: Richardson Bay	–0.506	0.102	–4.951	<0.001
Site: Strawberry Channel	0.111	0.097	1.148	0.252
Site: Yacht Harbor	–0.759	0.094	–8.073	<0.001

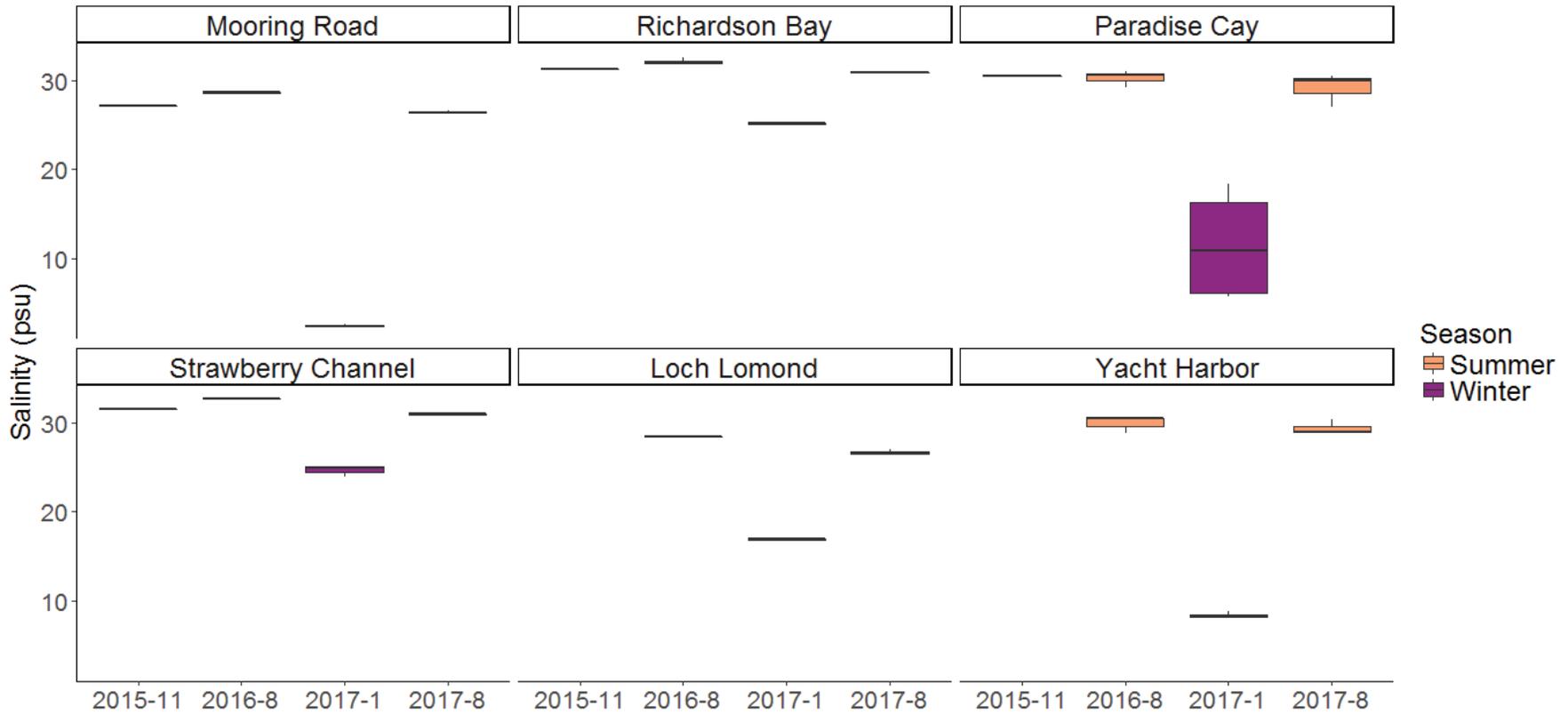


Figure 16. Summer and winter demersal salinity (psu) at six coring sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) during four sampling periods (November 2015, August 2016, January 2017, and August 2017). Boxes show values of the first and third quartiles around the median. Whiskers extend to 1.5-times the interquartile range.

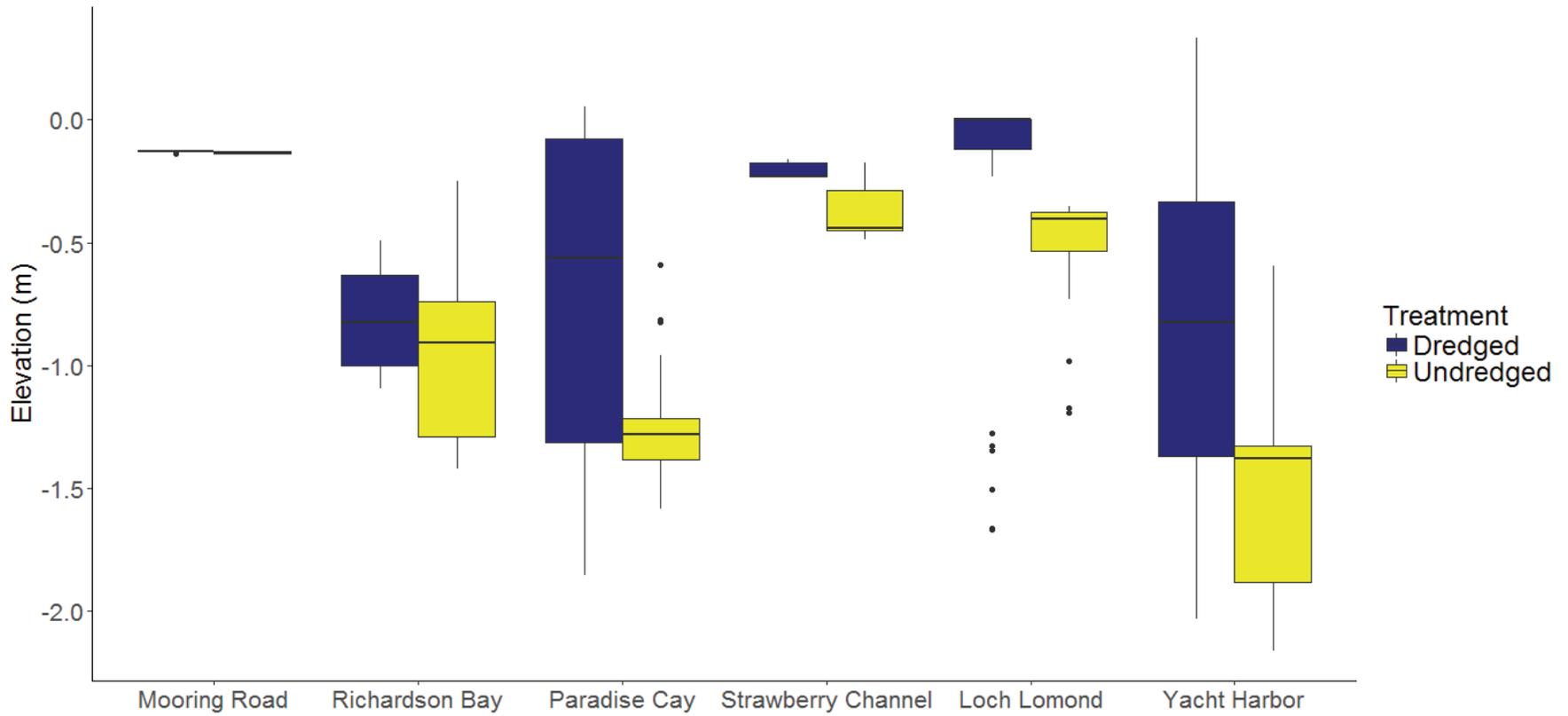


Figure 17. Elevation (meters) in dredged (blue) and undredged (yellow) areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor). Boxes show values of the first and third quartiles around the median. Whiskers extend to 1.5-times the interquartile range.

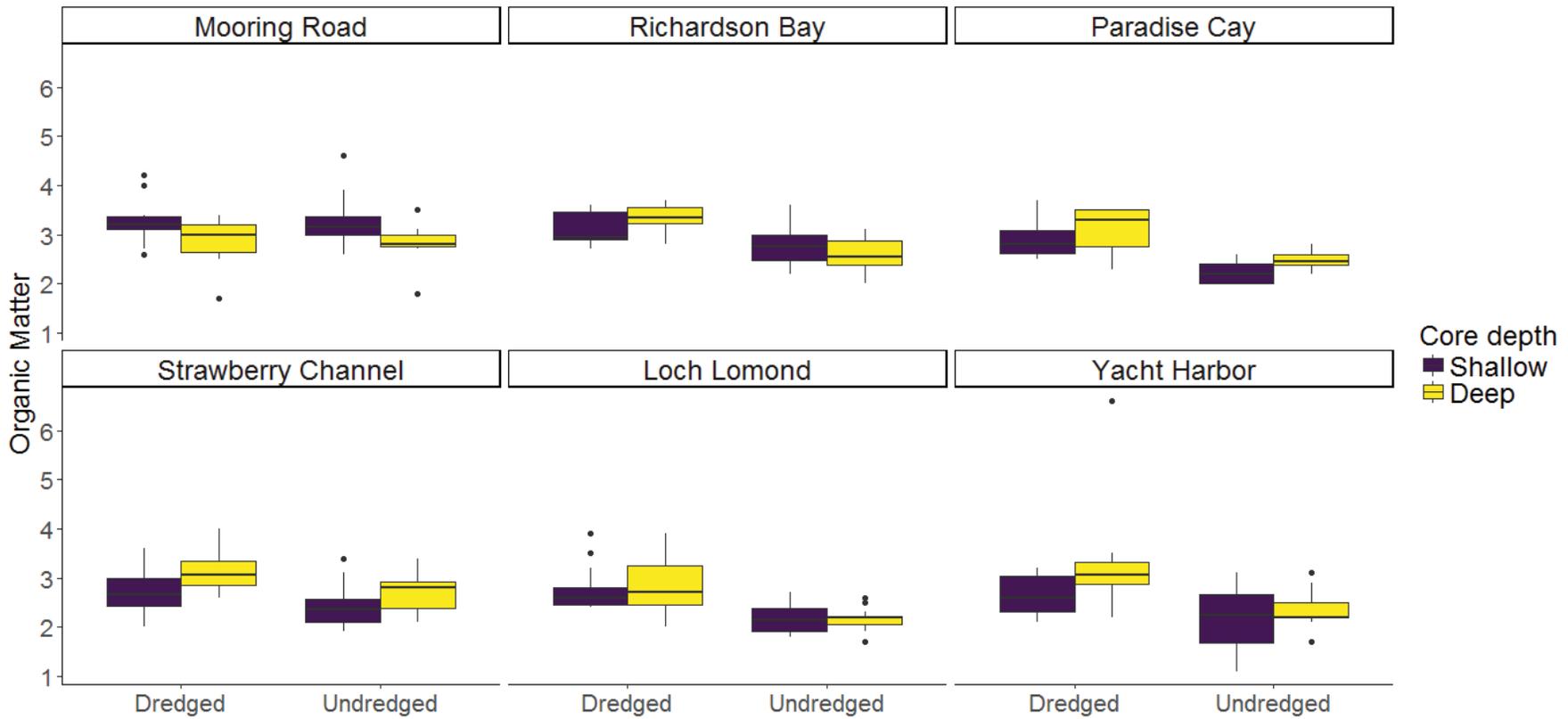


Figure 18. Sediment organic matter content measured as percent loss on ignition in shallow (0–4 centimeters [cm]; purple) and deep (4–10 cm; yellow) cores of dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay.

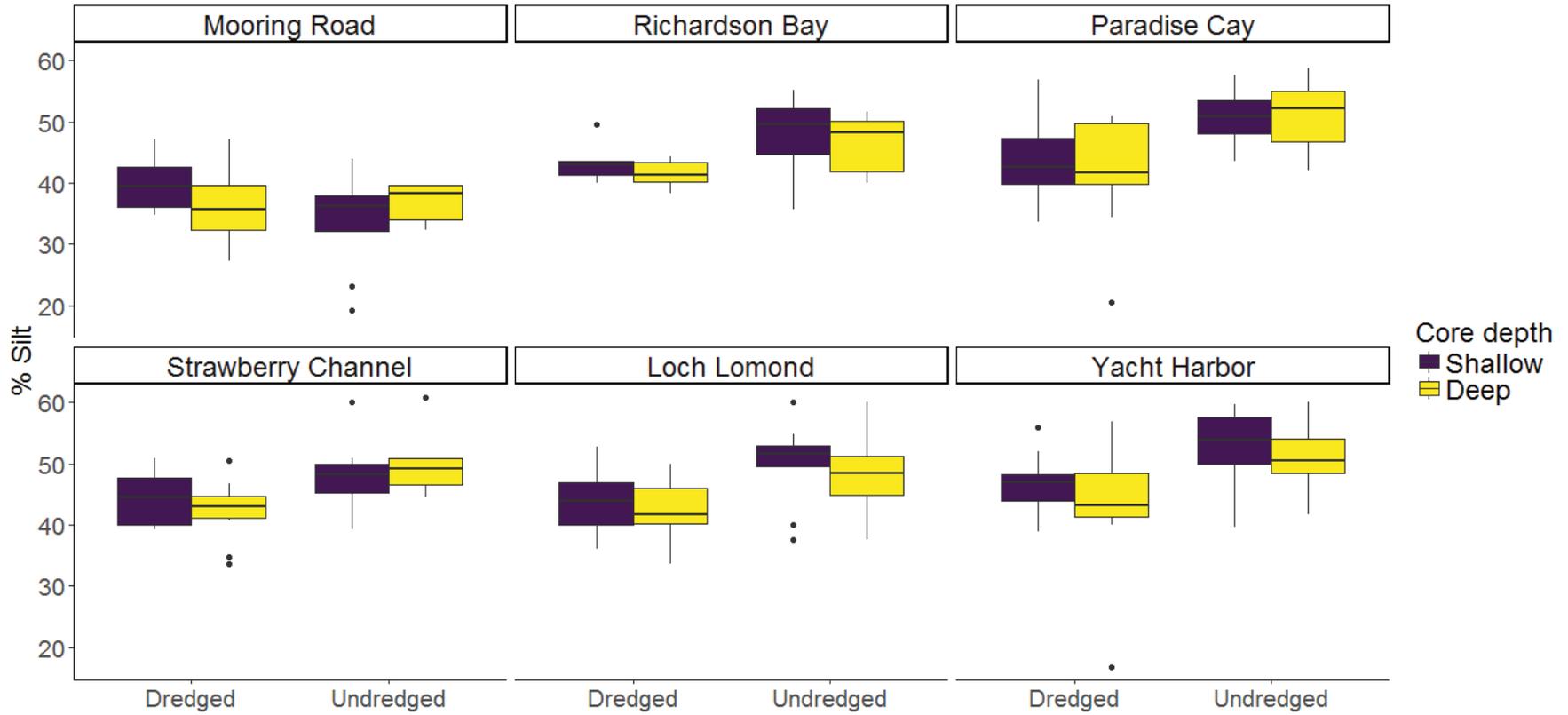


Figure 19. Percent silt in sediments from shallow (0–4 centimeters [cm]; purple) and deep (4–10 cm; yellow) cores of dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay.

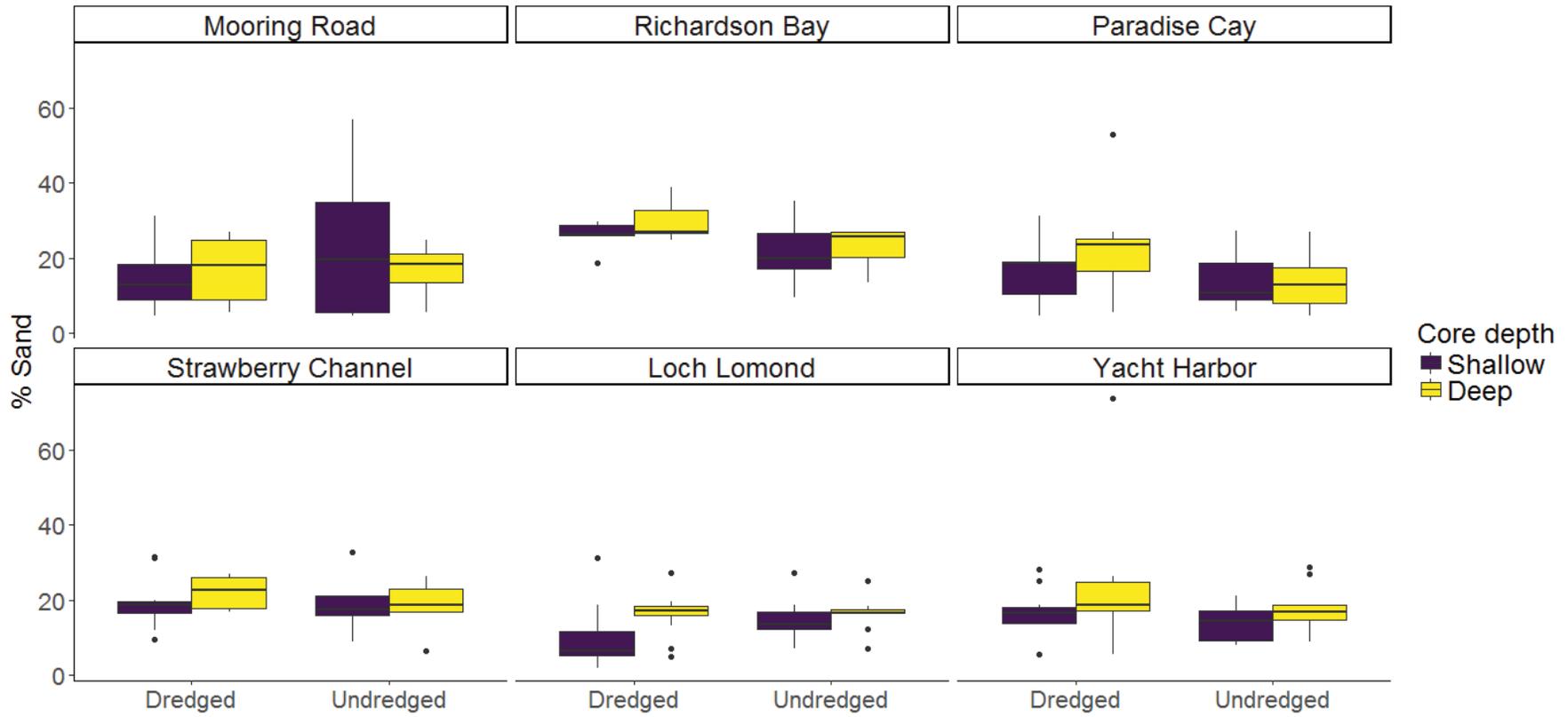


Figure 20. Percent sand in sediments from shallow (0–4 centimeters [cm]; purple) and deep (4–10 cm; yellow) cores of dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay.

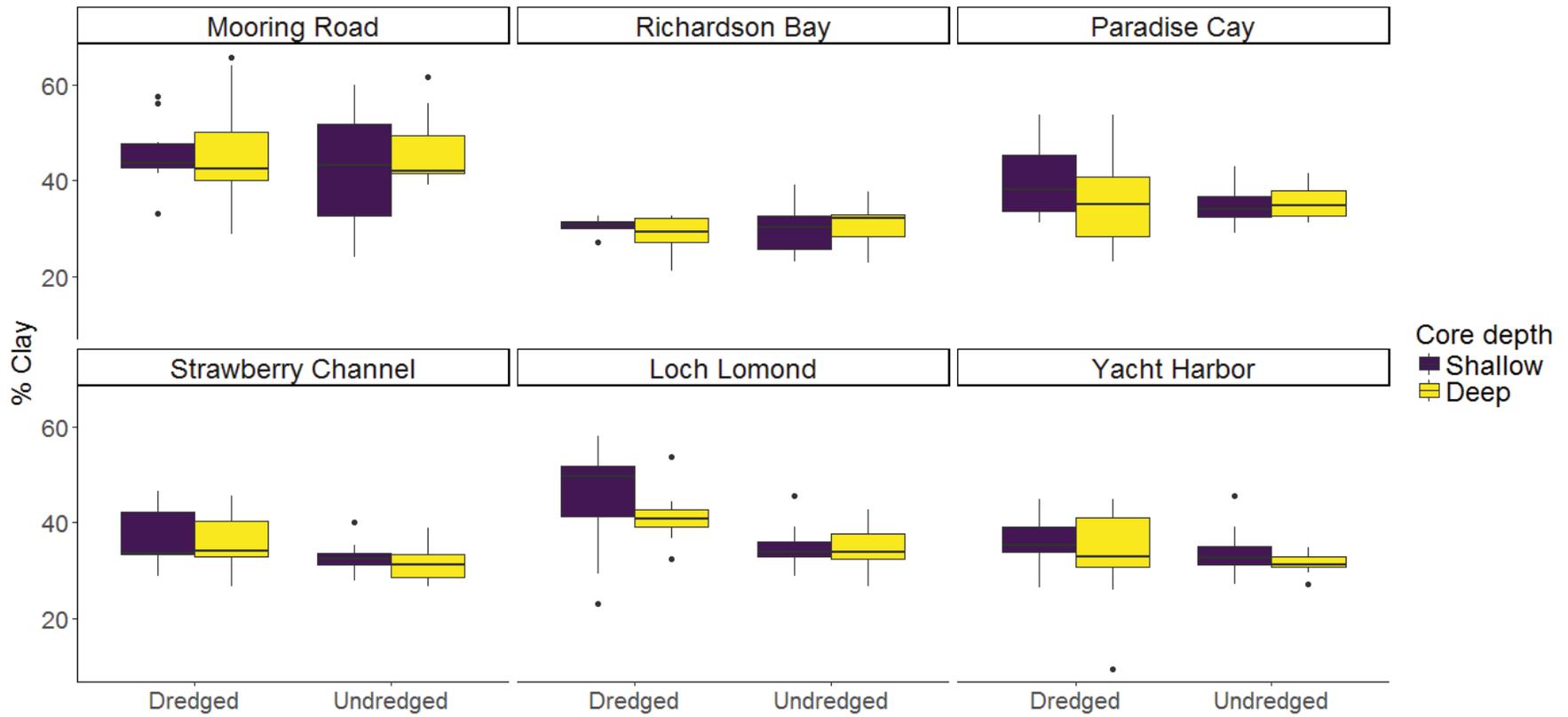


Figure 21. Percent clay in sediments from shallow (0–4 centimeters [cm]; purple) and deep (4–10 cm; yellow) cores of dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay.

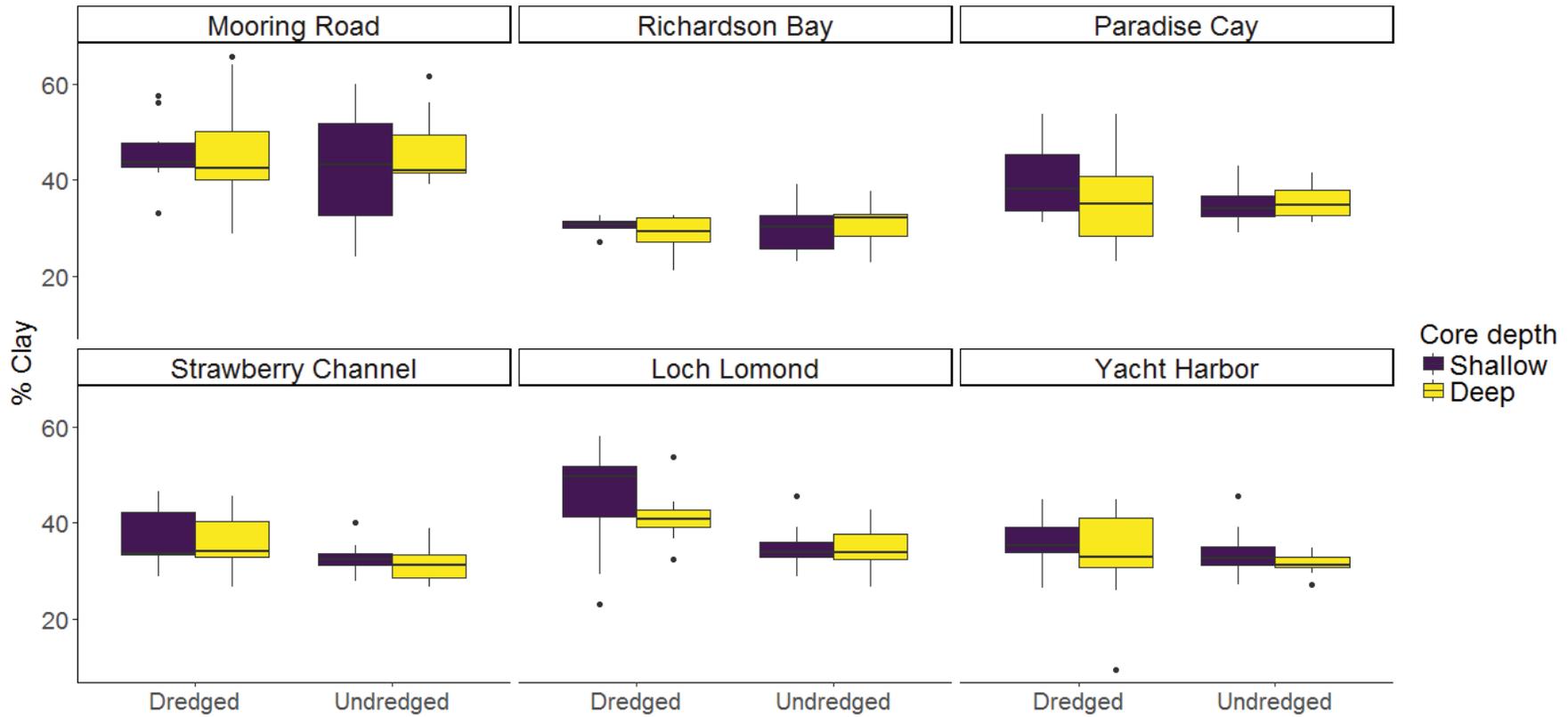


Figure 22. Sediment pH measured in shallow (0–4 centimeters [cm]; purple) and deep (4–10 cm; yellow) cores of dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay.

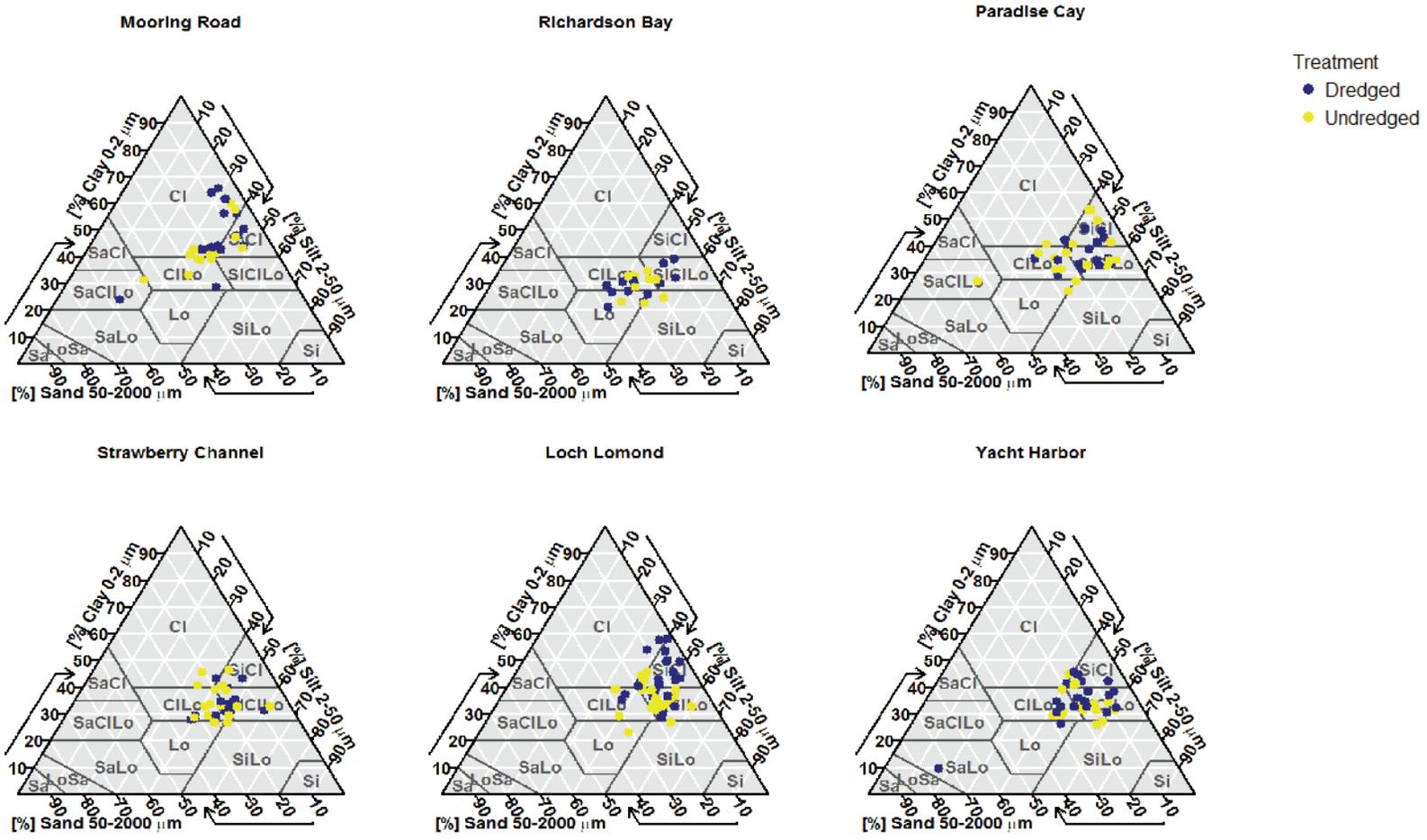


Figure 23. Sediment triangles used to classify sediment texture with percent sand, percent silt, and percent clay from sediments collected in dredged (blue) and undredged (yellow) areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Textures abbreviations: Sand (Sa), Silt (Si), Clay (Cl), Loam (Lo).

Within-Site Macroinvertebrate Community Composition, Density, Biomass, and Energy Content

We collected a total of 1,644 whole benthic cores: 288 during the pilot sampling effort and 1,356 during the full study. We identified 33 broad taxonomic groups of macroinvertebrates among the 6 sampling sites and 4 sampling dates. Although the focus of our study was on the foraging value of broad taxonomic macroinvertebrate groups, we identified organisms from a random subsample of cores from each site to lowest taxa as a measure of structural recovery. We detected 104 distinct taxa in the shallow (0–4 cm) depth (table 7) compared to 43 taxa in the deep (4–10 cm) depth range (table 8). Within the surface sediments (0–4 cm), we generally found a greater taxonomic richness in undredged areas compared to dredged areas (undredged:dredge taxonomic richness ratio; 1.3 Loch Lomond, 1.4 Mooring Road, 1.2 Paradise Cay, 0.9 Richardson Bay, 1.5 Strawberry Channel, and 1.9 Yacht Harbor). In the shallow sediments of Richardson Bay, we detected greater taxonomic richness within dredged areas compared to undredged (dredge area 59 taxa, undredged area 52 taxa). A similar pattern was also observed within deeper sections (4–10 cm) of the sediment profile where most sites had greater taxa richness in undredged areas (undredged:dredge taxonomic richness ratio; 0.9 Loch Lomond, 1.3 Mooring Road, 1.5 Paradise Cay, 1.0 Richardson Bay, 1.3 Strawberry Channel, and 1.7 Yacht Harbor). In the deep cores, we detected greater taxonomic richness within dredged areas compared to undredged at Loch Lomond (dredged area 12 taxa, undredged area 11 taxa).

During our study, we identified 13 adult specimens of the horseshoe shrimp (*Lightiella serendipita*), nearly doubling the number of known samples for this rare endemic Cephalocarid species. Thought to be extinct, this species has not been observed in SFB since 1988 (Jones, 1961; Schemel and others, 1988, 1990), despite previous attempts to locate it during 1997–99 (C. Rogers, University of Kansas, written commun., 2017, 2018) and in 2000 (R. Mooi, California Academy of Sciences, written commun., 2017, 2018). Based on the number of samples we collected, *L. serendipita* had a detection rate of 0.5 percent, making this finding a truly serendipitous rediscovery of the species.

To facilitate statistical analyses and interpretation of functional foraging habitat characteristics for fish, we consolidated macroinvertebrates into broad taxonomic groups (Amphipoda, Bivalvia, Cumacea, Nematoda, Oligochaeta, Polychaeta, and other taxa). Macroinvertebrate cumulative community composition, density, biomass, and energy content varied somewhat among study locations (figs. 24–26; table 9). Macroinvertebrate densities were generally dominated by Polychaeta and Amphipoda and to a lesser extent Oligochaeta, Bivalvia, and Nematoda across all sites (fig. 24). On the other

hand, macroinvertebrate biomass was clearly dominated by Bivalvia (especially at Mooring Road) and Polychaeta, with negligible contributions from other taxonomic groups (fig. 25), while Polychaeta contributed more substantially to energy content at each site (fig. 26). Below we summarize cumulative (calculated across all available sampling periods) site-specific trends in macroinvertebrate density, biomass, and energy content between dredged areas and their paired undredged reference areas.

Dredged in 2013

Overall, at Mooring Road macroinvertebrate density was 39 percent greater in undredged areas than dredged areas. Dominant taxa in dredged areas included bivalves (34 percent of the total density), polychaetes (24 percent), and oligochaetes (11 percent). In undredged areas, the community was predominated by polychaetes (30 percent) and bivalves (23 percent) and contained more oligochaetes (16 percent) relative to dredged areas. Biomass and energy content at both dredged and undredged areas in Mooring Road were driven primarily by bivalves and were 6 and nearly 2.5 times greater, respectively than the site with the next greatest biomass, Loch Lomond undredged (table 9; figs. 24–26).

Dredged and reference areas at the Pier 32 site sampled only during the pilot study were numerically dominated by polychaetes and contained more polychaetes than most other sites, except for the Paradise Cay dredged area. Polychaetes comprised 94 percent of the community in dredged areas and 78 percent in undredged areas, which also contained 16 percent bivalves (fig. 27). Biomass and energy content of macroinvertebrates were not measured during the pilot study.

At Richardson Bay, overall density was 29 percent greater in undredged areas than in dredged areas (table 9). Dredged areas were dominated by polychaetes (56 percent) followed by nematodes (20 percent) and oligochaetes (10 percent). Macroinvertebrate communities in undredged areas were dominated by nematodes (37 percent) and polychaetes (27 percent), but amphipods (16 percent) were more abundant than oligochaetes (11 percent). Biomass at Richardson Bay was 124 percent greater in the undredged area than the dredged area but biomass was dominated by bivalves and polychaetes in both areas. In the dredged area, bivalves accounted for 62 percent of the biomass, while polychaetes accounted for 36 percent; in the undredged area, bivalves and polychaetes accounted for almost equal percentages of the biomass (49 percent and 47 percent, respectively; table 9; fig. 25). Overall, the undredged area provided 166 percent more energy for demersal fish than the dredged area (table 9; fig. 26). In both dredged and undredged areas, polychaetes provided the greatest proportion of the energy content (75 percent and 83 percent respectively; fig. 26).

Table 7. Macroinvertebrate taxa identified in shallow (0–4 centimeters [cm];) cores from dredged (D) and undredged (U) locations at six sites—Mooring Road (MR), Richardson Bay (RB), Paradise Cay (PC), Strawberry Channel (SC), Loch Lomond (LL), and Yacht Harbor (YH)—in San Francisco Bay, California.—Continued

[In some cases, we identified to broader taxa (such as family) when pieces of organisms were encountered or when organisms were too small for distinguishing identifying features. Broader taxonomic categories are not included in total taxa count if they were represented by lower taxonomic identification (ID)]

Broad taxonomic group	Lowest taxonomic ID	Taxonomic rank	MR		RB		PC		SC		LL		YH	
			D	U	D	U	D	U	D	U	D	U	D	U
	<i>Cirratulus spectabilis</i>	Species				X								
	<i>Cirriformia</i>	Genus				X								
	<i>Cirriformia moorei</i>	Species		X	X	X			X	X				
	<i>Cossura pygodactylata</i>	Species	X		X	X	X	X					X	X
	<i>Euchone limnicola</i>	Species		X	X	X	X	X	X	X				
	<i>Heteromastus</i>	Genus	X	X		X		X						
	<i>Leitoscoloplos pugettensis</i>	Species							X		X			
	<i>Lumbrineridae</i>	Family						X						
	<i>Mediomastus</i>	Genus		X	X	X		X						
	<i>Ophellidae</i>	Family			X									
	<i>Orbiniidae</i>	Family				X			X					
	<i>Owenia collaris</i>	Species							X					
	<i>Pseudopolydora</i>	Genus	X	X		X		X						
	<i>Sabaco elongatus</i>	Species	X	X	X			X	X	X	X	X	X	X
	Sabellidae	Family			X		X							
	<i>Spionidae</i>	Family	X	X	X	X	X	X	X	X	X	X	X	X
	<i>Streblospio benedicti</i>	Species	X	X			X	X	X	X	X	X	X	X
	<i>Terebellidae</i>	Family					X		X					
Sipuncula	Sipuncula	Phylum			X	X	X	X	X					X
Tanaidacea	<i>Chondrochelia dubia</i>	Species			X	X								
	<i>Leptochelia</i>	Genus			X	X								
Tunicata	<i>Ascidiidae</i>	Family			X	X								
	<i>Molgula manhattensis</i>	Species				X								
	<i>Molgulidae</i>	Family			X	X								
Unknown	Unknown		X	X	X	X	X	X	X	X	X	X	X	X
Total taxa observed			22	37	54	56	30	43	29	46	27	33	18	39

Table 8. Macroinvertebrate taxa identified in deep (4–10 centimeters [cm]) cores from dredged (D) and undredged (U) locations at six sites—Mooring Road (MR), Richardson Bay (RB), Paradise Cay (PC), Strawberry Channel (SC), Loch Lomond (LL), and Yacht Harbor (YH)—in San Francisco Bay, California.

[In some cases, we identified to broader taxa (such as family) when pieces of organisms were encountered or when organisms were too small for distinguishing identifying features. Broader taxonomic categories are not included in total taxa count if they were represented by lower taxonomic identification (ID)]

Broad taxonomic group	Lowest taxonomic ID	Taxonomic rank	MR		RB		PC		SC		LL		YH	
			D	U	D	U	D	U	D	U	D	U	D	U
Actiniaria	Actiniaria	Order												X
Amphipoda	<i>Ampelisca abdita</i>	Species			X		X	X		X				X
	<i>Corophiidae</i>	Family			X									
	<i>Grandidierella japonica</i>	Species			X			X						X
	<i>Monocorophium</i>	Genus	X		X	X								
Annelida	Annelida	Phylum												X
Bacillariophyceae	Bacillariophyceae	Order						X	X					
	Coscinodiscales	Order						X						
Bivalvia	<i>Arcuatula senhousia</i>	Species		X			X							X
	<i>Gemma gemma</i>	Species	X	X										
	<i>Macoma petalum</i>	Species		X					X		X			
Bryozoa	Bryozoa	Phylum			X	X	X	X		X		X	X	X
Copepoda	Copepoda	Subclass					X	X	X					
Crustacea	Crustacea	Subphylum									X			
Cumacea	<i>Nippoleucon hinumensis</i>	Species	X	X	X	X	X	X	X	X	X	X	X	X
Gastropoda	Gastropoda	Class			X									
Hirudinea	Hirudinea	Subclass			X									
Hutchinsoniellidae	<i>Lightiella serendipita</i>	Species				X		X						X
Insecta	<i>Corixidae</i>	Family							X					
Isopoda	<i>Paranthurus japonica</i>	Species	X		X	X			X		X			
Leptostraca	<i>Nebalia</i>	Genus				X			X	X				
Nematoda	Nematoda	Phylum		X	X	X	X	X	X	X	X	X	X	X
Oligochaeta	Oligochaeta	Subclass	X	X	X	X	X	X	X	X	X	X	X	X
Osteichthyes	Osteichthyes	Superclass							X	X				X
Ostracoda	Myodocopida	Order	X											X
Pantopoda	Pantopoda	Order				x								
Polychaeta (Errantia)	<i>Alitta</i>	Genus		X										
	<i>Exogone lourei</i>	Species							X					
	Glycinde	Genus			X									X
	<i>Megasyllis nipponica</i>	Species				X								
	<i>Schistomeringos longicornis</i>	Species				X								
Polychaeta (Sedentaria)	<i>Capitella capitata</i>	Species				X								X
	<i>Capitellidae</i>	Family		X	X				X	X		X		X
	<i>Cirratulidae</i>	Family		X		X								
	<i>Cirratulus dillonensis</i>	Species				X								
	<i>Cirriformia</i>	Genus				X								
	<i>Cirriformia moorei</i>	Species				X	X			X				
	<i>Cossura pygodactylata</i>	Species	X		X	X	X	X						X
	<i>Leitoscoloplos pugettensis</i>	Species							X					

Table 8. Macroinvertebrate taxa identified in deep (4–10 centimeters [cm]) cores from dredged (D) and undredged (U) locations at six sites—Mooring Road (MR), Richardson Bay (RB), Paradise Cay (PC), Strawberry Channel (SC), Loch Lomond (LL), and Yacht Harbor (YH)—in San Francisco Bay, California.—Continued

[In some cases, we identified to broader taxa (such as family) when pieces of organisms were encountered or when organisms were too small for distinguishing identifying features. Broader taxonomic categories are not included in total taxa count if they were represented by lower taxonomic identification (ID)]

Broad taxonomic group	Lowest taxonomic ID	Taxonomic rank	MR		RB		PC		SC		LL		YH	
			D	U	D	U	D	U	D	U	D	U	D	U
	<i>Sabaco elongatus</i>	Species		X				X		X	X	X		X
	<i>Spionidae</i>	Family	X											
Sipuncula	Sipuncula	Phylum				X		X		X				X
Tanaidacea	Tanaidacea	Order				X								
Unknown	Unknown		X	X	X	X	X	X	X	X	X	X	X	X
Total taxa observed			12	9	17	18	8	14	11	15	9	7	9	16

Dredged in 2014

Macroinvertebrate density was 53 percent less in undredged areas than in dredged areas (table 9) at Paradise Cay. Polychaetes were dominant in dredged areas (72 percent), which also contained amphipods (17 percent). This differed from the undredged area at this site, which was dominated by amphipods (60 percent) and had notably fewer polychaetes (18 percent; fig. 24). Macroinvertebrate communities in the undredged area at Paradise Cay had the greatest density and percentage of amphipods relative to other sites. Biomass values in the dredged and undredged areas at Paradise Cay were similar (13.3 g/m² dry weight [dw] in dredged area versus 13.8 g/m² dw in undredged area; table 9). In the dredged area, polychaetes accounted for 72 percent of the biomass, while bivalves accounted for 24 percent; in the undredged area, polychaetes accounted for 28 percent of the biomass, while bivalves accounted for 59 percent (fig. 25). Overall, the dredged area provided 49 percent more energy than the undredged area (table 9), with polychaetes providing 98 percent of the energy in the dredged area versus 58 percent in the undredged area (fig. 26).

Strawberry Channel macroinvertebrate densities in undredged areas were 136 percent greater than in dredged areas (table 9). Communities within the dredged areas at this site primarily consisted of polychaetes (38 percent), oligochaetes (23 percent dredged), and nematodes (13 percent). In the undredged areas, polychaetes (38 percent), oligochaetes (22 percent), and amphipods (20 percent) were the most abundant taxa (fig. 24). Strawberry Channel macroinvertebrate communities had the greatest percentage of oligochaetes at dredged and undredged areas relative to other sites. Biomass in the dredged and undredged areas at

Strawberry Channel were similar (28.8 g/m² dw in dredged area versus 31.1 g/m² dw in undredged area; table 9). In the dredged area, bivalves accounted for 96 percent of the biomass; in the undredged area, however, polychaetes accounted for 19 percent of the biomass, while bivalves accounted for 79 percent (fig. 25). The undredged area provided 77 percent more energy than the dredged area (table 9). Polychaetes provided 54 percent of available energy in the undredged area, while bivalves supplied 41 percent and other taxa comprised the additional 5 percent. Bivalves provided 82 percent of available energy at the dredged area and polychaetes the remaining 18 percent (fig. 26).

Dredged in 2015

At Loch Lomond, macroinvertebrate densities in the undredged area were 219 percent greater than in the dredged area; the average density in the dredged area was the lowest among all the sites (table 9). Dominant taxa in the dredged area included polychaetes (24 percent), oligochaetes (18 percent), and nematodes (18 percent); the undredged area consisted mainly of polychaetes (32 percent), nematodes (22 percent), and amphipods (20 percent). Biomass at Loch Lomond was 171 percent greater in the undredged areas than in the dredged areas (table 9). In the dredged area, bivalves accounted for 90 percent of the biomass; in the undredged area, however, polychaetes accounted for 41 percent of the biomass, while bivalves accounted for 58 percent. Likewise, macroinvertebrate energy content in the undredged area was 475 percent greater than in the dredged area, with polychaetes contributing 79 percent and bivalves 21 percent of the energy in the undredged area (fig. 26).

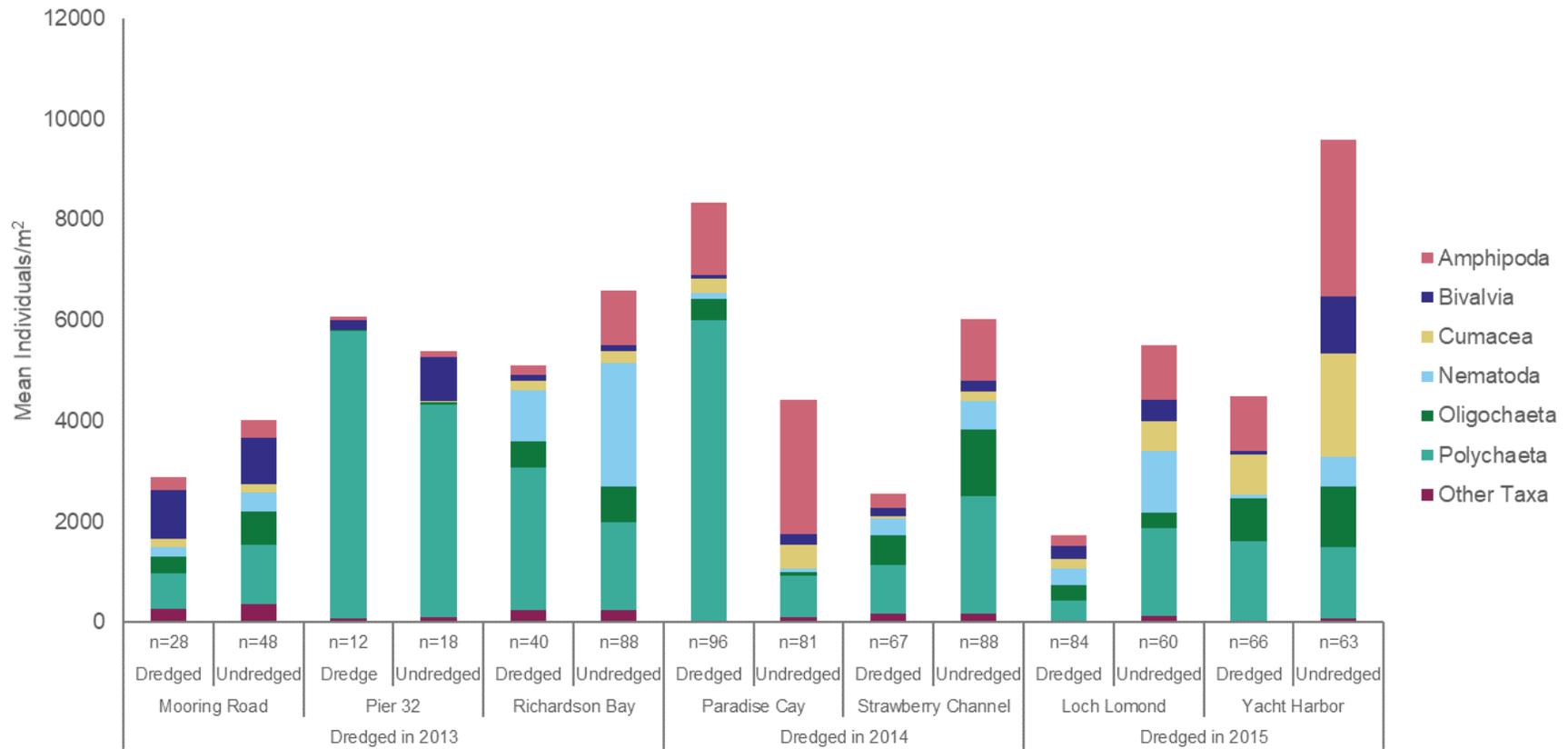


Figure 24. Mean densities (individuals/ square meter [m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa in dredged and undredged areas at seven sites (Mooring Road, Pier 32, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at Pier 32 during the pilot study (November 2015); at Mooring Road, Richardson Bay, Paradise Cay, and Strawberry Channel during the pilot and full studies (November 2015, August 2016, January 2017, August 2017); and at Loch Lomond and Yacht Harbor during the full study (August 2016, January 2017, August 2017).

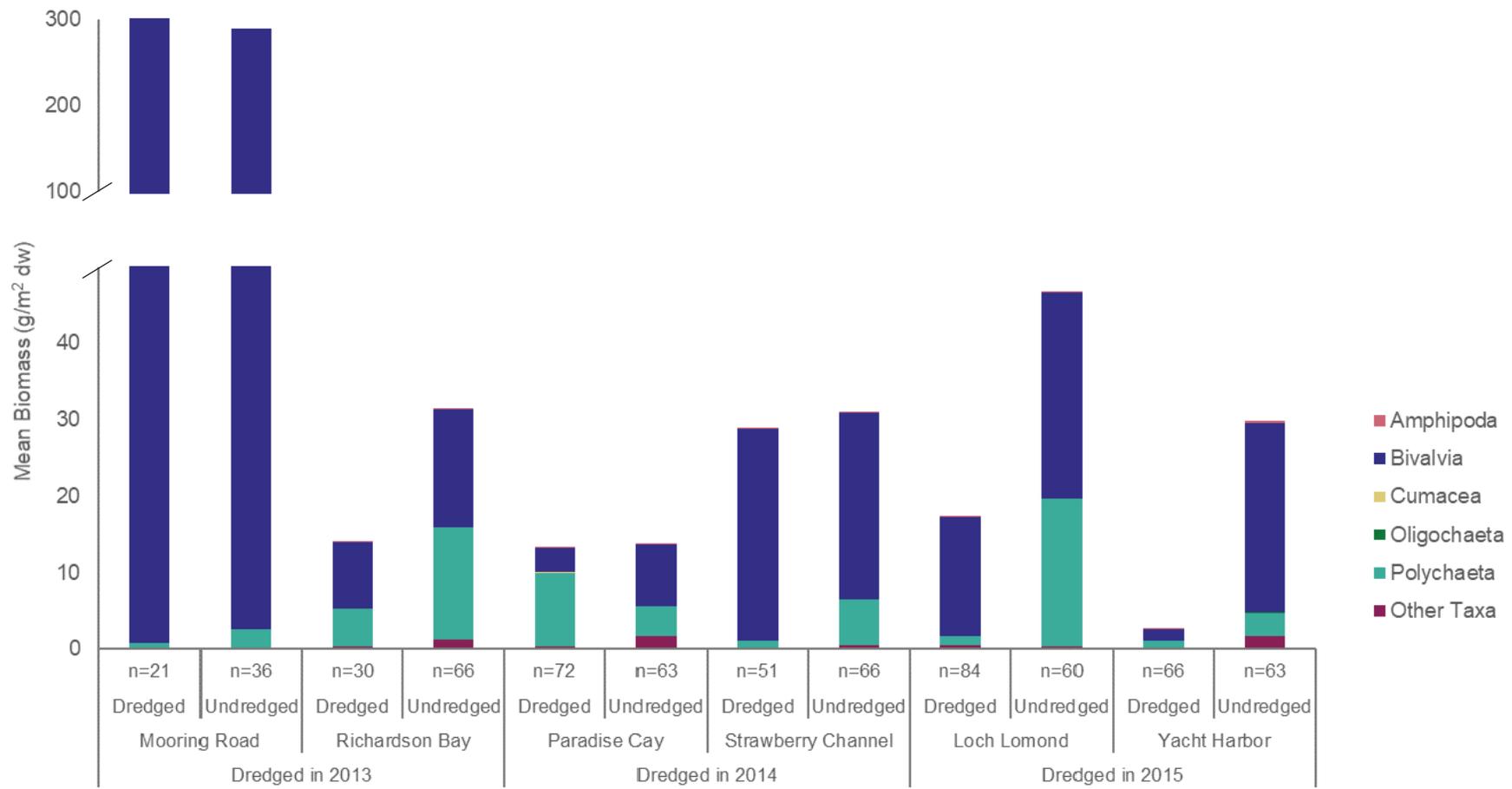


Figure 25. Mean biomass (grams per square meter [g/m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa in dredged and undredged areas at six sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at all sites during the full study (August 2016, January 2017, August 2017).

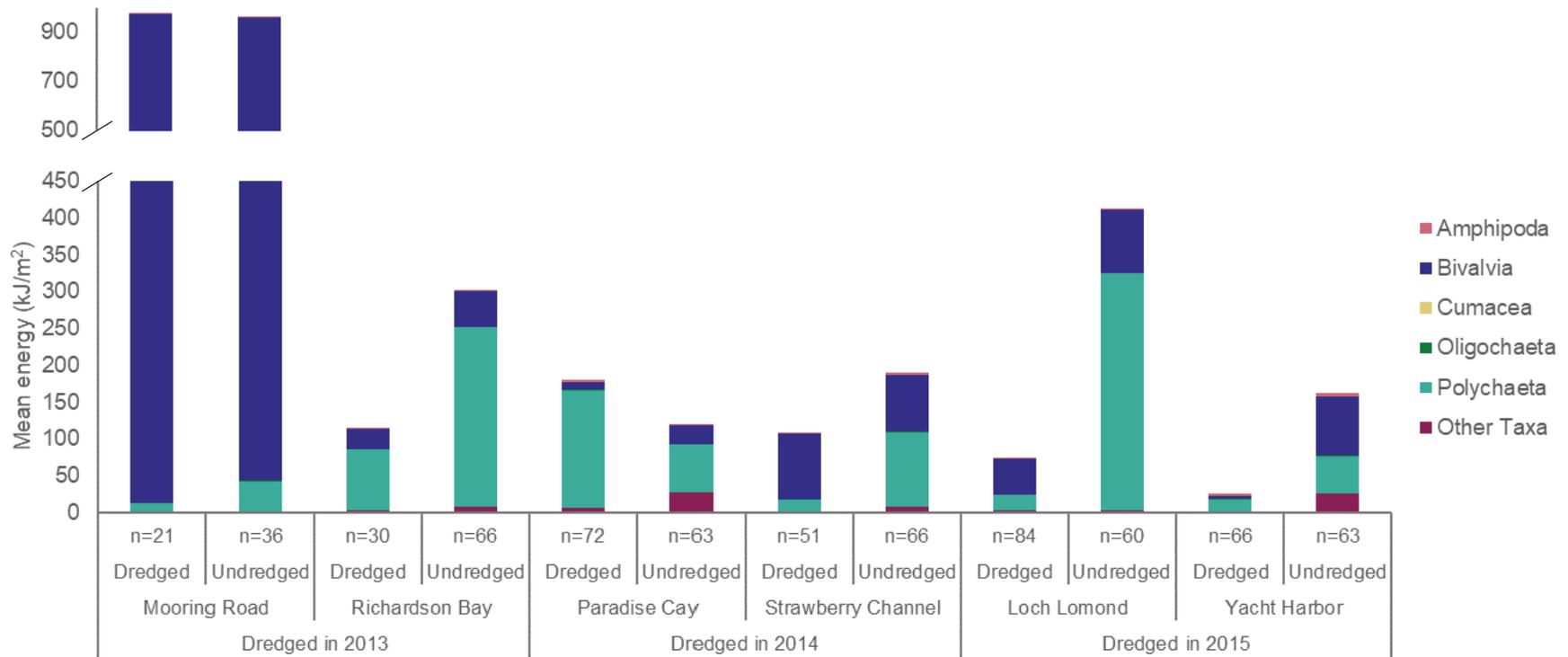


Figure 26. Mean energy (kilojoule per square meter [kJ/m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa in dredged and undredged areas at six sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at all sites during the full study (August 2016, January 2017, August 2017).

Table 9. Comparison of mean (\pm standard error) macroinvertebrate density (number of individuals/square meter [m²]), biomass (grams [g]/m²) in dry weight (dw), and energy (kilojoules per square meter [kJ/m²]) in dredged and undredged areas during the pilot and full study in each site.

[The number of cores taken at each site during each sampling period is given (N)]

Site	Dredged				Undredged			
	N	Mean density (individuals/m ²)	Mean biomass (g/m ² dw)	Mean energy (kJ/m ²)	N	Mean density (individuals/m ²)	Mean biomass (g/m ² dw)	Mean energy (kJ/m ²)
November 2015 (Pilot)								
Pier 32	12	6247.4 \pm 1331.4	—	—	18	5208.8 \pm 881.6	—	—
Mooring Road	7	1164.7 \pm 389.6	—	—	12	1321.7 \pm 451.6	—	—
Richardson Bay	20	2818.5 \pm 559.6	—	—	13	7520.9 \pm 1903.7	—	—
Paradise Cay	24	5146.0 \pm 1235.7	—	—	21	8135.3 \pm 901.9	—	—
Strawberry Channel	17	1502.5 \pm 497.7	—	—	22	1757.4 \pm 356.2	—	—
August 2016								
Mooring Road	7	6475.6 \pm 597.8	559.49 \pm 62.45	1791.5 \pm 199.2	12	8929.0 \pm 920.9	551.57 \pm 101.57	1828.4 \pm 327.8
Richardson Bay	10	4526.6 \pm 671.5	12.26 \pm 2.89	187.4 \pm 49.6	22	8661.3 \pm 2665.6	17.12 \pm 3.22	251.4 \pm 41.3
Paradise Cay	24	4995.1 \pm 935.5	0.57 \pm 0.11	8.5 \pm 1.3	21	1658.3 \pm 449.0	6.82 \pm 2.08	90.1 \pm 20.3
Strawberry Channel	17	3115.8 \pm 729.3	5.84 \pm 3.87	42.2 \pm 16.6	22	2743.4 \pm 423.8	2.75 \pm 0.33	46.7 \pm 5.5
Loch Lomond	28	1337.0 \pm 178.5	3.92 \pm 1.75	20.7 \pm 6.9	20	5838.1 \pm 897.5	27.38 \pm 4.58	392.0 \pm 66.3
Yacht Harbor	22	3828.6 \pm 604.3	1.14 \pm 0.33	11.1 \pm 2.0	21	8858.5 \pm 862.3	6.75 \pm 1.44	83.8 \pm 18.2
January 2017								
Mooring Road	7	3046.8 \pm 258.2	296.67 \pm 4.34	959.5 \pm 138.9	12	4552.0 \pm 979.6	286.32 \pm 69.15	945.4 \pm 224.2
Richardson Bay	10	9498.8 \pm 1758.1	1.92 \pm 0.32	30.1 \pm 5.1	22	5209.0 \pm 1246.8	28.72 \pm 5.15	452.9 \pm 79.7
Paradise Cay	24	11085.7 \pm 1319.6	1.06 \pm 0.14	13.9 \pm 1.5	21	2740.6 \pm 344.5	4.17 \pm 0.76	62.8 \pm 12.4
Strawberry Channel	17	2864.9 \pm 702.8	2.22 \pm 1.22	14.8 \pm 4.5	22	11129.8 \pm 1042.6	14.39 \pm 2.15	241.9 \pm 35.5
Loch Lomond	28	1502.9 \pm 525.6	0.50 \pm 0.10	8.0 \pm 1.7	20	4386.5 \pm 826.8	35.20 \pm 12.12	580.4 \pm 200.9
Yacht Harbor	22	4829.9 \pm 688.0	0.81 \pm 0.17	10.4 \pm 1.9	21	6994.1 \pm 1444.9	1.53 \pm 0.51	17.4 \pm 7.9
August 2017								
Mooring Road	7	645.7 \pm 98.7	52.16 \pm 24.18	179.9 \pm 76.6	12	1299.8 \pm 192.8	36.69 \pm 8.07	123.8 \pm 25.8
Richardson Bay	10	2482.9 \pm 659.6	27.82 \pm 12.51	122.6 \pm 43.9	22	7228.9 \pm 1567.9	48.39 \pm 9.16	203.5 \pm 32.6
Paradise Cay	24	9775.2 \pm 999.2	38.39 \pm 5.72	516.0 \pm 91.0	21	5987.5 \pm 516.5	30.45 \pm 6.52	208.2 \pm 51.6
Strawberry Channel	17	2629.0 \pm 466.6	78.48 \pm 15.26	263.5 \pm 50.0	22	8432.7 \pm 801.8	75.81 \pm 17.62	278.9 \pm 56.3
Loch Lomond	28	2342.0 \pm 269.6	47.28 \pm 8.73	191.1 \pm 31.0	20	6315.6 \pm 959.9	77.55 \pm 6.92	265.0 \pm 22.1
Yacht Harbor	22	4844.3 \pm 615.8	6.14 \pm 2.08	53.4 \pm 9.5	21	12948.3 \pm 1033.5	81.33 \pm 15.91	384.8 \pm 63.5
All Sampling Periods								
Mooring Road	28	2878.57 \pm 477.2	302.77 \pm 52.7	977.0 \pm 167.7	48	4012.22 \pm 569.9	291.53 \pm 53.4	965.9 \pm 174.4
Richardson Bay	40	5105.93 \pm 686.8	14.00 \pm 4.6	113.3 \pm 24.5	88	6594.40 \pm 910.0	31.41 \pm 3.9	302.6 \pm 34.1
Paradise Cay	96	8329.50 \pm 713.6	13.34 \pm 2.8	179.5 \pm 41.1	81	4416.47 \pm 396.2	13.81 \pm 2.7	120.4 \pm 20.2
Strawberry Channel	67	2554.20 \pm 298.2	28.85 \pm 7.2	106.9 \pm 23.3	88	6017.07 \pm 545.4	30.98 \pm 7.1	189.2 \pm 25.3
Loch Lomond	84	1727.29 \pm 208.9	17.23 \pm 3.7	73.3 \pm 13.9	60	5513.39 \pm 519.8	46.71 \pm 5.6	412.5 \pm 71.7
Yacht Harbor	66	4500.92 \pm 366.9	2.70 \pm 0.8	25.0 \pm 4.0	63	9600.28 \pm 718.8	29.87 \pm 7.0	162.0 \pm 29.8

Yacht Harbor had the greatest average macroinvertebrate density out of all the undredged areas at sites

(9,600 individuals/m²); this was 113 percent greater than the density in the dredged area (4,501 individuals/m²; table 9).

In the dredged area, polychaetes were the most abundant taxa (36 percent), followed by amphipods (24 percent) and oligochaetes (18 percent). In the undredged area, amphipods were the most abundant taxa, followed by cumaceans (21 percent) and polychaetes (15 percent). Biomass in the dredged area at Yacht Harbor was the lowest among all the sites (2.7 g/m² dw), while the biomass in the undredged area was 1007 percent greater (29.9 g/m² dw; table 9). Bivalves and polychaetes contributed the most biomass in both dredged (53 percent and 37 percent, respectively) and undredged areas (83 percent and 10 percent, respectively). Energy content was 548 percent greater in the undredged area compared to the dredged, and unlike other sites, this was driven mainly by bivalves (49 percent of total energy; fig. 26).

The Effect of Dredging on Macroinvertebrate Density, Biomass, and Energy Content

Total density of macroinvertebrate taxa was significantly greater in undredged areas compared to dredged areas for all size classes and depths (table 10). Macroinvertebrate density increased as salinity increased, decreased as elevation increased, and was greater during the winter than during the summer (table 10). The taxonomic composition of the benthic community differed among sampling periods with Polychaeta found in greatest densities during the November 2015 and January 2017 sampling periods, Nematoda found in the greatest densities during the August 2016 sampling period, and Amphipoda found in greatest densities during the August 2017 sampling period (fig. 27–30). Overall, the

number of broad taxa and macroinvertebrate densities were much greater in shallow core fractions (0–4 cm) compared to deeper core fractions (4–10 cm; figs. 31–32). Polychaeta with a 0–4 mm head width was the most abundant taxon in shallow cores (fig. 31).

Total biomass of macroinvertebrate prey of all sizes (0–50 mm) in both surface (0–4 cm) and whole cores (0–10 cm) was consistently greater in undredged areas compared to dredged areas (table 11). We did not detect any clear effects of season, salinity, or elevation on biomass; the effects varied depending on the core depth and macroinvertebrate size class (table 11). Biomass of 0–50 mm macroinvertebrates in whole cores (0–10 cm) varied among sampling periods. Biomass was much greater at Mooring Road compared to all other sites during the August 2016 sampling period, and it was much greater at Richardson Bay compared to all other sites during the January 2017 sampling period (figs. 33–34). Biomass was more similar among sites during the August 2017 sampling period (fig. 35). At all sites, most of the available biomass was from Bivalvia followed by Polychaeta and was found near the surface (0–4 cm deep; figs. 36–37). Bivalvia biomass was particularly high at Mooring Road during August 2016 and at Richardson Bay during January 2017 (figs. 33–34). Bivalvia near the surface (0–4 cm deep) in the 12–24 mm size class represented the greatest biomass at each site, followed by 4–12 mm and 24–50 mm Bivalvia near the surface and 12–24 mm Bivalvia in deeper sediments (4–10 cm deep; figs. 36–37). Polychaeta (0–4 mm head width) represented the taxa with the second greatest biomass in deeper sediments (fig. 37).

Table 10. Summary of general linear mixed model (GLMM) results for total density of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during August 2016, January 2017, and August 2017. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.1 to 1.5 in appendix for more information. Abbreviations: mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Macroinvertebrate size class	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	<0.001	0.490	<0.001
Treatment: undredged	<0.001	<0.001	<0.001	0.002	<0.001
Season: winter	<0.001	<0.001	0.005	0.484	0.024
Salinity	<0.001	<0.001	0.120	0.507	0.023
Elevation	<0.001	<0.001	0.019	0.271	<0.001

Table 11. Summary of general linear mixed model (GLMM) results for total biomass of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) within dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.7 to 1.11 in appendix for more information. Abbreviations: mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Macroinvertebrate size class	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	<0.001	<0.001	<0.001
Treatment: undredged	<0.001	<0.001	0.036	0.169	<0.001
Season: winter	<0.001	<0.001	0.006	<0.001	<0.001
Salinity	<0.001	<0.001	0.112	<0.001	0.012
Elevation	0.003	0.417	0.002	<0.001	0.002

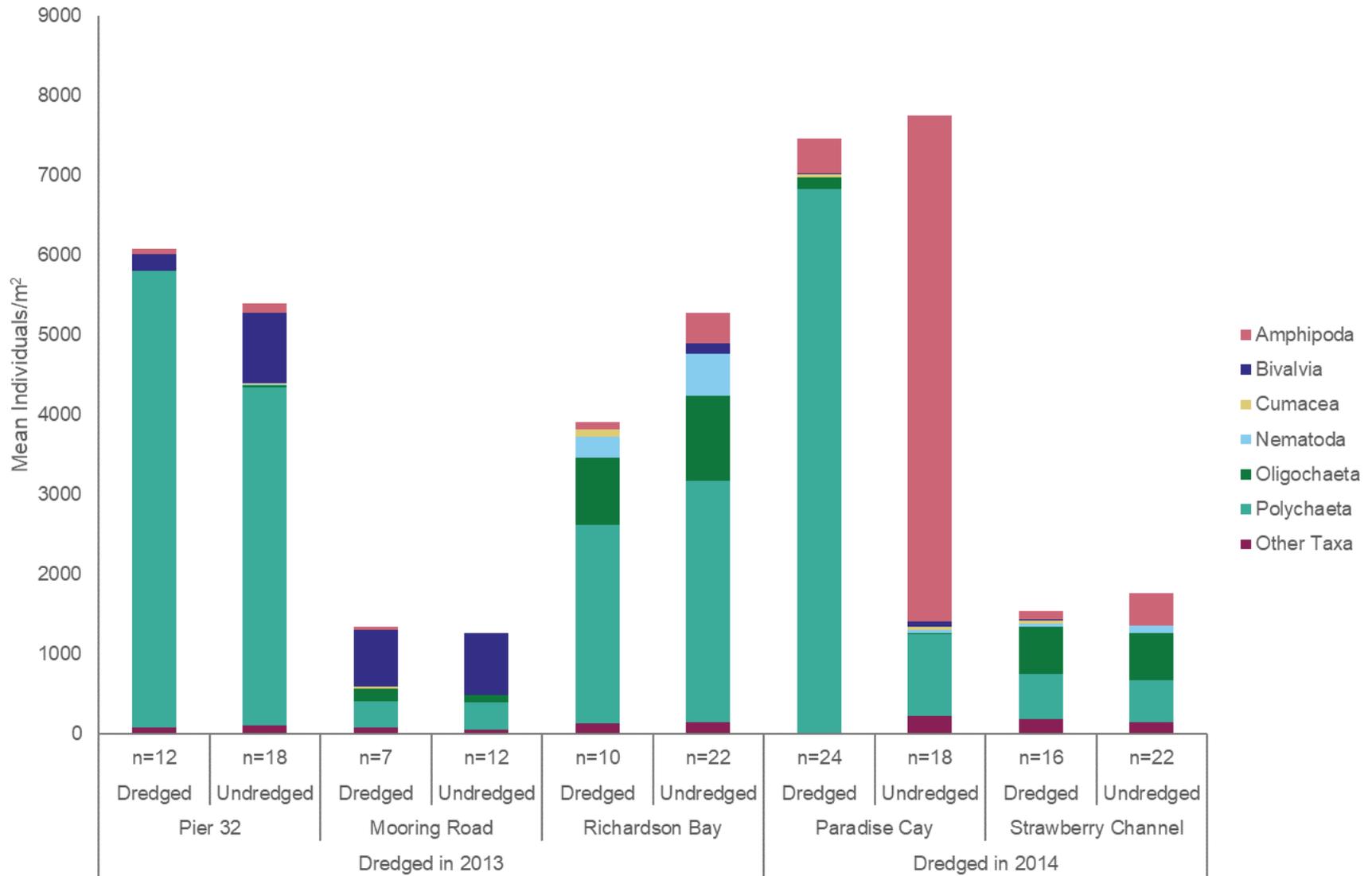


Figure 27. Mean densities (individuals/meter [m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at five pilot study sites (Pier 32, Mooring Road, Richardson Bay, Paradise Cay, and Strawberry Channel) in November 2015.

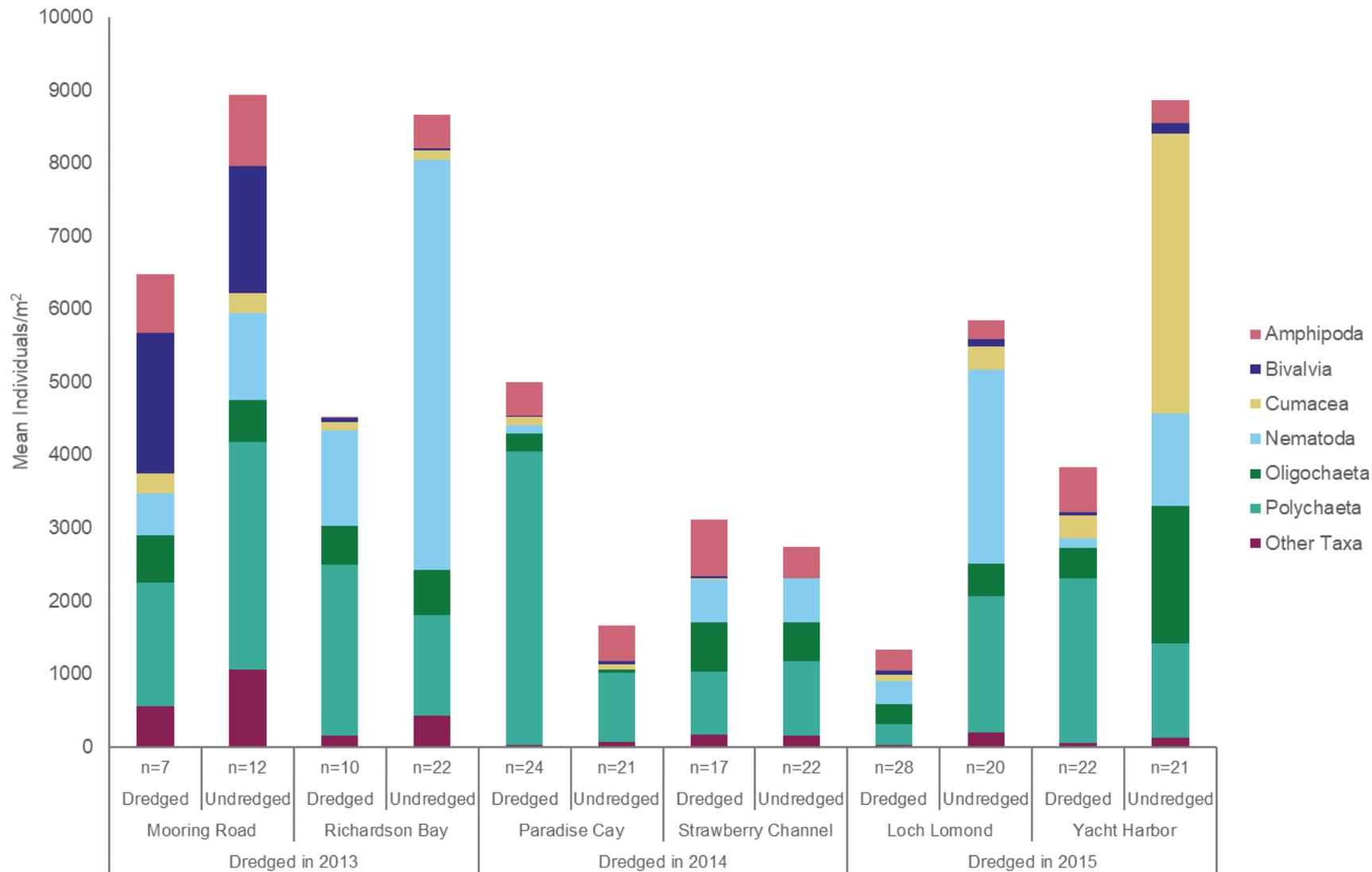


Figure 28. Mean densities (individuals/meter [m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in August 2016.

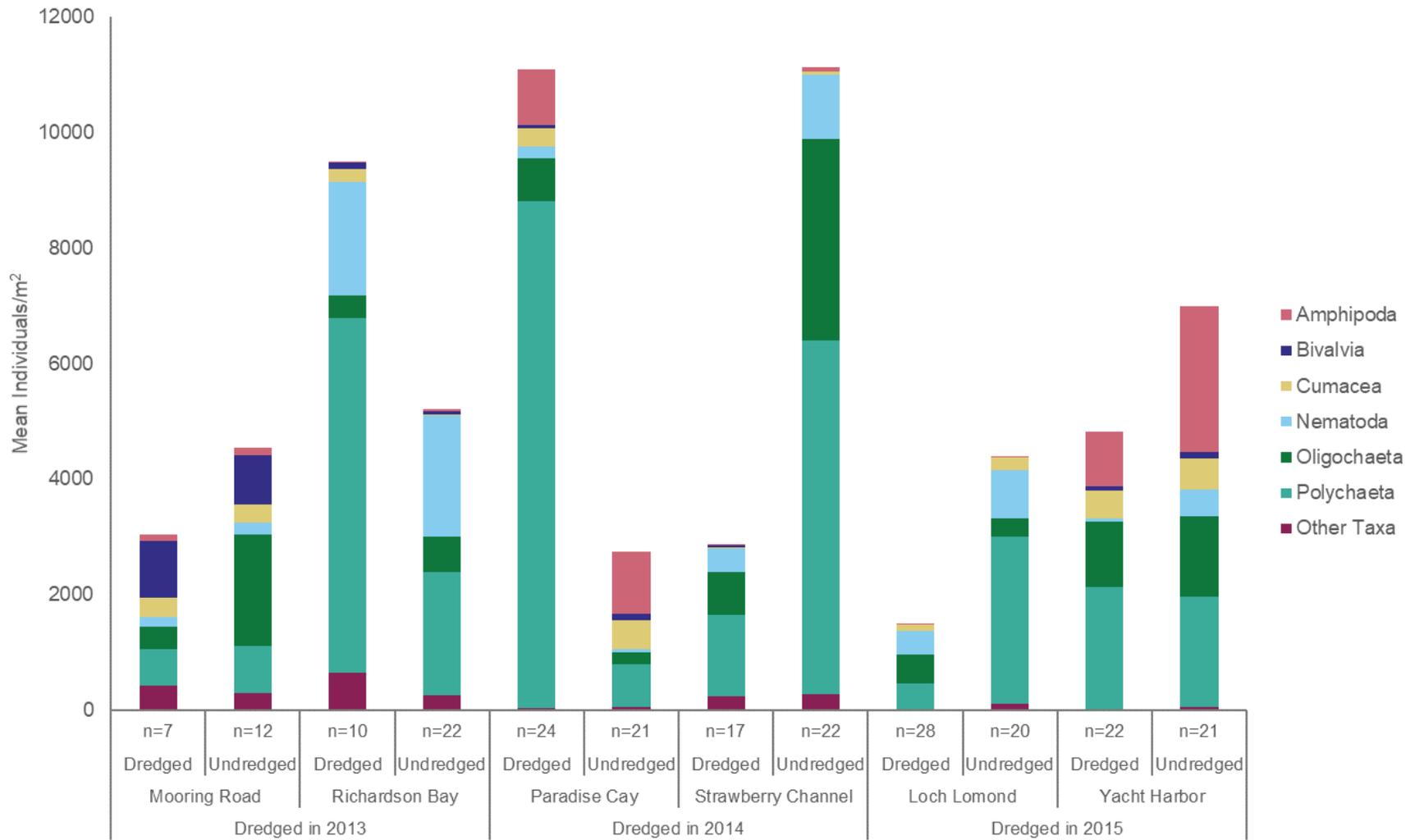


Figure 29. Mean densities (individuals/ meter [m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in January 2017.

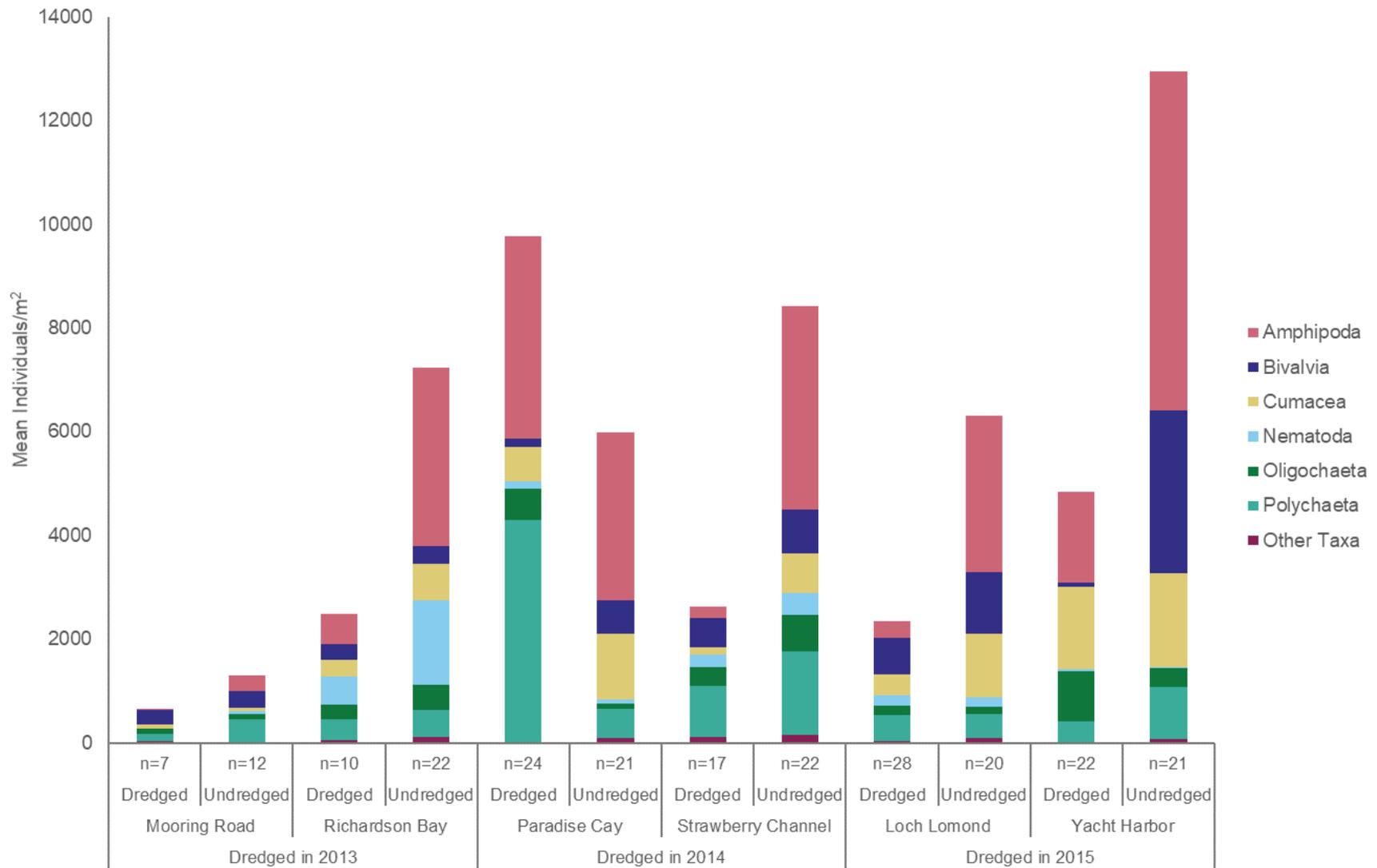


Figure 30. Mean densities (individuals/ meter [m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in August 2017.

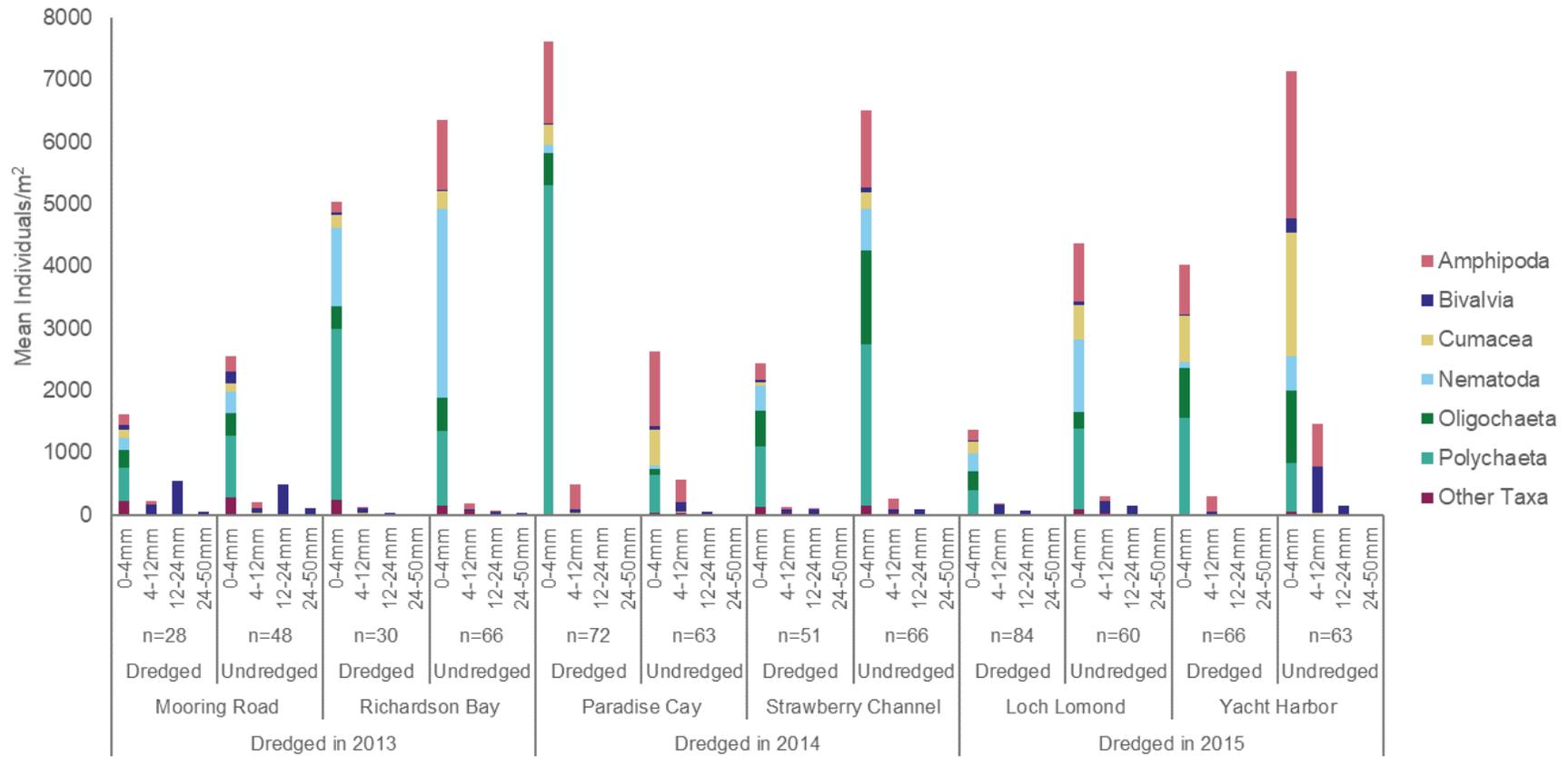


Figure 31. Mean density (individuals/ meter [m²]) of macroinvertebrate taxa from different size classes in shallow cores (0–4 centimeter [cm]) from dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at Mooring Road, Richardson Bay, Paradise Cay, and Strawberry Channel during the pilot and full studies (November 2015, August 2016, January 2017, August 2017) and at Loch Lomond and Yacht Harbor during the full study (August 2016, January 2017, August 2017).

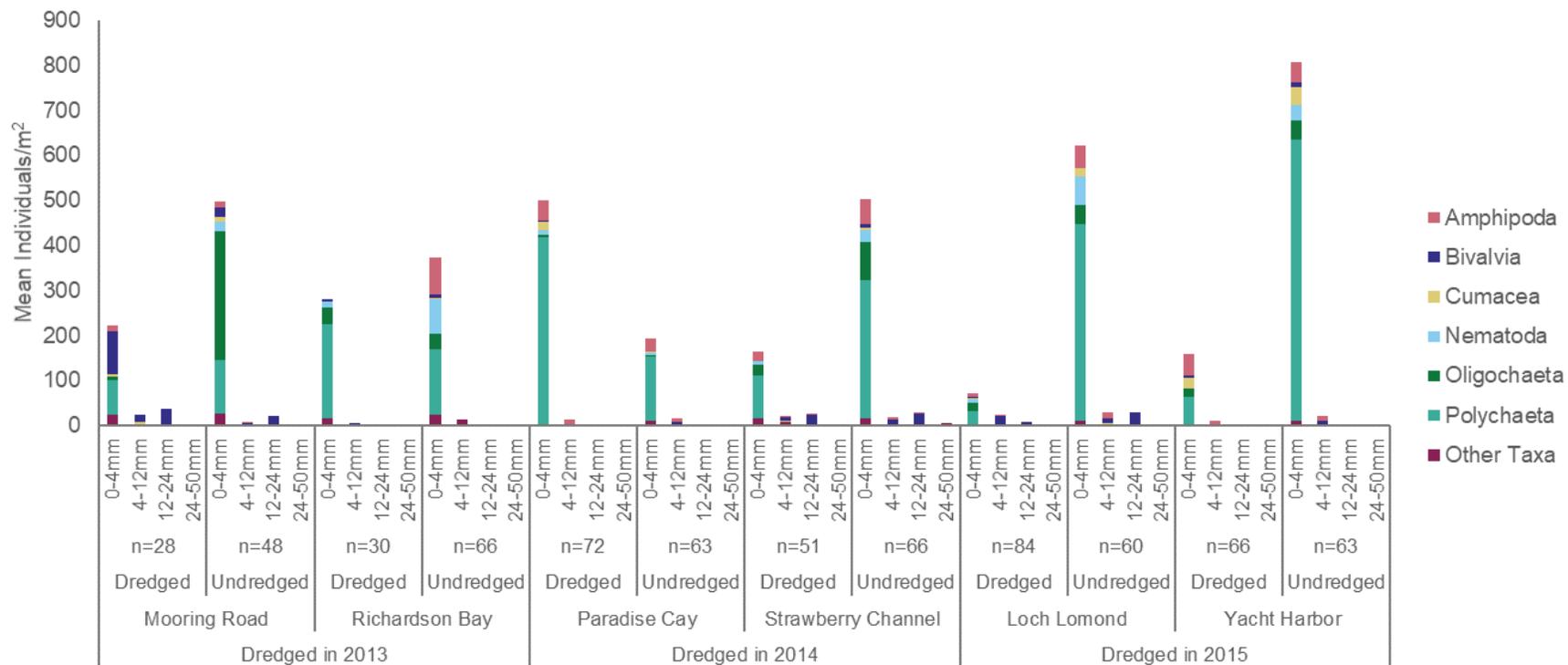


Figure 32. Mean density (individuals/meter [m²]) of macroinvertebrate taxa from different size classes in deep cores (4–10 centimeter [cm]) from dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at Mooring Road, Richardson Bay, Paradise Cay, and Strawberry Channel during the pilot and full studies (November 2015, August 2016, January 2017, August 2017) and at Loch Lomond and Yacht Harbor during the full study (August 2016, January 2017, August 2017).

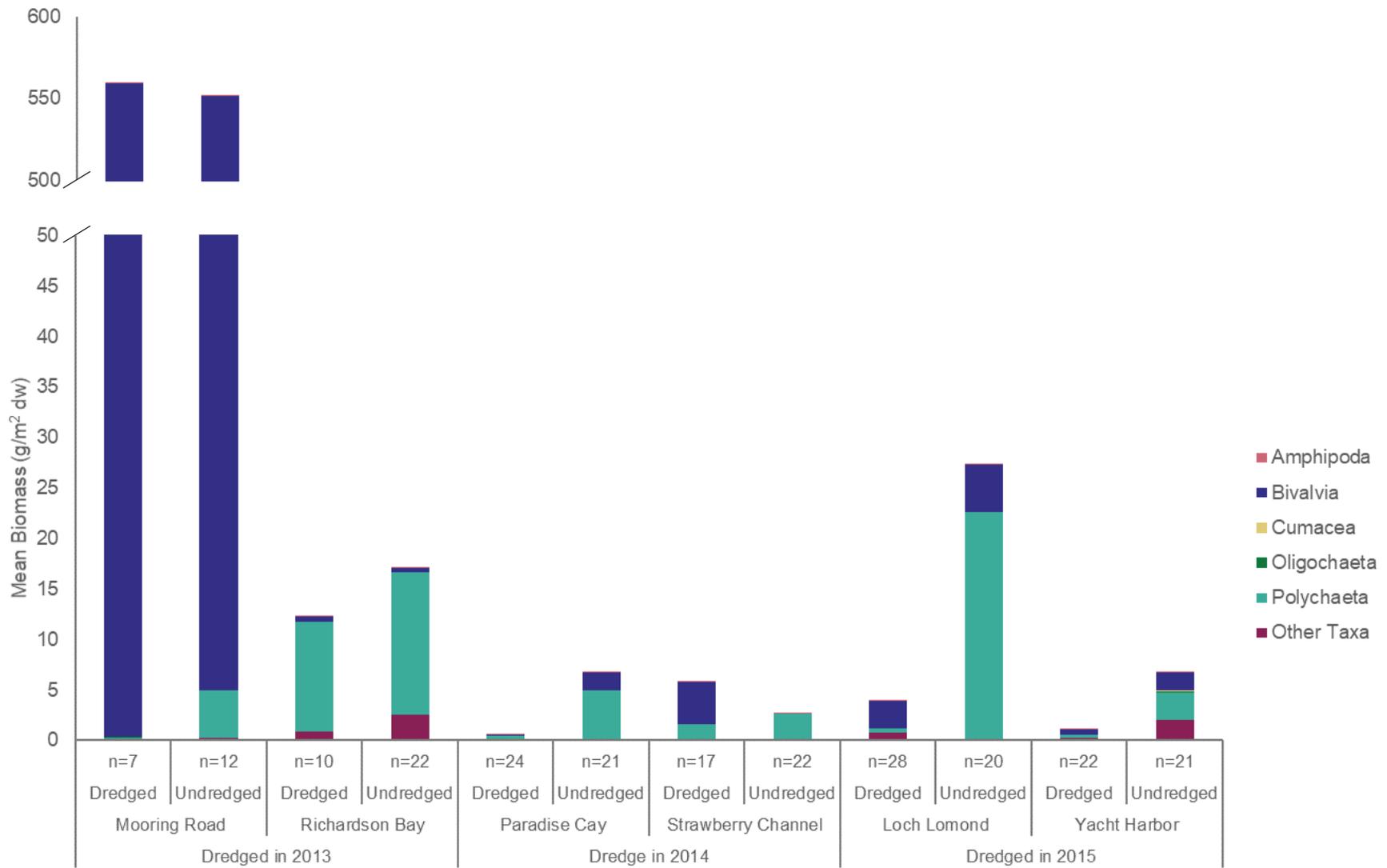


Figure 33. Mean biomass (grams per square meter [g/m²] dry weight (dw) to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in August 2016.

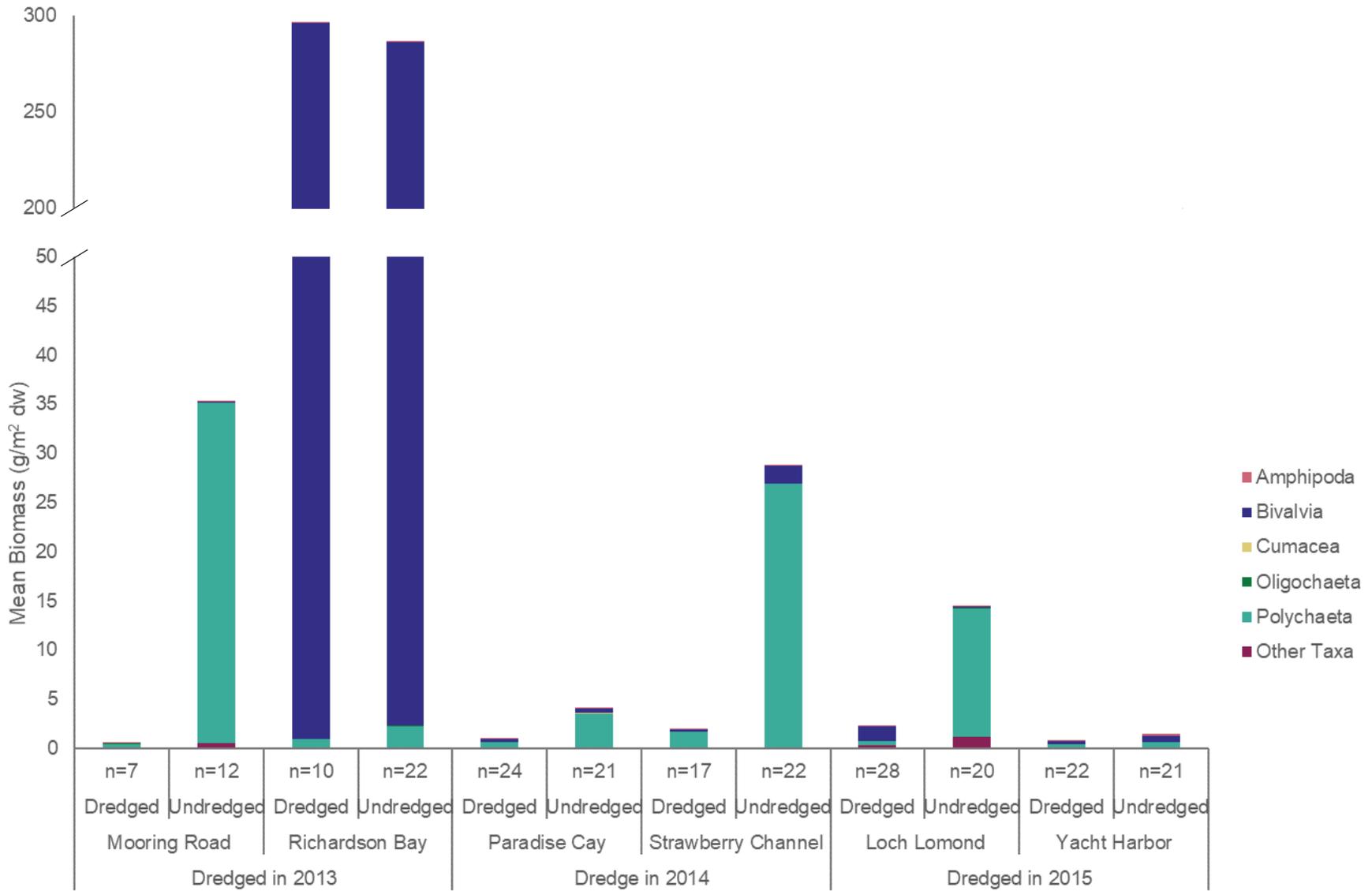


Figure 34. Mean biomass (grams per square meter [g/m²] dry weight (dw) to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in January 2017.

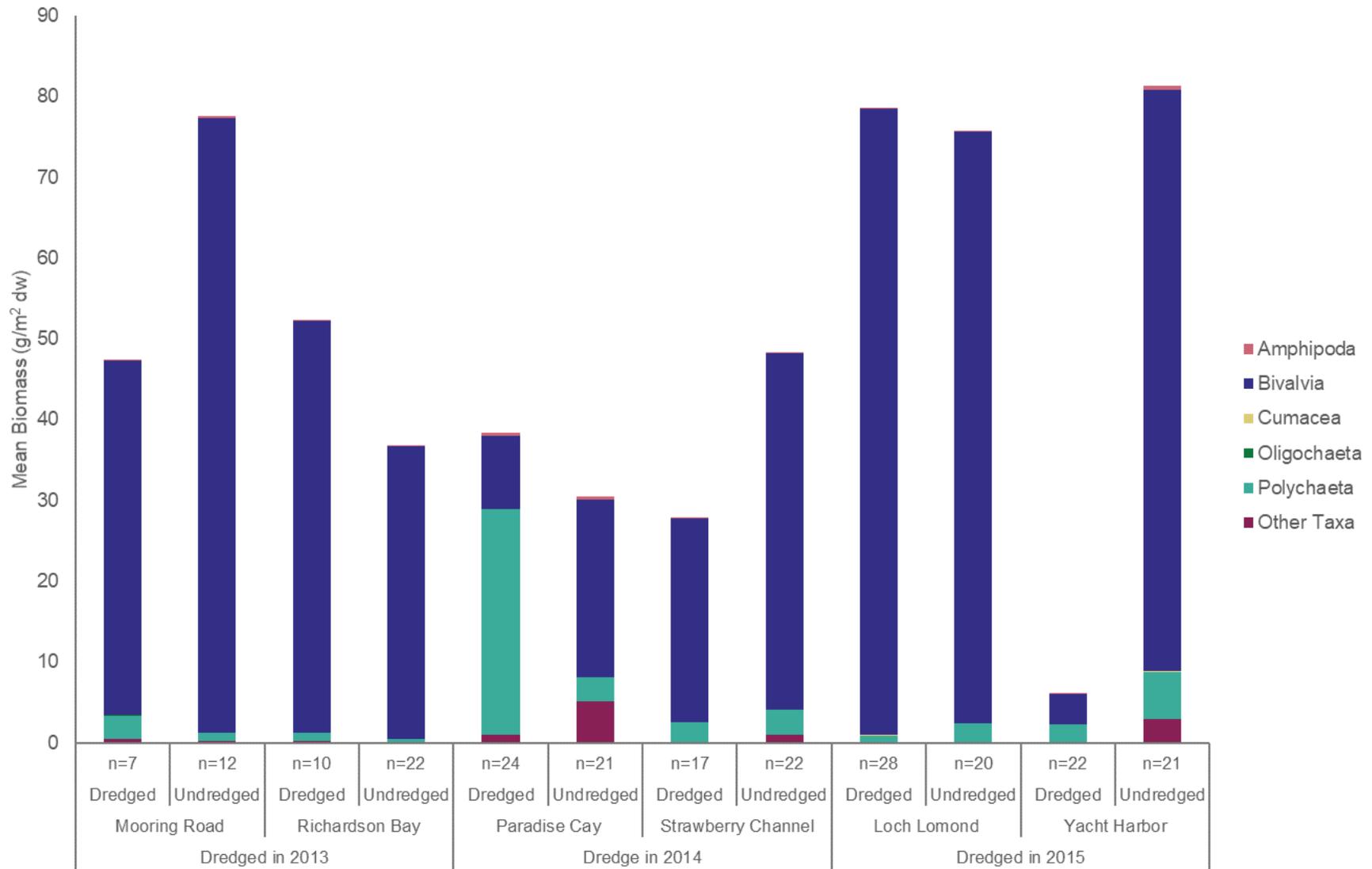


Figure 35. Mean biomass (grams per square meter [g/m²] dry weight (dw) to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in August 2017.

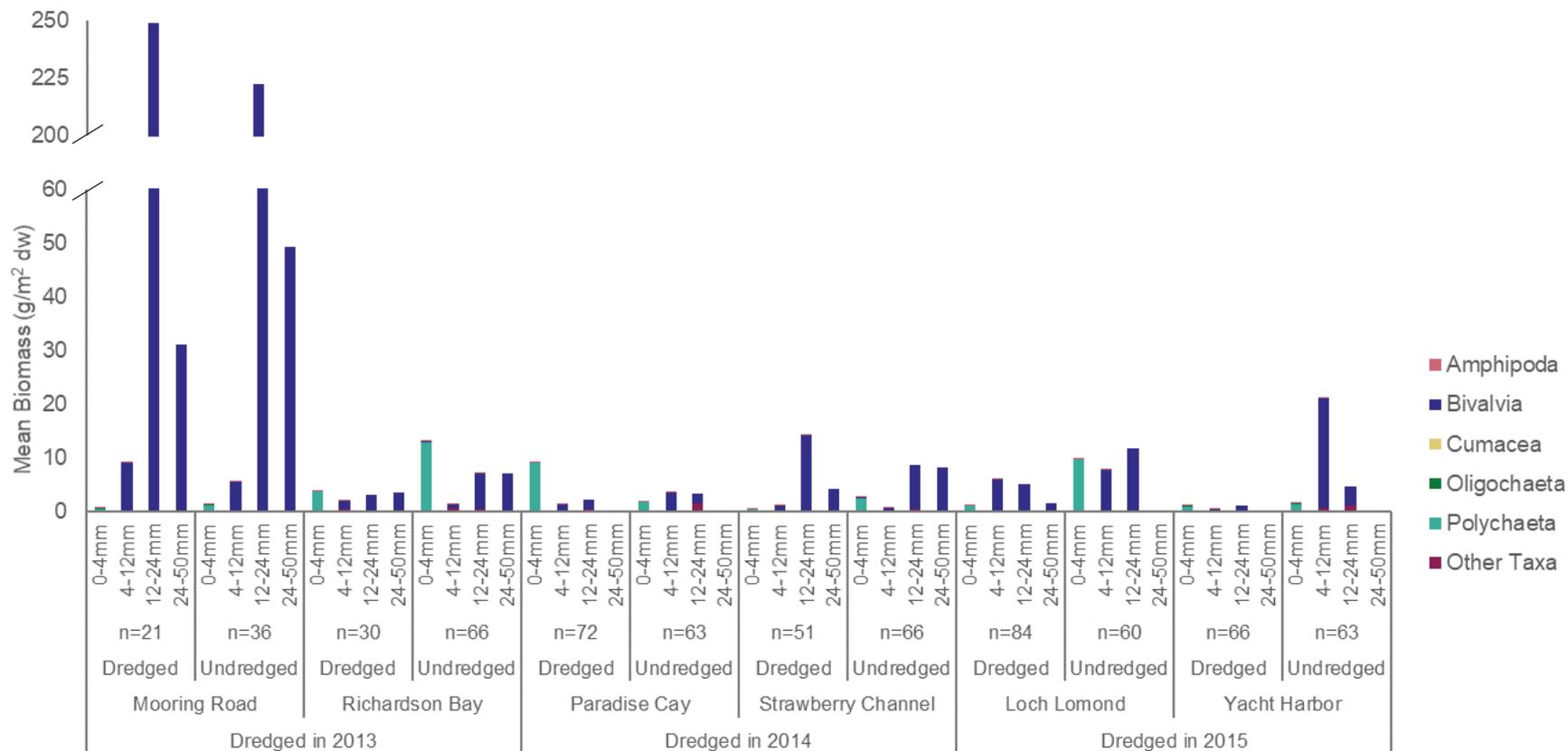


Figure 36. Mean biomass grams per square meter [g/m²] dry weight (dw) of macroinvertebrate taxa from different size classes in shallow cores (0–4 centimeter [cm]) from dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at all sites during the full study (August 2016, January 2017, August 2017).

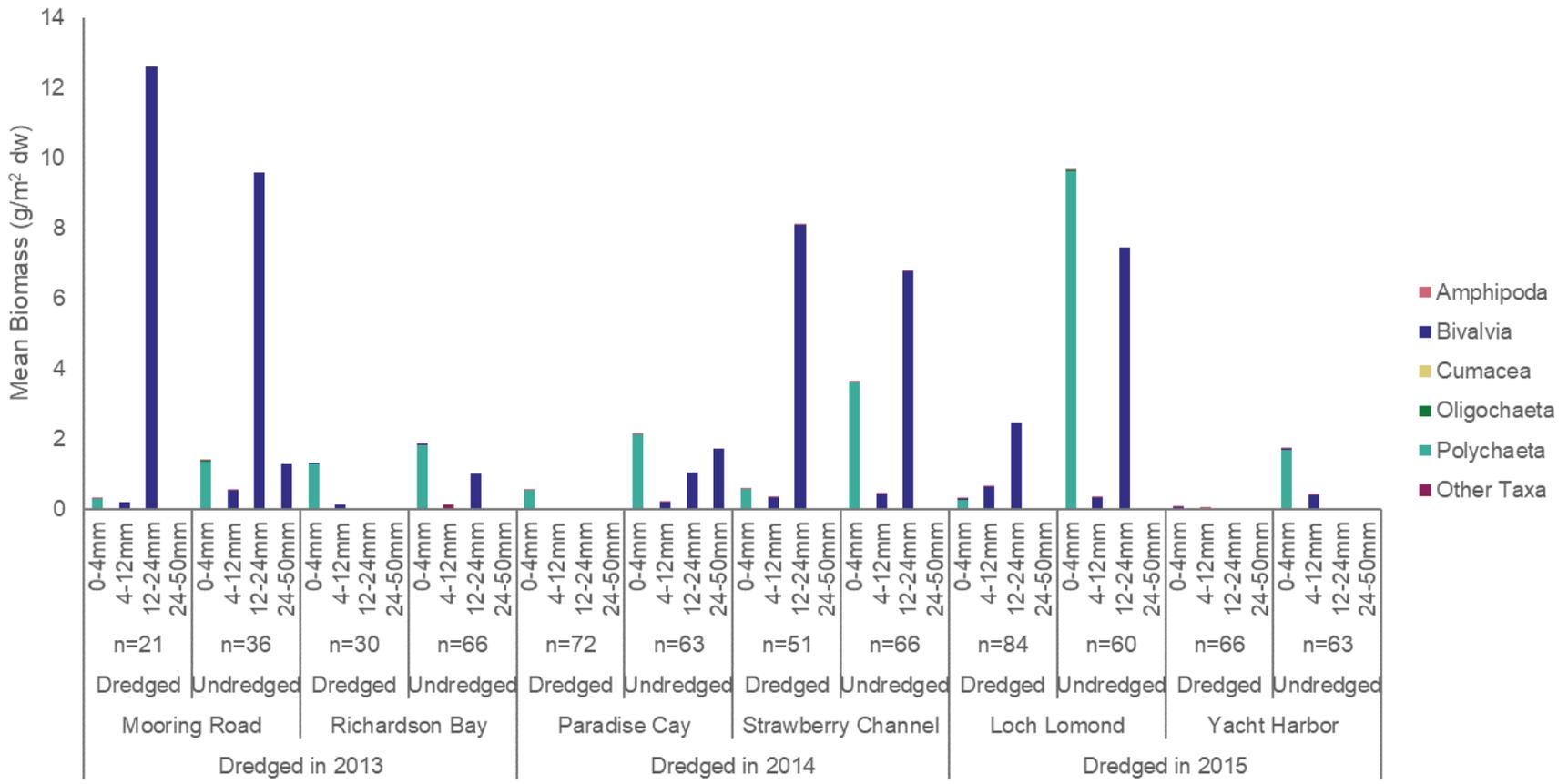


Figure 37. Mean biomass (grams per square meter [g/m²] dry weight (dw)) of macroinvertebrate taxa from different size classes in deep cores (4–10 centimeter [cm]) from dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at all sites during the full study (August 2016, January 2017, August 2017).

Total energy content of 0–4 mm and 4–12 mm macroinvertebrate prey in surface cores (0–4 cm) and 0–50 mm prey in whole cores (0–10 cm) was significantly greater in undredged areas compared to dredged areas (table 12). As with biomass, there were no clear effects of season, salinity, or elevation on energy content; instead, the effects varied depending on the core depth and macroinvertebrate size class (table 12). Overall, energy content of all macroinvertebrate size classes (0–50 mm) in whole cores (0–10 cm) varied among sampling periods. In August 2016 and January 2017, energy content was much greater at dredged and undredged locations at Mooring Road (dominated by *Bivalvia*) compared with all other sites that were dominated by *Polychaeta* (fig. 38, 39). Energy content was more similar among sites during the August 2017 sampling period, though Paradise Cay dredged area notably had the greatest energy content and was dominated by *Polychaeta* (fig. 40). In contrast to biomass, much of the available energy content at each site for both surface and deep

cores was from *Polychaeta*, except for Mooring Road which was dominated by energy from *Bivalvia* near the surface (0–4 cm deep) in the 12–24 mm size class (figs. 41–42).

Overall, potential trophic support for target fishes expressed as average prey biomass available for each species and age class across all sampling sites ranged from 3.04 g/m² for juveniles fishes that forage on 0–4 mm prey in the shallow (0–4 cm) sediment of dredged areas to 56.97 g/m² for larger fishes exploiting prey in all size classes (0–50 mm) in both shallow and deep (0–10 cm) sediment in undredged areas (table 2). Total mean available prey biomass in dredged sites range from 35 to 51 percent less than that in undredged sites (table 2). Average energy (secondary productivity) ranged from a low of 50.23 kJ/m² for 0–4 mm prey in shallow, dredged sediments to a high of 310.11 kJ/m² for fish that consume all prey size classes at all core depths (table 2). Total mean available energy was 40 to 50 percent less at dredged sites compared to undredged sites (table 2).

Table 12. Summary of general linear mixed model (GLMM) results for total energy of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) within dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.12 to 1.16 in appendix for more information. **Abbreviations:** mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	<0.001	<0.001	<0.001
Treatment: undredged	<0.001	<0.001	0.467	0.249	<0.001
Season: winter	<0.001	<0.001	0.952	<0.001	0.016
Salinity	<0.001	0.002	0.408	<0.001	0.001
Elevation	0.004	0.087	0.001	<0.001	0.794

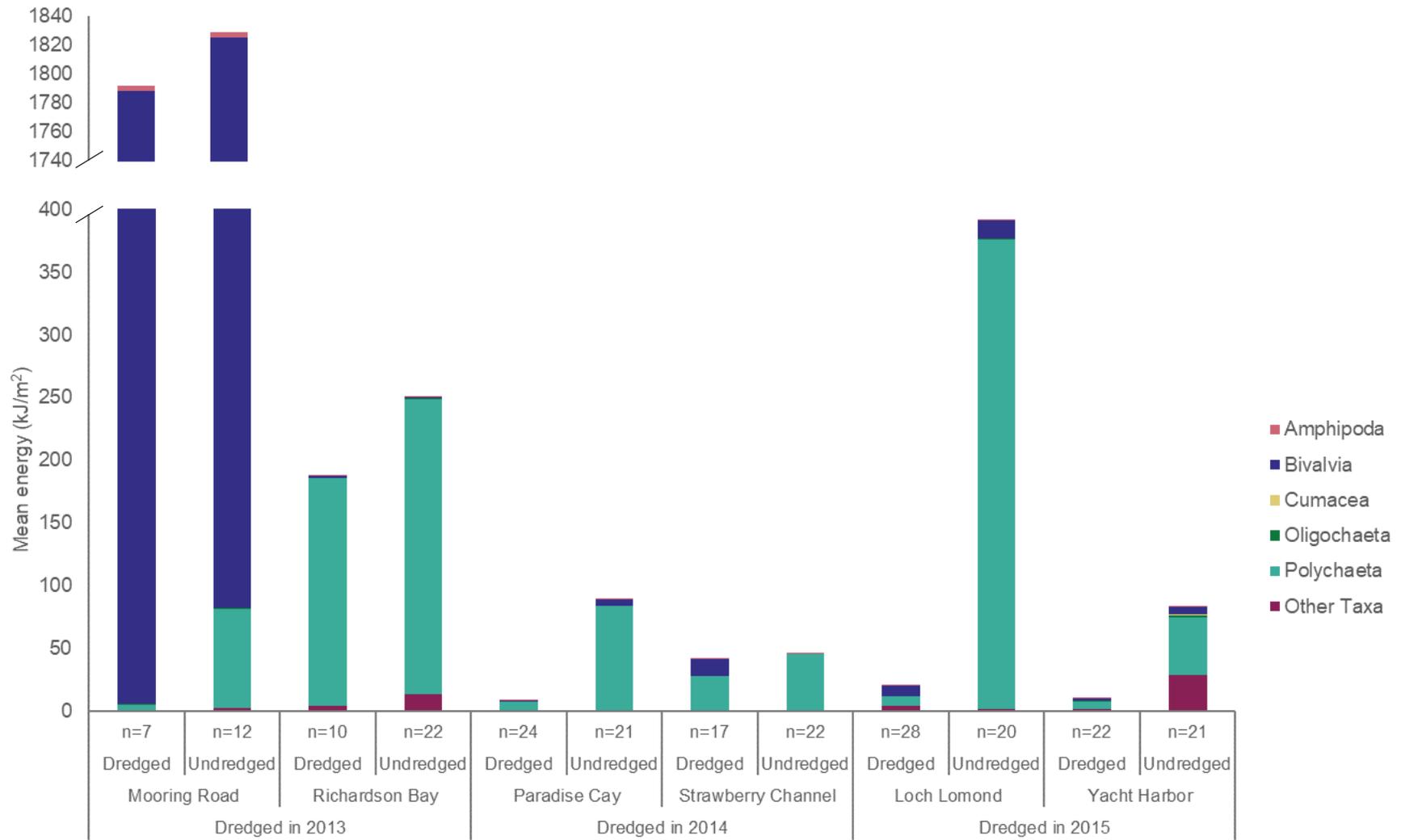


Figure 38. Mean energy (kilojoules per square meter [kJ/m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in August 2016.

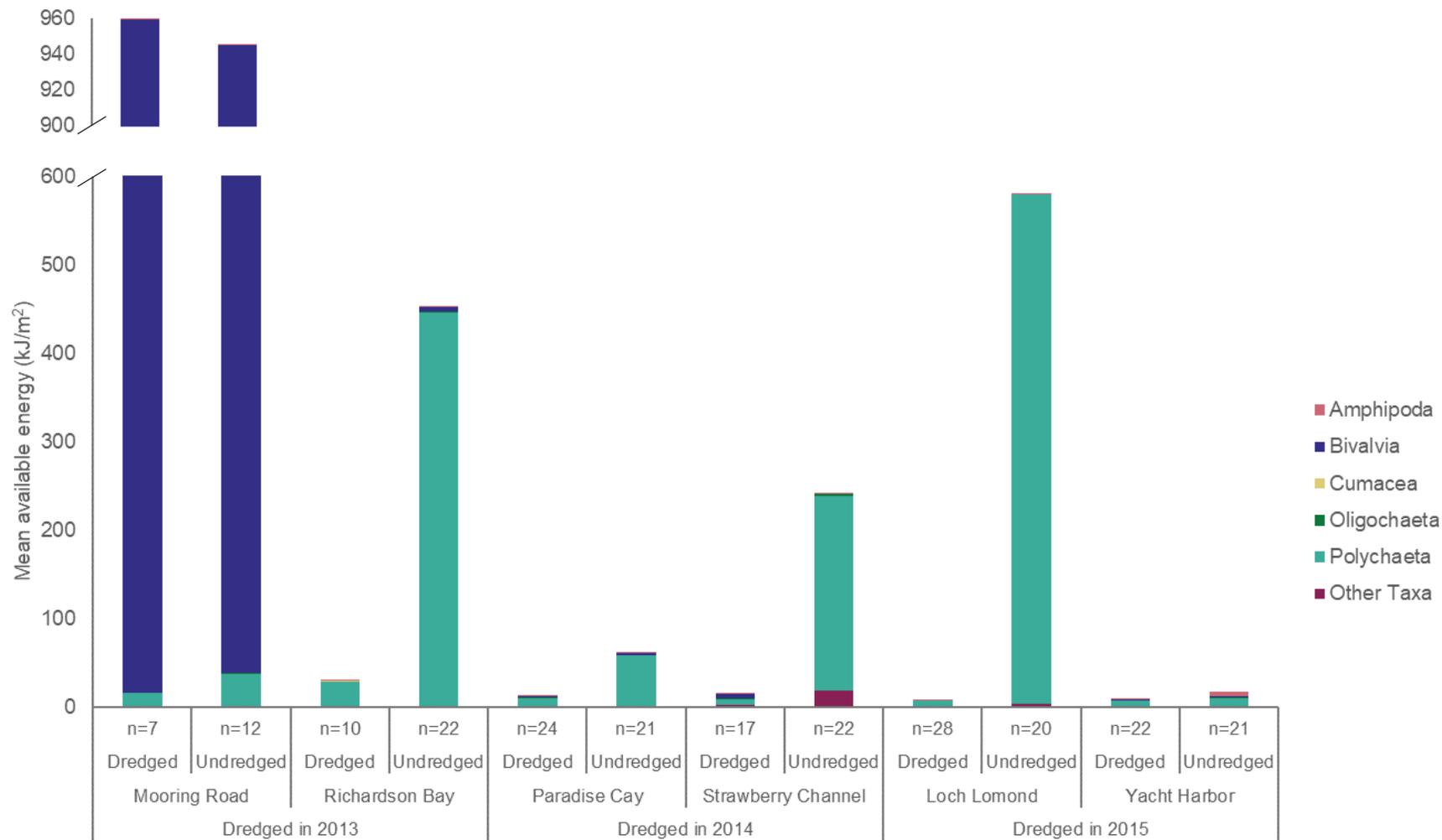


Figure 39. Mean energy (kilojoules per square meter [kJ/m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in January 2017.

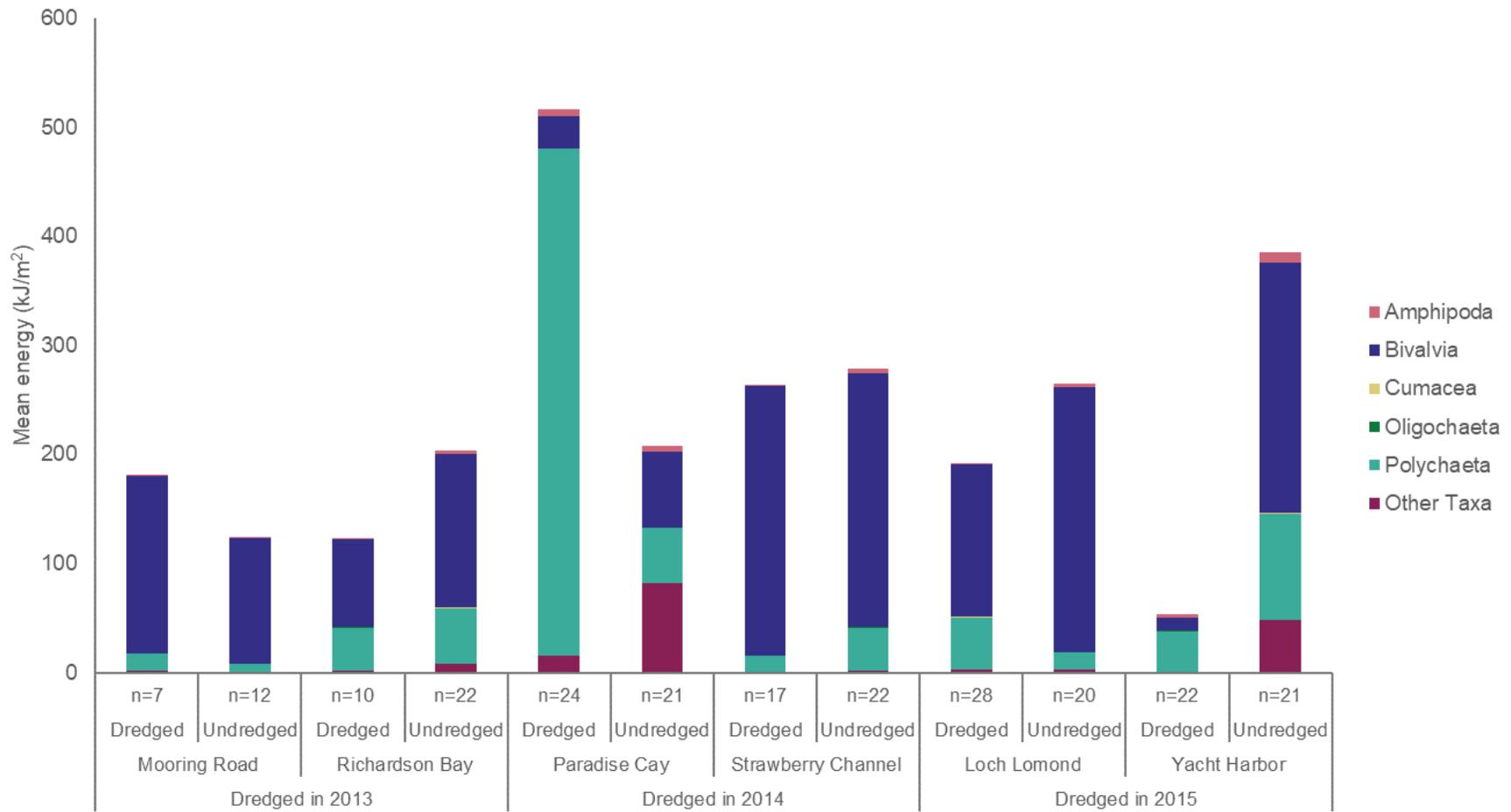


Figure 40. Mean energy (kilojoules per square meter [kJ/m²] to 10 centimeter [cm] depth) of macroinvertebrate taxa collected in dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in August 2017.

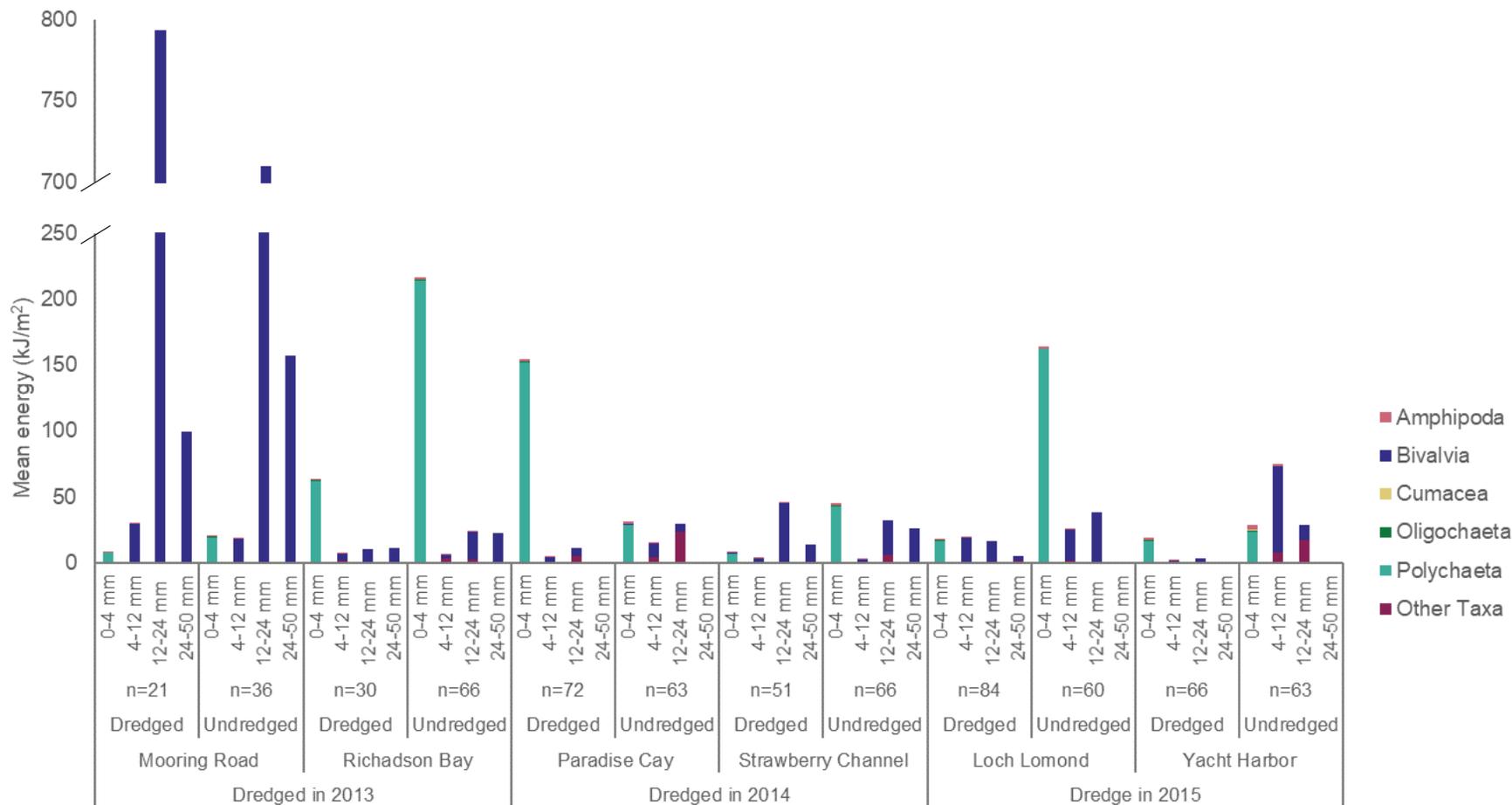


Figure 41. Mean energy (kilojoules per square meter [kJ/m²]) of macroinvertebrate taxa from different size classes in shallow cores (0–4 centimeter [cm]) from dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at all sites during the full study (August 2016, January 2017, August 2017).

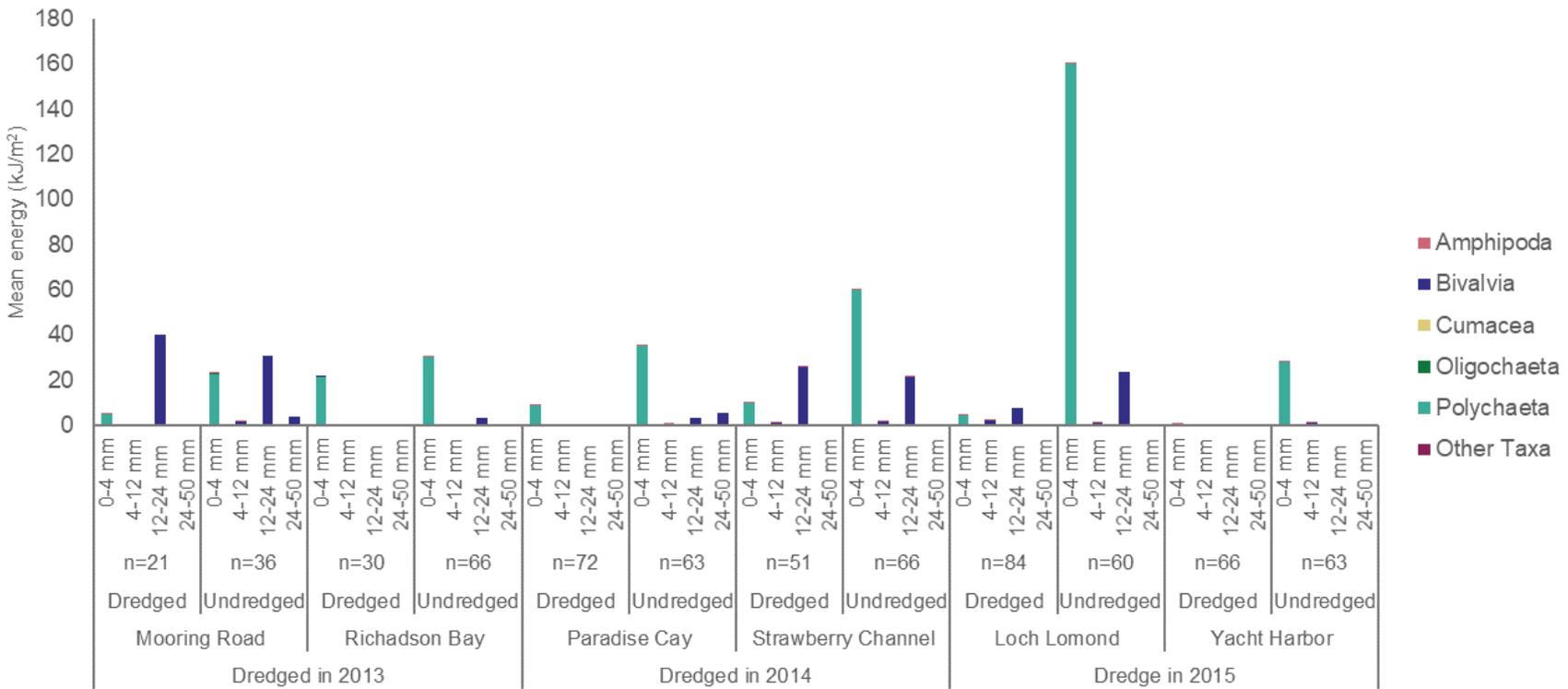


Figure 42. Mean energy (kilojoules per square meter [kJ/m²]) of macroinvertebrate taxa from different size classes in deep cores (4–10 centimeter [cm]) from dredged and undredged areas at six study sites (Mooring Road, Richardson Bay, Paradise Cay, Strawberry Channel, Loch Lomond, and Yacht Harbor) in San Francisco Bay. Cores were collected at all sites during the full study (August 2016, January 2017, August 2017).

The Effect of Distance and Time on Macroinvertebrate Density, Biomass and Energy Content

The effect of distance to nearest dredged area on macroinvertebrate density, biomass, and energy differed among macroinvertebrate size classes and core depths. Density of 0–4 mm macroinvertebrates at the surface (0–4 cm deep) decreased significantly with increasing distance from dredged area, while densities of all other size classes and core depths, except for 24–50 mm size-class at the surface were not significantly affected by the distance to nearest dredged area (table 13; fig. 43). Likewise, biomass of 0–4 mm macroinvertebrates at the surface (0–4 cm deep) also decreased significantly as distance to the nearest dredged area increased; however, biomass of 12–24 mm and 24–50 mm macroinvertebrate size classes at the surface and 0–50 mm macroinvertebrates in whole cores (0–10 cm deep) increased significantly as the distance to the nearest dredged area increased (table 14; fig. 44). Energy content of

0–4 mm surface (0–4 cm deep) macroinvertebrates followed the same patterns as density and biomass, decreasing significantly as distance to the nearest dredged area increased. Similar to biomass, energy content of 12–24 mm and 24–50 mm macroinvertebrates at the surface and 0–50 mm macroinvertebrates in whole cores (0–10 cm deep) increased significantly as the distance to the nearest dredged area increased (table 15; fig. 45).

We found a positive effect of time-since-dredging on macroinvertebrate density, biomass, and energy content. All three parameters increased significantly for all size classes and core depths as time-since-dredging increased, except for the density of 0–4 mm macroinvertebrates at the surface which was not significantly affected by time-since-dredging (tables 16–18; figs. 46–48). In addition, density, biomass, and energy models for 24–50 mm macroinvertebrates in surface cores did not converge, so an effect of time could not be evaluated for this class of macroinvertebrates. Season (winter) and salinity had a negative relationship with biomass and energy content for all size classes and core depths (tables 17–18).

Table 13. Summary of general linear mixed model (GLMM) results testing the effects of distance from dredged areas (meters [m]), season, salinity (practical salinity units [psu]), and elevation (m) on total density of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during August 2016, January 2017, and August 2017. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.17 to 1.21 in appendix for more information. Abbreviations: mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	<0.001	X ¹	<0.001
Distance from dredged (m)	0.043	<0.001	<0.001		0.423
Season: winter	<0.001	<0.001	0.006		0.018
Salinity	<0.001	<0.001	0.133		0.013
Elevation	<0.001	<0.001	0.235		<0.001

¹Model did not converge owing to limited data.

Table 14. Summary of general linear mixed model (GLMM) results testing the effects of distance to nearest dredged areas (meters [m]), season, salinity (practical salinity units [psu]), and elevation (m) on total biomass of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.22 to 1.26 in appendix for more information. Abbreviations: mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>P</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	0.004	<0.001	<0.001	<0.001	<0.001
Distance from dredged (m)	0.038	0.134	0.419	0.605	<0.001
Season: winter	<0.001	<0.001	0.005	<0.001	<0.001
Salinity	<0.001	<0.001	0.110	<0.001	0.053
Elevation	0.355	0.147	<0.001	<0.001	<0.001

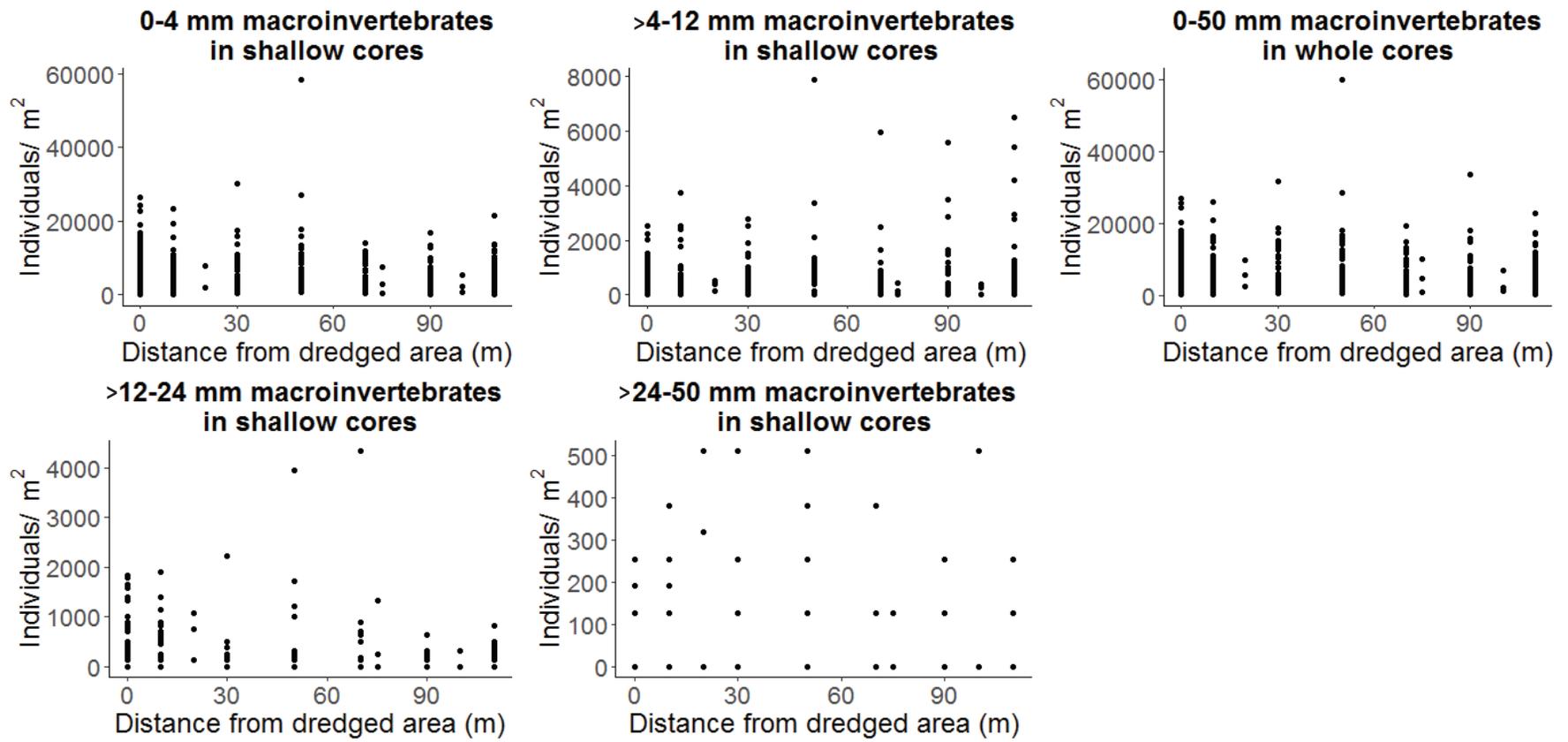


Figure 43. Change in macroinvertebrate density (individuals/square meter [m²]) by size class in shallow (0–4 centimeter [cm]) and whole (0–10 cm) core fractions with increasing distance (meter [m]) from a dredged area. Cores were collected at six study sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) in San Francisco Bay.

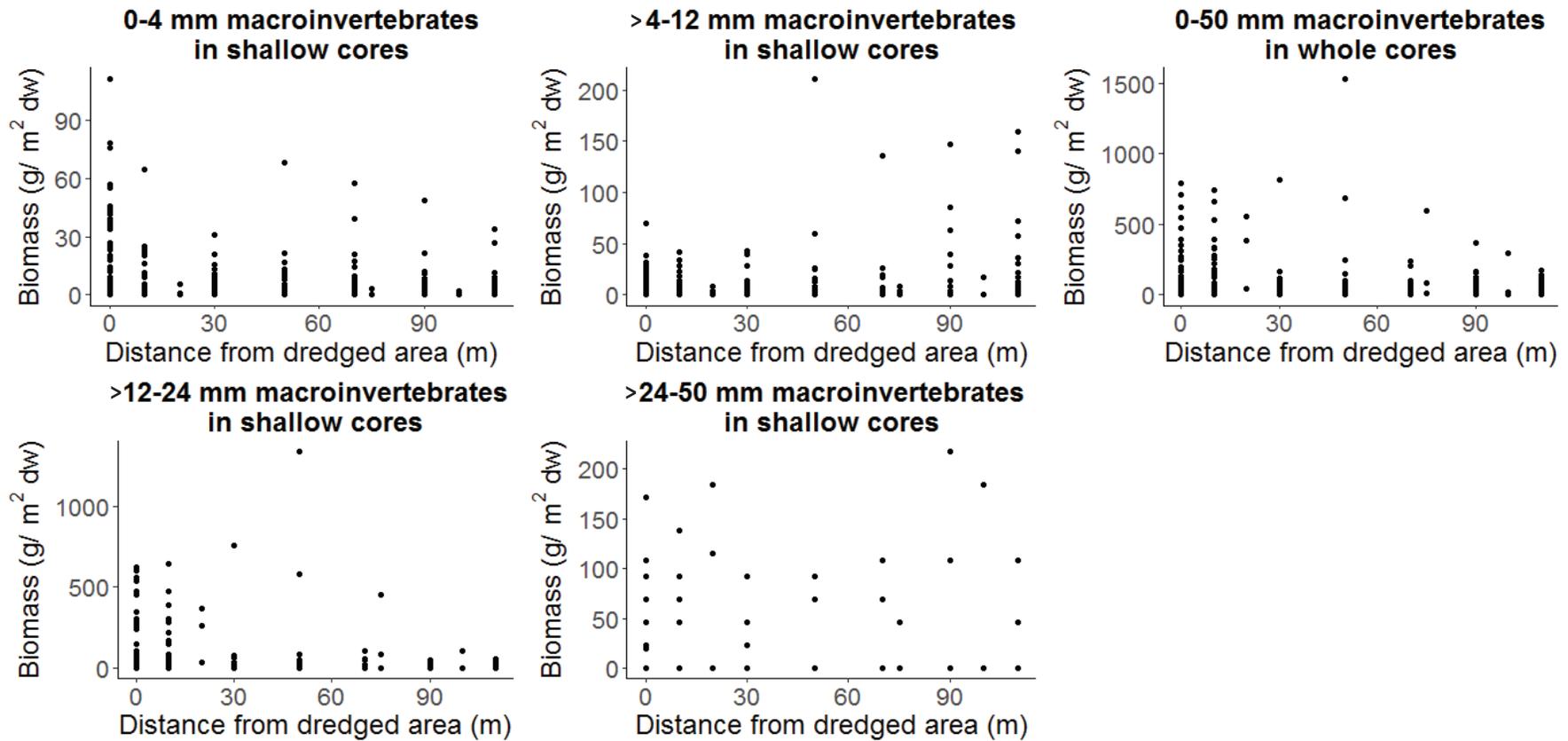


Figure 44. Change in macroinvertebrate biomass (grams per square meter dry weight [g/m² dw]) by size class in shallow (0–4 centimeters [cm]) and whole (0–10 cm) core fractions with increasing distance (meters [m]) from a dredged area. Cores were collected at six study sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) in San Francisco Bay.

Table 15. Summary of general linear mixed model (GLMM) results testing the effects of distance from dredged areas (meters [m]), season, salinity (practical salinity units [psu]), and elevation (m) on total energy of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.27 to 1.31 in appendix for more information. **Abbreviations:** mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Macroinvertebrate size class	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	<0.001	<0.001	<0.001
Distance from dredged (m)	0.032	0.061	0.277	0.570	<0.001
Season: winter	<0.001	<0.001	0.946	<0.001	0.136
Salinity	<0.001	0.003	0.415	<0.001	<0.001
Elevation	0.286	0.022	<0.001	<0.001	0.009

Table 17. Summary of general linear mixed model (GLMM) results testing the effects of time since dredged (years), season, salinity (practical salinity unit [psu]), and elevation (meter [m]) on total biomass of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.37 to 1.40 in appendix for more information. **Abbreviations:** mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Macroinvertebrate size class	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	0.177	<0.001	<0.001	X ¹	<0.001
Time since dredged (years)	<0.001	<0.001	0.025		<0.001
Season: winter	<0.001	<0.001	<0.001		<0.001
Salinity	0.032	<0.001	<0.001		<0.001
Elevation	0.003	0.059	0.167		0.414

¹Model did not converge owing to limited data.

Table 16. Summary of general linear mixed model (GLMM) results testing the effects of time-since-dredged (years), season, salinity (practical salinity units [psu]), and elevation (meters [m]) on total density of macroinvertebrates from different size classes found in shallow (0–4 centimeter [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during August 2016, January 2017, and August 2017. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.32 to 1.36 in appendix for more information. **Abbreviations:** mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Macroinvertebrate size class	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	0.262	X ¹	<0.001
Time since dredged (years)	0.144	0.025	0.015		0.001
Season: winter	0.032	<0.001	0.035		0.403
Salinity	0.092	<0.001	0.868		0.551
Elevation	0.141	0.005	0.220		0.174

¹Model did not converge owing to limited data.

Table 18. Summary of general linear mixed model (GLMM) results testing the effects of time since dredged (years), season, salinity (practical salinity units [psu]), and elevation (meters [m]) on total energy of macroinvertebrates from different size classes found in shallow (0–4 centimeters [cm]) and deep (0–10 cm) cores at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Orange indicates the relationship between density and the fixed effect was positive, and purple indicates that the relationship was negative. See full GLMM tables 1.41 to 1.44 in appendix for more information. **Abbreviations:** mm, millimeter; >, greater than; <, less than]

Core depth	0–4 cm				0–10 cm
	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Macroinvertebrate size class	0–4 mm	>4–12 mm	>12–24 mm	>24–50 mm	0–50 mm
Fixed effect	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>	<i>p</i>
Intercept	<0.001	<0.001	<0.001	X ¹	<0.001
Time since dredged (years)	<0.001	<0.001	0.003		<0.001
Season: winter	<0.001	<0.001	<0.001		<0.001
Salinity	0.019	<0.001	<0.001		<0.001
Elevation	0.006	0.003	0.129		0.013

¹Model did not converge owing to limited data.

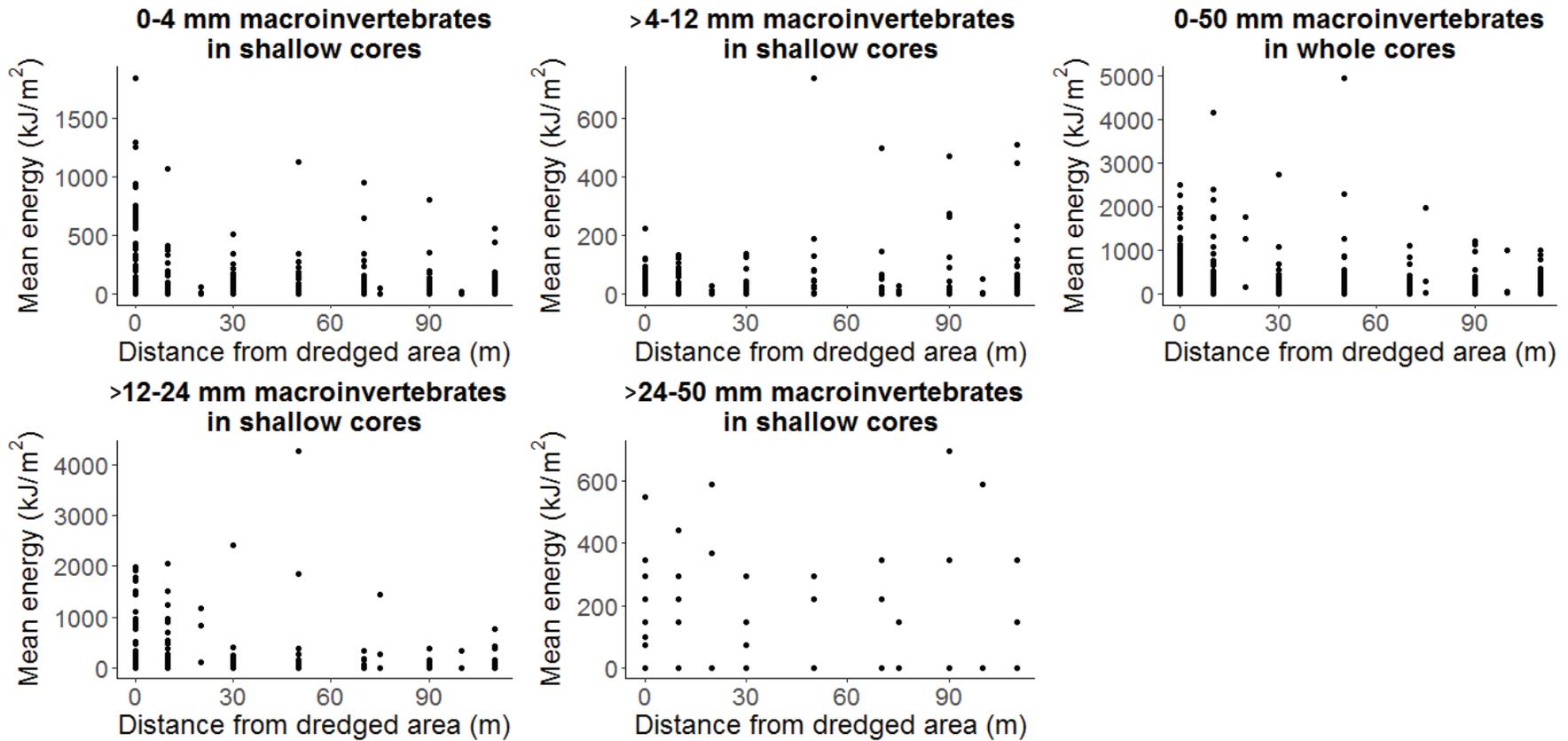


Figure 45. Change in macroinvertebrate energy (kilojoules per square meter [kJ/m²]) by size class in shallow (0–4 centimeter [cm]) and whole (0–10 cm) core fractions with increasing distance (m) from a dredged area. Cores were collected at six study sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) in San Francisco Bay.

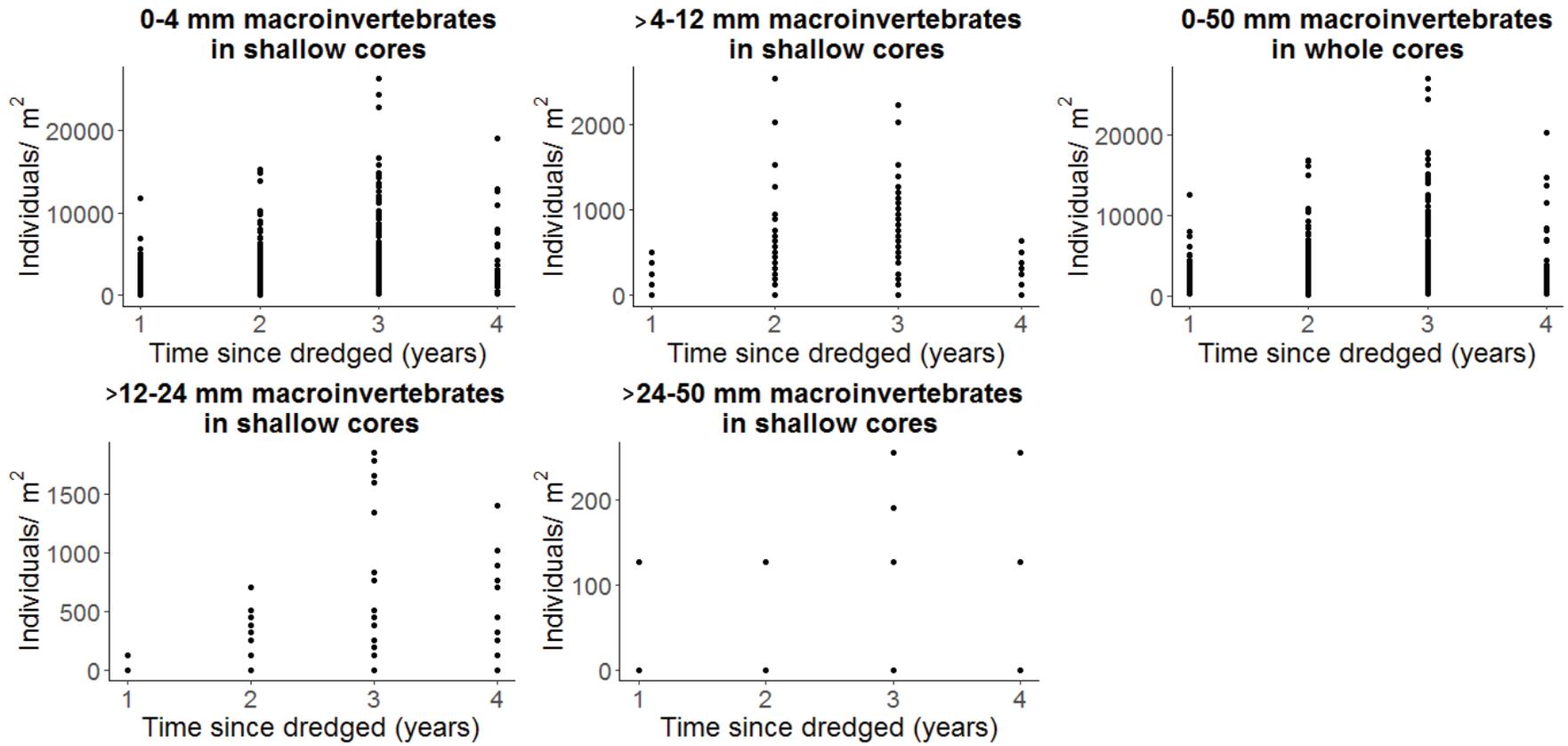


Figure 46. Change in macroinvertebrate density (individuals/square meter [m²]) by size class in shallow (0–4 centimeter [cm]) and whole (0–10 cm) core fractions with increasing time (years) since a site was dredged. Cores were collected at six study sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) in San Francisco Bay.

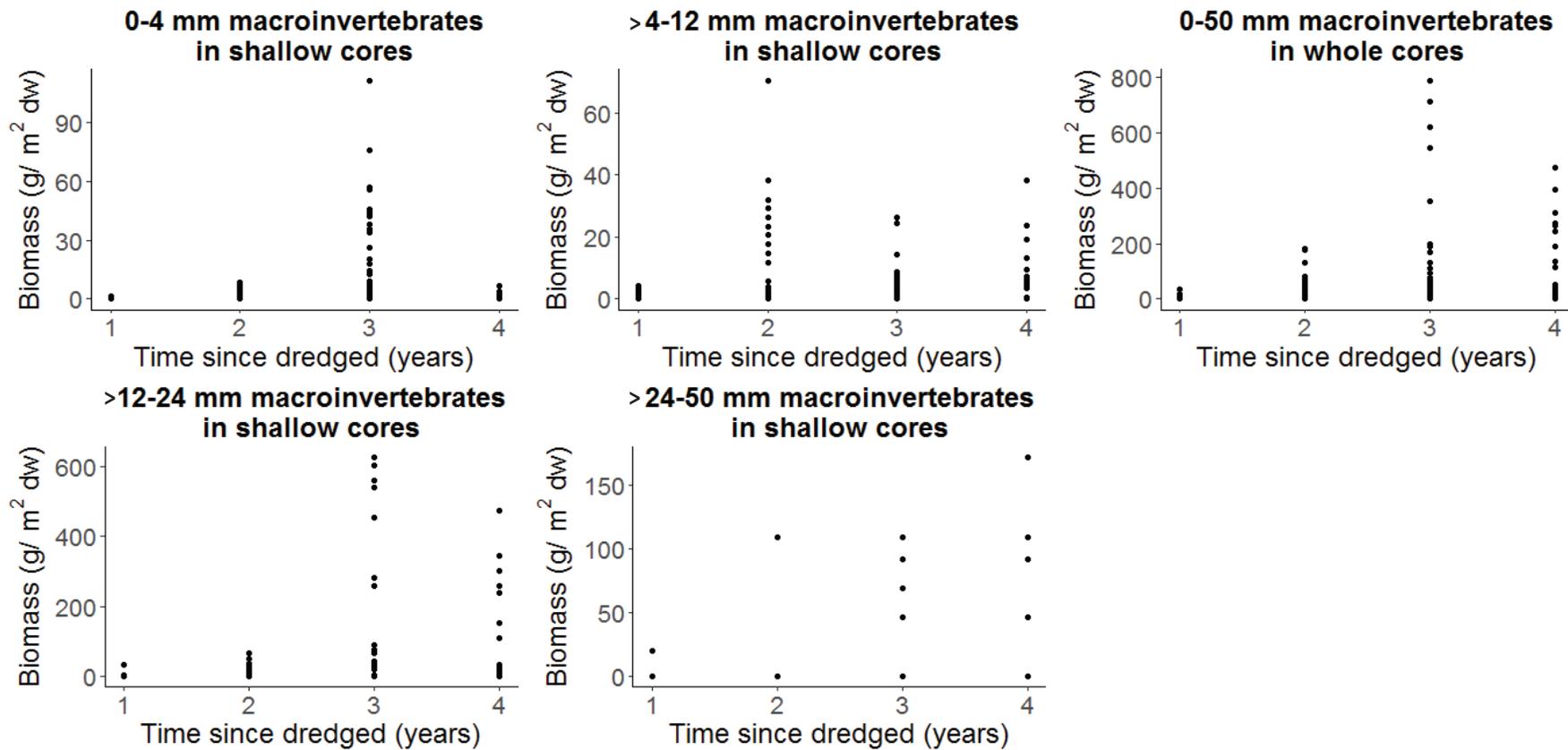


Figure 47. Change in macroinvertebrate biomass (grams per square meter dry weight [g/m² dw]) by size class in shallow (0–4 centimeters [cm]) and whole (0–10 cm) core fractions with increasing time (years) since a site was dredged. Cores were collected at six study sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) in San Francisco Bay.

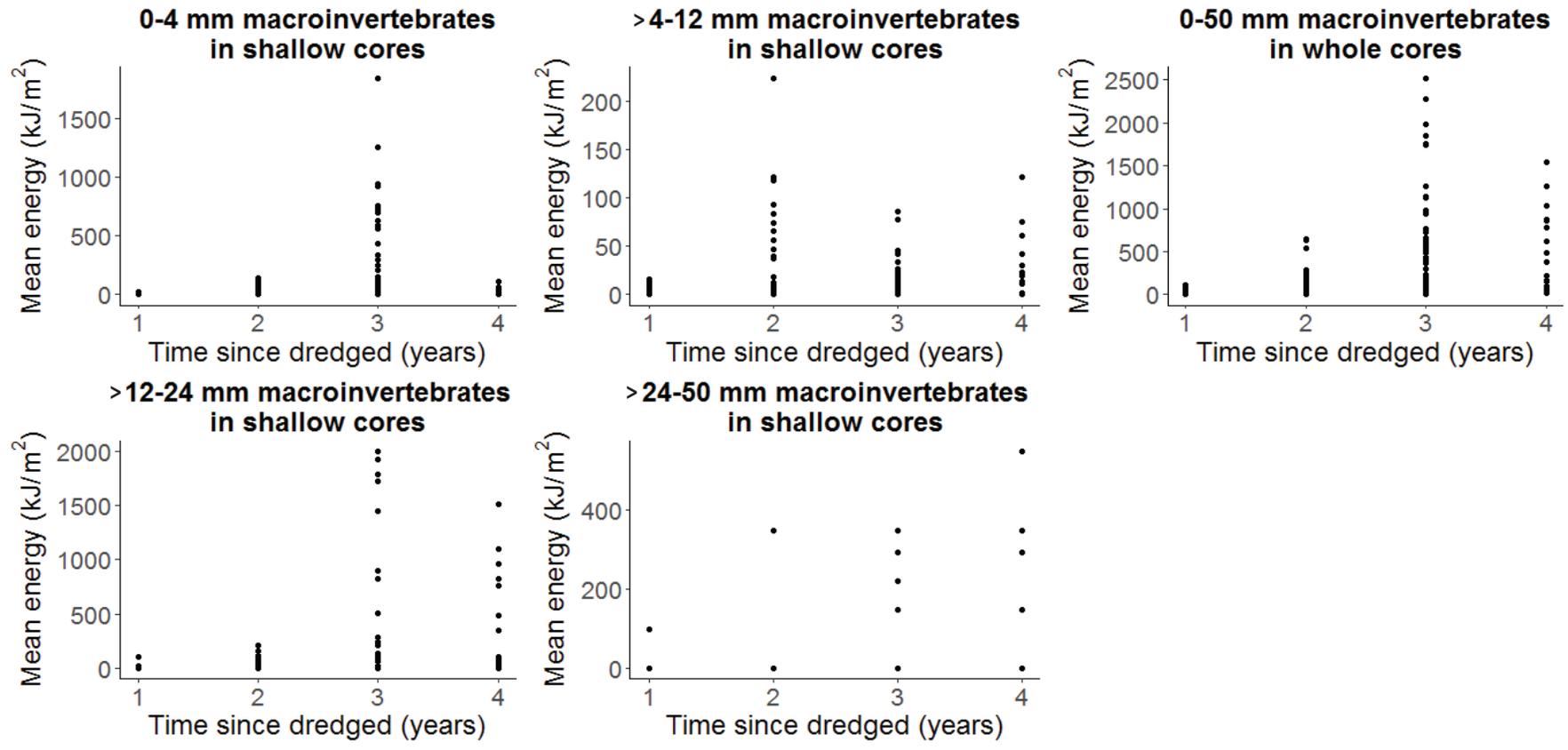


Figure 48. Change in macroinvertebrate energy (kilojoules per square meter [kJ/m²]) by size class in shallow (0–4 centimeters [cm]) and whole (0–10 cm) core fractions with increasing time (years) since a site was dredged. Cores were collected at six study sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) in San Francisco Bay.

Discussion

We evaluated the effects of maintenance dredging in shallow marinas on trophic support for target benthic foraging fish species that inhabit EFH in SFB. We used a MBRAT to evaluate foraging habitat quality in terms of prey availability for target fish species. We found significantly lower density, biomass, and energy content for all available prey size classes and depths in dredged compared to adjacent undredged areas; dredged areas had lower prey availability than undredged areas for all target fish species. However, our study also demonstrated significant increases in prey density, biomass, and energy as time since dredging increased, indicating functional recovery of dredged areas for benthic foraging fishes may begin within the 3-year window that we examined in this study. Distance to dredged area also influenced biomass and energy content of some sizes of macroinvertebrate prey, such that they increased significantly as distance from dredged area increased.

Given the scope of our study, we mainly focused on functional (biomass and energy content) metrics to compare macroinvertebrate prey availability for focal fish species as a function of dredging status (dredged versus undredged), distance to dredged areas, and time-since-dredging. The MBRAT method we used is a functional metric that integrated size class, vertical distribution in the sediment, biomass, and secondary productivity (energy content) to detect changes in prey resources as a response to dredging disturbance. While we did evaluate some structural measures (density and community taxonomic structure), our study was mainly focused on trophic support for target fish species, and thus our results were not intended to compare structural and functional recovery. Functional recovery of a site can occur before the structural recovery of a macroinvertebrate community (Cooper and others, 2008), and in fact there may be no clear relationship between the two. For example, in a study of 14 dredge disposal sites in England, Bolam (2012) did not find a relationship between multivariate structural changes and taxonomic contribution to total energy production, demonstrating change in structure does not always signify a significant functional impact or vice versa. Functional traits, such as those we measured (available biomass and energy), have been advocated for assessing anthropogenic effects (Elliott and Quintino, 2007) as well as implications of dredging activities for foraging predators in mudflats (Lunz and Kendall, 1982; Bolam, 2014).

Influence of Physical Characteristics

We deliberately selected sampling sites for this study to minimize differences among them, such that inference about the effects of dredging could be maximized. Criteria for site selection required that physical characteristics such as salinity,

sediment composition, and depth be within a narrow range among sites. However, localized seasonal influences, such as freshwater input from creeks, can influence site characteristics. The fact that we did find significant differences in some physical factors among sites emphasizes the importance of the localized, undredged reference areas included at each of our sampling sites to account for effects and variations that could not be completely accounted for across our sites, despite their proximity to one another.

Consistent with other studies (Boyd and others, 2005; Applied Marine Sciences Inc., 2009; Abdul Wahab and others, 2017), we found significant differences in sediment characteristics between dredged and undredged sites. Although overall, sediments from all dredged and undredged areas were characterized as loamy, we found that mean percent silt was significantly greater in undredged sediments and sand was greater in dredged sites. Benthic community assemblages can respond to differences in sediment type and particle size (Desprez, 2000; Wilber and Clarke, 2007). Fine-grained silty sediments typically have greater macroinvertebrate density and taxonomic richness (Thompson and others, 2000; Lee and others, 2003) compared to coarser sandy sediments (Thompson and others, 2007). Although our study was not designed to evaluate the role of subtle differences in sediment texture on species composition, such underlying characteristics may have contributed to the differences we measured among macroinvertebrate densities and biomass between dredged and undredged sites.

We measured a marked decrease in demersal salinity at all sites during the January 2017 sampling period compared with all other sampling periods, including the previous winter. Decreased salinity coincided with anomalous extreme rainfall and freshwater inputs to SFB (<https://nwis.waterdata.usgs.gov>; Swain and others, 2018) as a result of multiple large-scale storms during winter 2016–17. During our subsequent sampling period (August 2017), we observed broad taxonomic shifts in both dredged and undredged areas at all sites, including sharp decreases in polychaete, oligochaete, and bivalve densities and large increases in amphipod densities. While seasonal variation in the distribution and abundance of benthic communities in SFB is predominantly driven by annual salinity cycles, inter-annual variation, such as that seen our study, is largely influenced by Sacramento -San Joaquin River Delta outflow, local runoff, or pollution (Nichols and Pamatmat, 1988). Similar patterns have been observed in other estuaries. For example, In the Mondego estuary, Portugal, Grilo and others (2011) found prolonged flooding had a much stronger negative effect on macroinvertebrate abundance than drought in both mudflat and sandflat environments. Similar to our results, deposit and suspension feeding detritivores, such as bivalves and oligochaetes, showed the greatest decreases in abundance following prolonged freshwater inputs (Grilo and others, 2011).

Several benthic macroinvertebrate sub-assemblages within SFB exhibit strong responses to annual variability in freshwater influx (Markmann, 1986; Peterson and Vayssieres, 2010), but Central Bay assemblages typically remain consistent. The Central Bay sustains a more diverse benthic community across seasons because the salinity regime is relatively stable and not as influenced by freshwater flows compared with other SFB regions (Thompson and others, 2000). In winter, during increased freshwater input, the surface salinity in the Central Bay can rapidly decrease (from 30 to 10 ppt); however, salinity values in demersal waters tend to be more stable owing to density-driven stratification (Cloern and others, 2000). Still, large freshwater influx to the Central Bay can drive spatial patterns in benthic assemblages, particularly in shallow shoal areas (Thompson and others, 2007). For example, Thompson and others (2000) found that abundance of the amphipod *M. acherusicum* in the Central Bay varied substantially among years and peaked in association with increased freshwater inputs. This is similar to the response we detected in amphipod abundances at all sites in summer 2017 following the intense flooding events of winter 2016–17. Although we observed dramatic shifts in taxa following these freshwater events at all but one site (Paradise Cay), the number of taxa and overall densities still were greater in undredged compared to dredged areas the following summer.

The Effect of Dredging on Trophic Support for Target Fishes

Based on an extensive literature review (De La Cruz and others, 2016), we expected the greatest levels of trophic support to co-occur with peak summer densities among most target fishes in SFB. Although many studies have noted that density and biomass for some common fish prey taxa such as amphipods (Chapman, 1988; Cohen and Carlton, 1995; Greenstein and Tiefenthaler, 2013) and bivalves (Radtke, 1966; McKechnie and Fenner, 1971; Haderlie and Abbott, 1980; Emmett and others, 1991; Thompson and others, 2007) are higher during summer compared to winter months, we observed temporal variations in macroinvertebrate patterns that were independent of dredging status and were more likely driven by anomalous freshwater events (see discussion of physical characteristics above).

Similar to other studies (Hirsch and others, 1978; LaSalle, 1990; Clarke and others, 2000; Dernie and others, 2003; Wilber and others, 2008; Lebednik, 2004; Rich, 2010), we found dredged areas had significantly less macroinvertebrate density, biomass, and energy content compared to paired undredged areas, resulting in lower overall trophic support for target fish species. However, the degree of impact depended

on the macroinvertebrate size class consumed and the foraging depth of each target fish species. For example, juvenile Pacific sardine, longfin smelt, northern anchovy, and brown rockfish that consume the smallest prey size class (0–4 mm) and forage within the shallow benthos (0–4 cm depth) had the lowest mean prey biomass and energy available compared with all other target species and age classes. Both available biomass and energy were 44 percent less in dredged areas compared to undredged areas that were accessible to these fishes. Larger fishes and adult life stages that were able to exploit all macroinvertebrate size classes and both shallow and deep depths had more prey available to them at dredged sites, but this still represented an average of 41 percent less biomass and 50 percent less energy than at undredged sites. Interestingly, the greatest reduction (51 percent) of available mean biomass in dredged areas occurred for fish that forage on the smallest two size classes of macroinvertebrates (0–4 and 4–12 mm) in shallow sediments, such as juvenile English sole and juvenile starry flounder. Fish species that were least impacted by dredging (35 percent reduction in biomass and 40 percent reduction in energy compared to undredged) included those that forage on small and intermediate size classes (0–4, 4–12, and 12–24 mm) in shallow sediments, such as adult Pacific sardine and adult longfin smelt.

As expected, based on our pilot work and previous studies (Clarke, 1986), we found that macroinvertebrate densities and biomass were concentrated in the top 0–4 cm of cores in both dredged and undredged areas, though in many undredged areas a large proportion of the total biomass occurred in deeper fractions of the core. Concentration of prey at the surface often occurs in the early stages of succession post dredging and in some cases can increase prey availability for fish species (Rhoads and Germano, 1986). Later successional stage macroinvertebrates are typically larger, longer-lived species that can burrow deeper in the sediment (Rhoads and Germano, 1986). For example, we found most of the biomass and energy in whole cores from undredged areas was contributed by intermediate 12–24 mm bivalves or 0–4 mm (head width) polychaetes. Although fewer in number, intermediate to large-sized (12–24 and 24–50) macroinvertebrates can be important, high-caloric prey for deep, benthic-foraging, target fishes such as leopard shark, Dungeness crab, sturgeon, and skates (Talent, 1976; Barry, 1983; Barry and others, 1996; Adams and others, 2002; Ebert and Ebert, 2005; Yang, 2007; Bizzarro and others, 2007; Israel and Klimley, 2008; De La Cruz and others, 2016). In fact, across all undredged areas and time periods, deep core fractions provided up to 15 percent more available prey biomass and energy for species that could access this depth than the maximum biomass and energy contained in shallow core fractions from undredged areas.

The of Effects of Distance and Time

We found that macroinvertebrate density, biomass, and energy varied by distance from a dredged area. The density of the smallest macroinvertebrate size class (0–4 mm) at the surface (0–4 cm deep) decreased significantly the farther we sampled from a dredged area, and biomass and energy content of larger size classes at deeper depths increased with distance from dredged area. For small-scale disturbances that result in the localized removal of macroinvertebrates in adjacent areas, one way to evaluate the effect of a dredging operation is to evaluate the dispersal capacity of colonizing organisms (Günther, 1992). Organisms with prolonged larval periods that include a pelagic stage, such as crab and bivalve species, may have a relatively greater capacity for longer-distance dispersal and recolonization compared to macroinvertebrate taxa with crawling or brooding larvae, such as many polychaete species, that may disperse as juveniles or adults (Lundquist and others, 2004). Günther (1992) found that localized disturbances were associated with the dispersal and recolonization by post-larval life stages and to a lesser degree immigration of adults, whereas in larger disturbed sites, recovery was predominately from the dispersal of long-distance planktonic larvae. Lundquist and others (2004) conducted simulations with a hydrodynamic and particle-tracking model and predicted that small larvae would disperse farther than larger, heavier larvae and juveniles. At our sites, the greatest densities and biomass of the smallest macroinvertebrate species were found closer to dredged areas, while larger species increased with increasing distance from the dredge area, indicating maintenance dredging may have created localized disturbance that impacted the size class, depth, biomass, and energy content of adjacent benthic communities at short distances. Fishes that forage on the smallest prey on the sediment surface (such as, juvenile Pacific sardine, juvenile longfin smelt, juvenile rockfish) may in some cases benefit from such disturbance, while larger fishes that consume larger prey (0–24 mm or 0–50 mm) at the surface or to 10-cm depth (such as, adult northern anchovy, adult starry flounder, adult brown rockfish, adult California halibut) may experience reduced available prey resources.

By incorporating marinas that were dredged at 1, 2, and 3 years prior to our study, we were able to examine

how quickly structural and functional metrics of benthic habitat for foraging fish might begin to approximate those of adjacent undredged areas. We found that macroinvertebrate density, biomass, and energy content within every size class and depth, except density of 0–4 mm prey and energy from 12 to 24 mm prey in shallow sediments, increased with time-since-dredging. From the standpoint of trophic support for fishes, our findings indicate an increase in available prey coincided with time-since-dredging for most species and ages of target fishes. However, after repeatedly sampling the same sites during four sampling periods across 2 years, we found that overall prey density, biomass, and energy in dredged areas only approximated that of undredged areas at two sites, Mooring Road and Paradise Cay, dredged 3 and 2 years prior to the study's inception. Thus, whereas a site may begin to be recolonized shortly after dredging, our study indicated it can take more than 1 to 3 years for a site to recover trophic functions that approximate those of adjacent undredged areas.

Defining benthic recovery and determining the time required for recovery remains a major challenge for the scientific community (Rhoads and Germano, 1986; Bolam and Rees, 2003; Wilber and Clarke, 2007; Wilber and others, 2008). Recovery is often defined as the return of a dredged area to a baseline, pre-impact, or, like the local undredged areas that we evaluated in this study, some definable reference state. Limited information exists about benthic community recovery from dredge disturbance in SFB, and no previous SFB studies have evaluated recovery of relative foraging value for benthic fishes. In contrast to our study conducted in shallow, fine-grained sediment marinas, a sand mining study in deep-water channels within the Central Bay indicated no significant differences in number of taxa or abundance between control areas and areas mined within the previous 3 years (Applied Marine Sciences Inc., 2009). Kenny and Rees (1994) monitored recolonization of a benthic community after a dredge event in the North Sea and observed similar rapid recolonization rates as in our study, but no notable increase in biomass, which in their study indicated the loss of large taxa. At our sites, we observed lower biomass and energy content among larger prey size classes in dredged areas, particularly at sites dredged 1 to 2 years before our study.

Summary

We measured macroinvertebrate density, biomass, and energy content in adjacent dredged and undredged areas at six Central Bay shallow marinas dredged during 2013, 2014, or 2015 to evaluate trophic support for SFB benthic foraging fishes in relationship to: (1) dredged versus undredged locations, (2) distance to dredged areas, and (3) years since dredging. We found several implications for foraging target fish species using these habitats:

- Low salinity events in the Central Bay during winter 2016–17 resulted in broad taxonomic shifts in both dredged and undredged areas at all sites, including sharp decreases in polychaete, oligochaete, and bivalve densities and large increases in amphipod densities. At all but one site (Paradise Cay), the number of taxa and overall densities were greater in undredged compared to dredged areas during the following summer sampling period.
- We detected 104 unique taxa in the shallow (0–4 cm) depth compared to 43 unique taxa in the deep (4–10 cm) depth range. We found a greater taxonomic richness in undredged areas compared to dredged areas.
- Overall, in comparison to undredged reference areas, dredged areas had lower trophic support for all species and ages of fishes included in our study.
- There appeared to be differential impacts of dredging on trophic support for fishes based on macroinvertebrate size class that can be consumed and the depth to which certain fish can forage. For example, fish species that forage on the two smallest size classes of macroinvertebrates (0–4 and 4–12 mm) in shallow benthic habitats, namely juvenile English sole and juvenile starry flounder, experienced the greatest potential impact (51 percent decline in available prey biomass in dredged compared to undredged areas). While fish that were able to exploit small and intermediate prey size classes (0–4, 4–12, and 12–24 mm) in shallow benthic habitats, such as adult Pacific sardine and adult longfin smelt, only experienced a 35 percent reduction in biomass at dredge compared to undredged areas.
- The impact of distance from a dredged area varied by prey size class. Density, biomass, and energy content of the smallest prey size class (0–4 mm) increased closest to dredge disturbance, while larger macroinvertebrate prey resources (12–24 mm and 24–50 mm) had increasing biomass associated with increasing distance from a dredged area.
- In general, macroinvertebrate density, biomass, and energy content within every size class and depth, except density of 0–4 mm prey in shallow sediments, increased with time-since-dredging.
- We found a positive effect of time-since-dredging on macroinvertebrate density, biomass, and energy content such that all three increased for most size classes and depths over time; however, there was little evidence that these measures in dredged areas were equivalent to those of undredged areas within the one to three-year time window we examined.

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Appendix 1.

Supplemental tables and figures

Table 1.1. GLMM results for total density of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.107	0.203	10.365	<0.001
Treatment: undredged	0.332	0.063	5.284	<0.001
Season: winter	0.490	0.112	4.368	<0.001
Salinity	0.033	0.007	5.062	<0.001
Elevation	-0.200	0.055	-3.652	<0.001

Table 1.3. GLMM results for total density of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	1.330	0.346	3.842	<0.001
Treatment: undredged	0.302	0.090	3.347	0.001
Season: winter	-0.783	0.279	-2.801	0.005
Salinity	-0.018	0.012	-1.555	0.120
Elevation	0.182	0.078	2.343	0.019

Table 1.2. GLMM results for total density of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	1.914	0.238	8.048	<0.001
Treatment: undredged	0.402	0.072	5.588	<0.001
Season: winter	-0.797	0.142	-5.611	<0.001
Salinity	-0.033	0.008	-4.111	<0.001
Elevation	-0.279	0.058	-4.780	<0.001

Table 1.4. GLMM results for total density of 24–50 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	-1.252	1.815	-0.690	0.490
Treatment: undredged	0.359	0.114	3.149	0.002
Season: winter	1.186	1.693	0.700	0.484
Salinity	0.042	0.064	0.664	0.507
Elevation	-0.239	0.217	-1.102	0.271

Table 1.5. GLMM results for total density of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.834	0.194	14.586	<0.001
Treatment: undredged	0.420	0.061	6.927	<0.001
Season: winter	0.243	0.107	2.268	0.024
Salinity	0.014	0.006	2.279	0.023
Elevation	-0.187	0.053	-3.538	<0.001

Table 1.7. GLMM results for total biomass of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	-1.233	0.287	-4.294	<0.001
Treatment: undredged	0.736	0.100	7.336	<0.001
Season: winter	1.229	0.172	7.147	<0.001
Salinity	0.135	0.010	14.081	<0.001
Elevation	0.241	0.083	2.919	0.004

Table 1.6. GLMM results for total density of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2015–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	3.531	0.146	24.227	<0.001
Treatment: undredged	0.458	0.059	7.730	<0.001
Season: winter	-0.161	0.069	-2.326	0.020
Salinity	-0.010	0.005	-2.174	0.030
Elevation	-0.203	0.053	-3.843	<0.001

Table 1.8. GLMM results for total biomass of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.548	0.429	12.936	<0.001
Treatment: undredged	0.610	0.151	4.050	<0.001
Season: winter	-3.464	0.258	-13.429	<0.001
Salinity	-0.074	0.015	-5.046	<0.001
Elevation	-0.100	0.123	-0.813	0.417

Table 1.9. GLMM results for total biomass of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	6.704	0.412	16.254	<0.001
Treatment: undredged	-0.226	0.108	-2.100	0.036
Season: winter	-0.938	0.339	-2.765	0.006
Salinity	-0.022	0.014	-1.589	0.112
Elevation	0.294	0.093	3.161	0.002

Table 1.11. GLMM results for total biomass of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.658	0.309	18.292	<0.001
Treatment: undredged	1.022	0.120	8.537	<0.001
Season: winter	-1.943	0.184	-10.554	<0.001
Salinity	-0.027	0.011	-2.534	0.012
Elevation	-0.296	0.095	-3.110	0.002

Table 1.10. GLMM results for total biomass of 24–50 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	24.185	1.828	13.227	<0.001
Treatment: undredged	0.159	0.116	1.376	0.169
Season: winter	-16.280	1.706	-9.540	<0.001
Salinity	-0.625	0.064	-9.722	<0.001
Elevation	-1.326	0.221	-6.004	<0.001

Table 1.12. GLMM results for total energy of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	1.370	0.289	4.746	<0.001
Treatment: undredged	0.710	0.102	6.985	<0.001
Season: winter	1.294	0.174	7.442	<0.001
Salinity	0.142	0.010	14.707	<0.001
Elevation	0.247	0.084	2.929	0.004

Table 1.13. GLMM results for total energy of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.693	0.364	15.656	<0.001
Treatment: undredged	0.595	0.123	4.852	<0.001
Season: winter	-2.246	0.217	-10.347	<0.001
Salinity	-0.039	0.012	-3.096	0.002
Elevation	-0.170	0.099	-1.713	0.087

Table 1.15. GLMM results for total energy of 24–50 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	23.253	1.793	12.968	<0.001
Treatment: undredged	0.131	0.114	1.154	0.249
Season: winter	-14.339	1.674	-8.568	<0.001
Salinity	-0.551	0.063	-8.736	<0.001
Elevation	-1.149	0.216	-5.310	<0.001

Table 1.14. GLMM results for total energy of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor) with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	6.867	0.447	15.365	<0.001
Treatment: undredged	-0.085	0.117	-0.728	0.467
Season: winter	-0.022	0.370	-0.060	0.952
Salinity	0.013	0.015	0.829	0.408
Elevation	0.345	0.101	3.410	0.001

Table 1.16. GLMM results for total energy of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites with dredged and undredged areas.

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.936	0.282	21.056	<0.001
Treatment: undredged	1.083	0.107	10.088	<0.001
Season: winter	-0.414	0.171	-2.417	0.016
Salinity	0.031	0.010	3.207	0.001
Elevation	0.023	0.086	0.262	0.794

Table 1.17. GLMM results for the effects of distance from a dredged area on total density of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.283	0.202	11.283	<0.001
Distance from dredged area	-0.002	0.001	-2.030	0.043
Season: winter	0.496	0.112	4.445	<0.001
Salinity	0.034	0.007	5.260	<0.001
Elevation	-0.238	0.054	-4.427	<0.001

Table 1.19. GLMM results for the effects of distance from a dredged area on total density of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	1.377	0.341	4.040	<0.001
Distance from dredged area	0.003	0.001	2.969	0.003
Season: winter	-0.765	0.280	-2.737	0.006
Salinity	-0.017	0.012	-1.506	0.133
Elevation	0.093	0.078	1.190	0.235

Table 1.18. GLMM results for the effects of distance from a dredged area on total density of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.015	0.238	8.451	<0.001
Distance from dredged area	0.004	0.001	4.361	<0.001
Season: winter	-0.810	0.143	-5.678	<0.001
Salinity	-0.034	0.008	-4.248	<0.001
Elevation	-0.347	0.058	-6.005	<0.001

Table 1.20. GLMM results for the effects of distance from a dredged area on total density of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	3.018	0.194	15.586	<0.001
Distance from dredged area	-0.001	0.001	-0.801	0.423
Season: winter	0.253	0.107	2.377	0.018
Salinity	0.016	0.006	2.477	0.013
Elevation	-0.233	0.052	-4.468	<0.001

Table 1.21. GLMM results for the effects of distance from a dredged area on total density of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2015–17. Collection site and transects were included in the GLMM as random effects. **Abbreviation:** <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	3.716	0.146	25.522	<0.001
Distance from dredged area	0.001	0.001	0.669	0.504
Season: winter	-0.157	0.069	-2.256	0.024
Salinity	-0.009	0.005	-2.034	0.042
Elevation	-0.249	0.052	-4.765	<0.001

Table 1.23. GLMM results for the effects of distance from a dredged area on total biomass of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. **Abbreviation:** <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.712	0.428	13.353	<0.001
Distance from dredged area	0.003	0.002	1.502	0.134
Season: winter	-3.441	0.258	-13.321	<0.001
Salinity	-0.073	0.015	-4.975	<0.001
Elevation	-0.176	0.121	-1.452	0.147

Table 1.22. GLMM results for the effects of distance from a dredged area on total biomass of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. **Abbreviation:** <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	-0.811	0.282	-2.879	0.004
Distance from dredged area	-0.002	0.001	-2.076	0.038
Season: winter	1.196	0.162	7.389	<0.001
Salinity	0.134	0.009	14.476	<0.001
Elevation	0.075	0.081	0.926	0.355

Table 1.24. GLMM results for the effects of distance from a dredged area on total biomass taxa of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. **Abbreviation:** <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	6.622	0.409	16.179	<0.001
Distance from dredged area	-0.001	0.001	-0.809	0.419
Season: winter	-0.944	0.339	-2.786	0.005
Salinity	-0.022	0.014	-1.601	0.110
Elevation	0.333	0.093	3.571	<0.001

Table 1.25. GLMM results for the effects of distance from a dredged area on total biomass of 24–50 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	24.247	1.857	13.059	<0.001
Distance from dredged area	0.001	0.002	0.518	0.605
Season: winter	-16.240	1.725	-9.416	<0.001
Salinity	-0.624	0.065	-9.563	<0.001
Elevation	-1.287	0.220	-5.852	<0.001

Table 1.27. GLMM results for the effects of distance from a dredged area on total energy of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	1.764	0.283	6.242	<0.001
Distance from dredged area	-0.003	0.001	-2.154	0.032
Season: winter	1.266	0.164	7.740	<0.001
Salinity	0.142	0.009	15.227	<0.001
Elevation	0.088	0.082	1.068	0.286

Table 1.26. GLMM results for the effects of distance from a dredged area on total biomass of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.587	0.307	18.198	<0.001
Distance from dredged area	0.008	0.001	5.529	<0.001
Season: winter	-1.758	0.173	-10.165	<0.001
Salinity	-0.020	0.010	-1.942	0.053
Elevation	-0.512	0.094	-5.452	<0.001

Table 1.28. GLMM results for the effects of distance from a dredged area on total energy of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.841	0.363	16.097	<0.001
Distance from dredged area	0.003	0.001	1.874	0.061
Season: winter	-2.213	0.217	-10.203	<0.001
Salinity	-0.037	0.012	-2.962	0.003
Elevation	-0.226	0.098	-2.298	0.022

Table 1.29. GLMM results for the effects of distance from a dredged area on total energy of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	6.883	0.446	15.438	<0.001
Distance from dredged area	-0.002	0.001	-1.088	0.277
Season: winter	-0.025	0.371	-0.067	0.946
Salinity	0.013	0.015	0.815	0.415
Elevation	0.391	0.101	3.853	<0.001

Table 1.31. GLMM results for the effects of distance from a dredged area on total energy of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	5.931	0.279	21.223	<0.001
Distance from dredged area	0.006	0.001	4.669	<0.001
Season: winter	-0.240	0.161	-1.492	0.136
Salinity	0.039	0.009	4.117	<0.001
Elevation	-0.223	0.085	-2.624	0.009

Table 1.30. GLMM results for the effects of distance from a dredged area on total energy of 24–50 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	23.345	1.821	12.818	<0.001
Distance from dredged area	0.001	0.002	0.568	0.570
Season: winter	-14.343	1.692	-8.478	<0.001
Salinity	-0.552	0.064	-8.615	<0.001
Elevation	-1.108	0.215	-5.148	<0.001

Table 1.32. GLMM results for the effects time since an area was dredged on total density of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects. Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.457	0.329	7.473	<0.001
Years since an area was dredged	0.088	0.060	1.463	0.144
Season: winter	0.421	0.195	2.159	0.032
Salinity	0.018	0.011	1.690	0.092
Elevation	0.118	0.080	1.474	0.141

Table 1.33. GLMM results for the effects time since an area was dredged on total density of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	1.998	0.350	5.706	<0.001
Years since an area was dredged	0.160	0.071	2.257	0.025
Season: winter	-0.927	0.223	-4.156	<0.001
Salinity	-0.050	0.012	-4.023	<0.001
Elevation	-0.228	0.081	-2.822	0.005

Table 1.35. GLMM results for the effects time since an area was dredged on total density of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.753	0.315	8.753	<0.001
Years since an area was dredged	0.197	0.058	3.383	0.001
Season: winter	0.157	0.188	0.837	0.403
Salinity	0.006	0.011	0.597	0.551
Elevation	0.105	0.077	1.363	0.174

Table 1.34. GLMM results for the effects time since an area was dredged on total density of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	0.492	0.438	1.124	0.262
Years since an area was dredged	0.193	0.079	2.451	0.015
Season: winter	-0.679	0.320	-2.122	0.035
Salinity	-0.002	0.013	-0.167	0.868
Elevation	0.125	0.102	1.229	0.220

Table 1.36. GLMM results for the effects time since an area was dredged on total density of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2015–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	3.636	0.230	15.794	<0.001
Years since an area was dredged	0.153	0.059	2.601	0.010
Season: winter	-0.245	0.125	-1.965	0.050
Salinity	-0.018	0.007	-2.530	0.012
Elevation	0.182	0.076	2.384	0.018

Table 1.37. GLMM results for the effects of time since an area was dredged on total biomass of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	-0.711	0.525	-1.354	0.177
Years since an area was dredged	1.918	0.093	20.524	<0.001
Season: winter	-2.938	0.283	-10.398	<0.001
Salinity	-0.035	0.016	-2.159	0.032
Elevation	0.357	0.121	2.945	0.003

Table 1.39. GLMM results for the effects of time since an area was dredged on total biomass of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	8.774	0.588	14.925	<0.001
Years since an area was dredged	-0.239	0.106	-2.253	0.025
Season: winter	-2.068	0.436	-4.744	<0.001
Salinity	-0.071	0.018	-3.982	<0.001
Elevation	0.189	0.136	1.387	0.167

Table 1.38. GLMM results for the effects of time since an area was dredged on total biomass of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	3.525	0.685	5.147	<0.001
Years since an area was dredged	1.027	0.140	7.321	<0.001
Season: winter	-3.771	0.408	-9.251	<0.001
Salinity	-0.101	0.023	-4.441	<0.001
Elevation	-0.332	0.175	-1.896	0.059

Table 1.40. GLMM results for the effects of time since an area was dredged on total biomass of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.904	0.485	5.985	<0.001
Years since an area was dredged	2.178	0.092	23.704	<0.001
Season: winter	-4.753	0.283	-16.787	<0.001
Salinity	-0.103	0.016	-6.417	<0.001
Elevation	0.099	0.122	0.817	0.414

Table 1.41. GLMM results for the effects of time since an area was dredged on total energy of 0–4 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	2.163	0.529	4.090	<0.001
Years since an area was dredged	1.919	0.095	20.220	<0.001
Season: winter	-2.977	0.285	-10.436	<0.001
Salinity	-0.039	0.016	-2.361	0.019
Elevation	0.343	0.123	2.794	0.006

Table 1.43. GLMM results for the effects of time since an area was dredged on total energy of 12–24 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	9.970	0.523	19.072	<0.001
Years since an area was dredged	-0.285	0.094	-3.027	0.003
Season: winter	-1.919	0.388	-4.948	<0.001
Salinity	-0.067	0.016	-4.220	<0.001
Elevation	0.185	0.122	1.524	0.129

Table 1.42. GLMM results for the effects of time since an area was dredged on total energy of 4–12 mm macroinvertebrates from 0 to 4 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	4.788	0.561	8.542	<0.001
Years since an area was dredged	0.868	0.112	7.737	<0.001
Season: winter	-3.054	0.334	-9.135	<0.001
Salinity	-0.089	0.019	-4.737	<0.001
Elevation	-0.411	0.137	-3.008	0.003

Table 1.44. GLMM results for the effects of time since an area was dredged on total energy of 0–50 mm macroinvertebrates from 0 to 10 cm depth at six sites (Loch Lomond, Mooring Road, Paradise Cay, Richardson Bay, Strawberry Channel, and Yacht Harbor).

[Cores were collected during summer and winter 2016–17. Collection site and transects were included in the GLMM as random effects.

Abbreviation: <, less than]

Fixed effect	Estimate	Standard error	t-value	p
Intercept	4.857	0.469	10.356	<0.001
Years since an area was dredged	1.868	0.085	22.057	<0.001
Season: winter	-3.754	0.262	-14.331	<0.001
Salinity	-0.077	0.015	-5.102	<0.001
Elevation	0.288	0.115	2.511	0.013

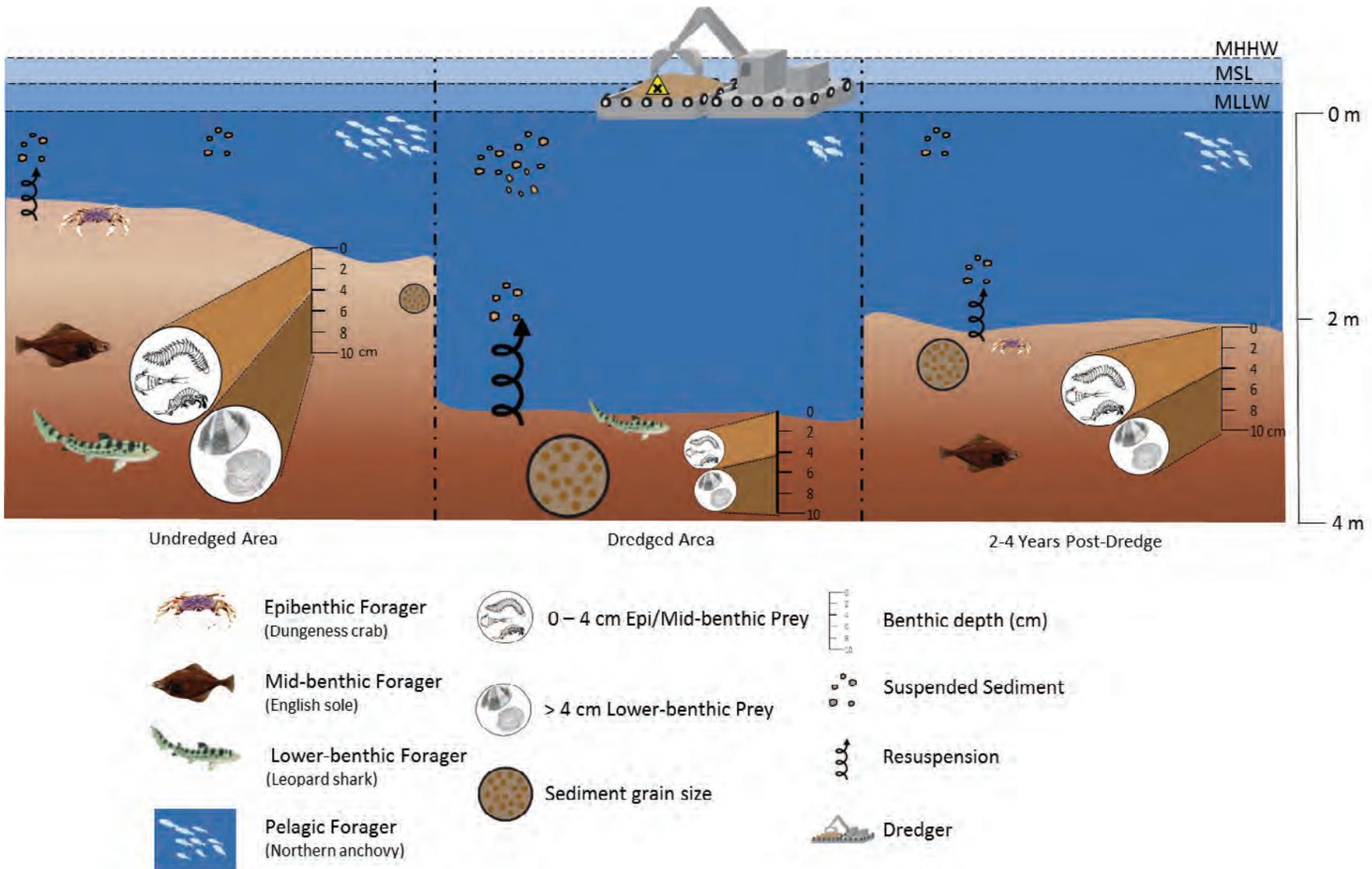


Figure 1.1. Conceptual diagram illustrating the comparison between an undredged benthic habitat (left), a recently dredged area (center), and 2–4 years after dredging activity (right). Undredged areas are characterized by an abundant and diverse prey base of benthic infauna of varying size and depths. 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 density, size, or magnitude. MHHW = Mean Higher High Water; MSL = Mean Sea Level; MLLW = Mean Lower Low Water. Not to scale.)

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