Marine Invasive Species in San Francisco Bay

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The Marine Invasive Species Program (MISP) is responsible for analysis of shipping vectors responsible for the introduction of non-indigenous species (NIS) into California's coastal waters. MISP has collaborated with the Smithsonian Environmental Research Center (SERC) and Molecular Ecology Laboratory at Moss Landing Marine Labs (MLML) to undertake an extensive program to analyze spatial and temporal patterns of NIS invasions in marine and estuarine waters of California.

The monitoring program included statistically robust field sampling, DNA-assisted taxonomic analyses, and data analysis. The surveys primarily focused on 10 estuaries or bays and high-salinity waters along the California open coast. Three communities were surveyed: hard substrate, soft-sediment, and plankton.

A combination of traditional morphologically-based taxonomy and molecular detection methods were used to identify the organisms collected. For each morphological voucher, corresponding molecular vouchers were also collected to verify species-level identity and build the DNA library.

In this poster, we present results from surveys of nine estuaries in comparison to San Francisco Bay, a culmination of a 5-year sampling program. We will present analyses of geographical distribution and patterns of spread for marine and estuarine NIS in San Francisco Bay; the mechanism(s) of introduction and spread from all 10 estuaries; and changes in the patterns (rate, spread, prevalence) of NIS in response to ballast water management strategies.

The details of the MISP program are on the Web at https://www.wildlife.ca.gov/OSPR/Science/Marine-Invasive-Species-Program

Keywords: Invasive species, non-indigenous, marine, monitoring, DNA, ballast water, taxonomy

Poster Topic Invasive Species

The Golden Bear Research Facility - Ballast Water Treatment System Testing in the San Francisco Estuary

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Ballast water from ships has long been recognized as an important vector for the introduction of aquatic invasive species (AIS) around the world. To lessen the threat, international, federal, and state regulations have adopted numeric ballast water discharge performance standards. In response, technology companies have developed numerous ballast water treatment systems (BWTS) that reduce the number of living organisms found in ballast water discharge. These BWTS must undergo rigorous land-based and shipboard testing to demonstrate their efficacy of treating for NIS before they are approved by the USCG or the IMO for use on vessels.

The Golden Bear Research Center (GBRC), located on the San Francisco Estuary, one of the most heavily invaded bodies of water in the world, is a research and development center at the CSU Maritime Academy that is committed to creating, promoting, and facilitating solutions to the maritime industry's current and future environmental challenges. Currently, our predominant focus is testing of BWTSs for IMO and USCG type approval. The Academy's training ship, the 500-foot *Golden Bear*, actively operates as a "plug and play" ballast treatment testing facility, allowing for both land-based and shipboard testing. In addition to testing technologies that will reduce the introductions of NIS, the GBRC provides an effective platform for the research, development, testing and evaluation of technologies and practices that reduce other environmental impacts from marine vessels, such as vessel biofouling, air emissions, and other effluents.

Keywords: ballast water, environmental testing, type approval

Poster Topic Invasive Species

Assessing Aquatic Plant Invasiveness to Facilitate Management in the Sacramento-San Joaquin Delta

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The California Department of Parks and Recreation's Division of Boating and Waterways (Division) is the lead agency of the state for the purpose of cooperating with other state, local, and federal agencies in identifying, detecting, controlling, and administering programs to manage, control, and when feasible, eradicate invasive aquatic plants in the Sacramento-San Joaquin Delta (Delta), its tributaries, and the Suisun Marsh. However, until 2015, the Division was authorized to treat only 3 aquatic invasive plant species*, Egeria densa, Eichhornia crassipes*, and *Limnobium laevigatum*, with each species having required legislation to do so. Recent legislative action (AB763; 2013) has reformed the mechanism for granting the Division the authority to treat additional invasive aquatic plant species in the Delta, now requiring that the California Department of Fish and Wildlife (CDFW), in consultation with partner agencies, conduct a risk assessment determining whether the aquatic plant is to be considered invasive. CDFW utilizes the U.S. Aquatic Weed Risk Assessment tool to assess the species' ecology, reproductive potential, dispersal mechanisms, competitive ability, resistance to management, and actual and potential impacts to navigation and recreation, health and stability, bird habitats, native plants, water quality, the economy, and human health, as specified in Harbors and Navigation Code (HNC) §64.5. To date, the Division has requested assessments of 6 aquatic plant species: *Potamogeton crispus, Myriophyllum spicatum, Ludwigia hexapetala, Ceratophyllum demersum, Cabomba caroliniana*, and *Hydrocotyle ranunculoides*. The first 5 species were determined to be invasive aquatic plants, per the invasive aquatic plant definition provided in HNC, and authorized for treatment within the Delta. *H. ranunculoides* is currently being assessed. Accuracy of the assessment tool, assessment questions, species scores, and overall findings will be presented.

Keywords: Invasive species, aquatic plants, Delta, management, risk assessment

Poster Topic Invasive Species

Storms, Droughts, Blobs and Invasions: Environmental Influences on Invasions in San Francisco Estuary Sessile Invertebrate Communities (2000 to 2016)

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Invasions by non-native species are well-known drivers of significant ecological change worldwide. Yet ecological communities are also strongly controlled by environmental conditions. Thus despite considerable available information on marine invasions in the San Francisco Bay region, it remains challenging to detect new invasions and estimate actual changes in invasion patterns, such as rate and spread. These data are key to understanding invasion processes and informing management and policy aimed at prevention of new invasions and responses to existing invasions. How do invasion patterns in the San Francisco Bay change over time, and how are they related to environmental changes?

We conducted repeated, standardized surveys of fouling communities throughout the San Francisco Estuary over a seventeen-year period spanning a wide range of environmental conditions, including two major droughts, several wetter winters, and a major marine heat wave.

Non-native species were prevalent throughout the estuary, but achieved greater dominance following dry winters. Community composition at any given site during the summer (May to October) was predicted by environmental conditions, especially the previous winter's precipitation (linked to salinity levels) and mean temperatures. Rarefaction analyses and richness estimators indicate that the number of species detected varied both as a function of the number of sites sampled in a given year and with environmental conditions, suggesting that standardized sampling across a broad range of conditions over time is needed. For years in which at least ten were sampled, an asymptote in estimated richness was reached, indicating statistically sufficient sampling to estimate the true richness of the community. In addition, several southern species were detected during a recent marine heat wave, suggesting a possible role of shifting conditions in facilitating potential new invasions. This large set of data allows us to better understand the influence of physical characteristics on invasion patterns in the San Francisco Estuary.

Keywords: Invasions, salinity, temperature, diversity

Poster Topic Invasive Species

A Classic Estuarine Lagoon of the 1960s Undergoes Oceanization by the 2010s: Remarkable Changes in the Biodiversity and Community Composition of Lake Merritt, Oakland, California

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Between 1962 and 1972 a detailed survey of the invertebrate, algal, and fish communities of Oakland's Lake Merritt, an estuarine arm of San Francisco Bay, was conducted by James Carlton. In September-October 2016, a re-survey of Lake Merritt was conducted by the Smithsonian Environmental Research Center to determine if and how the Lake's biodiversity may have changed over the past 50 years. Experimental panels were deployed at piers (three months earlier) and shallow-water soft sediment samples were taken around the Lake's perimeter at the same stations sampled by Carlton in the 1960s for biofouling and infaunal communities. Former lake-wide reefs of the introduced brackish-water Australian tubeworm *Ficopomatus enigmaticus* have been largely replaced by reefs of the introduced Mediterranean marine mussel *Mytilus galloprovincialis*. Seawall zonation of the 1960s consisting of a higher intertidal zone of the introduced barnacles *Amphibalanus improvisus* and *A. amphitrite*, a mid-zone of *F. enigmaticus*, and a lower zone of the brackish-water Atlantic mussel *Geukensia demissa* now consists of an upper zone of barnacles and a lower zone of *M. galloprovincialis*. At least 12 introduced species of marine ascidians and bryozoans, none present in the Lake 50 years ago, now characterize biofouling communities. Masses of the introduced "spaghetti weed" bryozoan *Amathia verticillata* were found to impede tidal flow at the Lake's flood control station. Vast carpets of the introduced seaweeds *Lomentaria hakodatensis, Gracilaria* sp., *Sargassum muticum,* and *Codium fragile fragile* covered the shallow floor of the Lake; only small colonies of the latter were present in the Lake in the 1960s. Remnants of the 1960s communities remained on seawalls at the tips of the brackish arms of the Lake. We discuss changes in the Bay's hydrography and salinity regimes, and the modern history of Lake water management, that may have led to the oceanization of Lake Merritt.

Keywords: monitoring, climate change, invasive species, Lake Merritt, oceanization, estuarine lagoon

Poster Topic Invasive Species

Survival of the *Gemma gemma* Clam in Low Salinity Conditions: Field and Laboratory Observations

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Massive precipitation experienced in California during the 2016-17 winter brought the salinity of surface waters in San Francisco Bay down to values not seen in years. Bay-dwelling organisms such as intertidal clams are at risk of mortality in salinity conditions that exceed their tolerance limits. While some fluctuation in salinity and other environmental conditions is a staple feature of estuarine life, extreme conditions – such as this past winter's low salinity – may present an exceptional stress. The introduced clam, *Gemma gemma*, is a prominent member of Bay mudflat clam communities whose range may increase within SF estuary should drought conditions in CA become the norm, but its responses to low salinity extremes are poorly known.

Observations from the field and in the laboratory provide insight into the role of salinity on the distribution of *G. gemma* in SF estuary. A field study conducted at six sites along a salinity gradient between Richardson Bay and San Pablo Bay revealed a trend in decreasing abundance of *G. gemma* populations with increasing distance northward from the Golden Gate Bridge. The lack of *G. gemma* at the least saline sites in San Pablo Bay was reflected by the higher mortality observed in laboratory treatments where salinity was less than ten. In the long run, reduced availability of freshwater flow from the SF Delta due to future drought and diversions may increase the likelihood of the spread of *G. gemma* to regions upstream from its current distribution. Yet this spread may be counteracted by occasional extremely wet winters – like this past winter.

Student Award Competition: Yes

Keywords: invasive species, salinity tolerance, wet winter mortality, mudflat, intertidal

Poster Topic Invasive Species

The Impact of Invasive Aquatic Vegetation on Turbidity and Marsh Accretion in the Sacramento-San Joaquin Delta

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Invasive aquatic vegetation (IAV), dominated by Brazilian waterweed (*Egeria densa*), water hyacinth (*Eichhornia crassipes*), and water primrose (*Ludwigia* spp.), is acting as an "ecosystem engineer" in the Sacramento-San Joaquin Delta (hereafter, Delta) in part by altering sediment transport. In 2015, IAV covered nearly 1/3 of the Delta's waterways. We hypothesize that long-standing, widespread presence of IAV is reducing vertical accretion on marshes and impacting fish habitat quality by reducing water column turbidity. In this project, we are determining the impact of IAV on sediment dynamics in flooded island, channel, and between island sites chosen using remotely-sensed imagery of the Delta. The objectives of the project are (1) to determine the effect of IAV on sediment flux and sediment trapping using (a) measurements of sediment flux along transects landward and seaward of IAV patches and (b) time-series measurements of velocity and suspended-sediment concentration (SSC) within and outside IAV patches, and (2) to determine the impact of IAV on inorganic sedimentation by measuring short (1-2 years) and long-term (past 50-100 years) vertical accretion in marshes situated adjacent to IAV.

To date we have collected transect data in Lindsey Slough and the Mokelumne River. Preliminary results suggest that there are strong horizontal gradients in suspended sediment flux near IAV patches. At Lindsey Slough, ten days of velocity and SSC data were collected within a Brazilian waterweed patch, and in the adjacent channel. Average SSC in the patch was reduced by 10-20%, compared to the channel. Currents were almost completely damped by the vegetation. Future work will focus on additional sediment flux measurements and measuring inorganic sedimentation in marshes adjacent to IAV. The ultimate goals of the project are to quantify the entire Delta sediment sink under IAV and determine the relative impact of long-term IAV infestation on marsh accretion rates.

Keywords: invasive aquatic vegetation, *Egeria densa*, sediment dynamics, vertical accretion

Poster Topic Invasive Species

Exploring the Distribution of an Invasive Crab and Its Impact on Cordgrass Restoration in San Francisco Bay

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Predators structure ecosystems by interacting with other trophic levels directly and indirectly. These indirect interactions can have large effects, yet are understudied in the context of restoration. We explored how predators, among other environmental factors, may impact crab distributions in the intertidal zone, and potential consequences of the resulting distributional shifts on restoration efforts of the native cordgrass (*Spartina foliosa*) in San Francisco Bay. Perceived threat from or direct consumption by subtidal predators at low tidal elevations, or other environmental factors, may cause *C. maenas* to seek refuge in high tidal elevations. These areas may include restored cordgrass habitat where crab foraging activity may cause damage. Crab distribution and predation on crabs were quantified using trapping and tethering experiments across tidal elevations. We then evaluated the effects of crab activity within *S. foliosa* patches using a field enclosure experiment, caging newly planted cordgrass with and without crabs to assess impacts on cordgrass growth and survival.

Caged treatments with green crabs had significantly fewer *S. foliosa* shoots at the end of a three-month period than plots without cages or crabs, suggesting that crab presence may hinder successful *S. foliosa* establishment. This work has important implications for management as interactions between multiple trophic levels can confound restoration efforts but are rarely considered in restoration settings. Illuminating the intricacies of species interactions will make future restoration attempts more efficacious and informed.

Student Award Competition: Yes

Keywords: invasive species, restoration, cordgrass, European green crab, trophic interactions

Poster Topic Invasive Species

The Direct Economic Costs to Manage Invasive Aquatic Weeds in the Bay-Delta

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Water hyacinth and Brazilian waterweed are two aquatic weeds of economic importance in the Bay Delta. Between 2013 and 2016 there was an explosion of water hyacinth in 2014 and 2015, followed with much smaller infestations in 2016. This explosion was met with a significant increase in management by those businesses and agencies whose activities were affected by the water hyacinth infestations. Considerable management costs were incurred by the U.S. Bureau of Reclamation Tracy fish facility where weeds had to be extracted from the river before water could be pumped into the California aqueduct; marinas to prevent boats from being blocked in docks; and the Port of Stockton to keep commercial shipping viable, among others. In addition it made the cost to protect human health more expensive as mosquitos can use water hyacinth mats as breeding areas. Treating mosquitos to prevent the spread of West Nile Virus may then rise when large mats of water hyacinth are present. Finally, during the last several years night time navigation on the deep river channel between Oakland and Stockton was suspended from October through February due to thick densities of water hyacinth that can interfere with a ship's radar.

Between 2013 and 2016 the total cost to manage invasive aquatic weeds by the agencies and businesses affected by infestations was $5.84 million. Almost half of that cost was incurred by the U.S. Bureau of Reclamation at $2.75 million, followed closely by marinas at $2 million. In 2016, due to a combination of improved rainfall and management in the previous years, total costs fell by 21%. However, the cost decreases were due primarily to lower costs to manage water hyacinth, as costs by marinas to manage Brazilian waterweed increased.

Keywords: Water hyacinth, Brazilian water weed, management, costs

Poster Topic Invasive Species

Controlling Algerian Sea Lavender in San Francisco Estuary Tidal Marshes

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Algerian sea lavender [*Limonium ramosissimum* (LIRA)] is an invasive plant spreading in tidal marshes of both northern and southern California. LIRA is one of four noxious weeds listed as the Highest Priority for management in the South San Francisco Bay Weed Management Plan (2013) prepared by the Don Edwards San Francisco Bay National Wildlife Refuge. It is also the least widespread of these four priority weed species, offering the best opportunity for a successful Early Detection/Rapid Response program.

Infestations of LIRA in the Estuary have been well studied by two graduate students in Dr. Katharyn Boyer's lab at San Francisco State University (Gavin Archbald and Kerstin Kalchmayr). LIRA was found to produce an estimated 36,000 to 130,000 seeds per m^2, and grow most vigorously (and produce the most seed) at the tidal elevations found in the high marsh and the estuarine-terrestrial transition zone, precisely the tidal areas in shortest supply due to impacts from development over the last century. Replacement of native plants such as *Grindelia stricta* (gumplant), *Frankenia salina* (alkali heath), and *Distichlis spicata* (saltgrass) with short rosettes of LIRA is unlikely to provide comparable refugia from predators, especially at high tides when endangered species such as California Ridgway's rail and salt marsh harvest mice are most vulnerable.

Mapping showed an increase from 15,000m^2 in 2008 to 32,000m^2 in 2015 (113% increase; a conservative estimate), and LIRA was also found in an additional 45 locations in the Estuary. With funding from the National Fish and Wildlife Foundation, the California Invasive Plant Council began a two-year pilot project in 2016, treating invasive *Limonium* at 15 sites in Alameda, Marin, and San Mateo Counties using chemical and manual control methods. Test plots were also established to evaluate the efficacy of imazapyr, glyphosate, and a combination of both active ingredients.

Keywords: *Limonium ramosissimum*, invasive sea lavender, tidal marsh, herbicide treatment

Poster Topic Invasive Species

Decreasing the Risk of Aquatic Species Invasion from Vessels Arriving at Bay-Delta Ports

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Nonindigenous species (NIS) are organisms introduced through human activities to an area where they do not naturally or historically occur. Once established, NIS can have ecological, economic, and human health impacts on the receiving environment. The coastal waters of California are some of the most invaded areas of North America, roughly 89% of western North America's currently established marine NIS were first documented in California. In coastal environments, the commercial shipping pathway has contributed up to 79.5% of NIS introductions to North America and 81% in California. Commercial vessels transport organisms through ballast water and biofouling vectors. The California State Lands Commission's Marine Invasive Species Program (MISP) is responsible for preventing or minimizing the release of NIS from vessels that are 300 gross registered tons and above. To assess the likelihood for vessels to introduce NIS into California waters and/or spread NIS to other areas, an examination and analysis of vessels' NIS management practices and their previous and subsequent ports of call was conducted for the seven port zones within the Sacramento/San Joaquin Delta and the San Francisco Bay. Understanding ballast water and biofouling management patterns and the movement of vessels can inform risk management strategies to decrease the introduction, establishment, and spread of NIS.

Keywords: marine invasive species nonindigenous aquatic vector prevention ballast water biofouling

Poster Topic Invasive Species

Innovative Techniques for Removal of *Arundo donax* in the Sacramento/San Joaquin Delta, Solano County, CA

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The invasive plant *Arundo donax* has become widespread in California. The Sacramento-San Joaquin Delta Conservancy and the California Department of Water Resources have begun an initiative to eradicate *Arundo* from the California Legal Delta. In 2015 the Sonoma Ecology Center was contacted to map and prioritize *Arundo* eradication throughout the Delta. Eradication of *Arundo* along levees can be difficult due to access constraints, steep slopes, and large stands that are approachable only on one side. In 2016 and 2017, Sonoma Ecology Center began *Arundo* eradication efforts in Solano County using a novel technique. Combining a hydraulic lift with a telescoping boom and a truck-mounted spray rig, we have been able to gain access to large stands of *Arundo* along levees and other difficult to reach locations. This innovative technique allows us to spray directly onto the invasive foliage from above, while minimizing over-spray and impacts on surrounding native vegetation. The submitted poster provides detailed images of the lift and spray-rig in action.

Keywords: *Arundo donax*, invasive species, eradication, restoration, habitat

Poster Topic Invasive Species

Biotic Filters Shaping *Limonium* Invasion in San Francisco Bay Salt Marshes

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Coastal salt marshes in San Francisco Bay have seen aggressive expansion of invasive plants, displacing native species and the broader communities and functions they support. Three recent invaders–*Limonium ramosissimum*, *Limonium duriusculum*, and a third, unidentified species–thrive in the mid to upper salt marsh and marsh-terrestrial ecotone. These areas host high species richness and provide critical habitat for endangered vertebrates. Marsh patches containing invasive *Limonium* have experienced a marked decline in native halophytes, including the only *Limonium* native to California: the Western marsh rosemary, *Limonium californicum*.

My project investigates the relative invasion potential of three *Limonium* species via vegetative competition and pollinator interactions. Given the spatial proximity and relatedness, the congeners likely influence each other's growth and compete for resources. I grew pairwise combinations of invasive seedlings watered with high and low salinity water to assess differences in vegetative growth. I also set up treatments with two-year-old *L. californicum* paired with seedlings of each invader to simulate new introductions and quantify effects on growth of the native. Furthermore, pollinators such as bees visit both native and invasive *Limonium;* the reproductive mechanisms for these species are still unresolved, and shifting pollinator habits may favor the spread of one species over another and increase interspecific pollen transfer. Through controlled pollinations in the greenhouse, I will determine whether each species is self-compatible, how interspecific pollen affects seed production, and whether or not hybridization is possible.

This research explores multiple ways in which invasive *Limonium* may outcompete native species and alter salt marsh biodiversity. If I find that one species is dominant or hybridization occurs, my results can direct managers on the targeted removal of any or all invaders. My investigation will also provide a mechanistic understanding of wetland invasion more generally and provide new information about the reproductive strategies within the highly-variable *Limonium* genus.

Student Award Competition: Yes

Keywords: *Limonium*, salt marshes, invasive species, wetland pollinators

Poster Topic Invasive Species