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Synthesis for Issue 8: Impact of Invasive Species and other Nuisance Species

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What is the importance of this issue as it relates to the Project Objectives?

Invasive or nuisance species are typically non-indigenous (otherwise known as "exotic" or "alien") species that are introduced into a ecosystem either purposefully (I.E. agriculture, recreation) or on accident (I.E. ballast water), or species that have increased dramatically due to human activities and have a perceived negative impact on that ecosystem through alteration of ecosystem function and/or structure. Not all "nuisance" species are non-indigenous, and may include native species that in relation to human activity or ecosystem alteration have a perceived negative impact.

The San Francisco Bay estuary is one of the most highly invaded aquatic ecosystems in North America. From microscopic algae to sport fish, almost every type of organism has been introduced to the Bay. As of 1995, there were over 212 introduced species in San Francisco Estuary: 69 percent of these are invertebrates, 15 percent are fish and other vertebrates, 12 percent are vascular plants and 4 percent are probsts. In addition, since 1970, a new invasive species has become established once every 24 weeks (Cohen and Carlton, 1995, 1998). With so many invasive species, many ecosystem functions are controlled by non-indigenous species. For example, "grazing" (filter feeding) is the primary mechanism controlling phytoplankton biomass during summer and fall in South San Francisco Bay (Cloern 1982, 1996; Thompson 1999). The dominant filter feeders in the South Bay are the introduced Japanese clams *Venerupis*, *Musculista,* and *Mogula* (Cohen and Carlton, 1995). This displays the degree that non-indigenous species have integrated into the South Bay ecosystem.

Invasive and nuisance species can impact the restoration process through food web alteration, the prevention of ecosystem function, destruction or degradation of physical structure associated with restoration activities, hybridization with native species, predation or exclusion of desired sensitive species, and by dominating the biomass of a restored site. The effects of invasive species can be very subtle such as alteration of the movement of contaminants or spread of a toxic dinoflagellate through an ecosystem or can be quite obvious through the conversion of

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habitats by invasive plants. However, the nature and extent of any one invasive species on ecological processes is largely unknown until that species becomes dominant within the system.

The purpose of this report is to discuss the role of invasive species and other nuisance species with respect to the objectives of the restoration including a discussion of how design and management measures can maintain or improve current levels of vector management, control predation on special status species, and manage the spread of non-native invasive species (Objective 5).

Without adequate control and prevention measures, invasive and nuisance species could ultimately hamper or ruin restoration efforts through displacement of desired species and prevention of the desired natural ecosystem, prevention of physical restoration processes, or loss of special status species post-restoration. Many invasive and nuisance species are adapted for rapid colonization of disturbed areas, can compete with or directly impact special status species, disrupt the natural food web, cause harm to humans, or have a structural impact on restoration structures. These characteristics make these species difficult to control in the restoration environment and make them likely to impact post-restoration ecosystems.

What do we know about this issue as it relates to the Project?

San Francisco Bay is one of the most studied estuaries in the world and a great deal of information exists on the taxa, populations, and role of invasive species within this ecosystem. Despite this wealth of knowledge, very few individual invasive species have been studied in depth as to their specific ecological impacts, impacts on restoration, or potential for control.

Cohen and Carlton's 1995 study, *Non-indigenous Aquatic Species in a United States Estuary: A case study of biological invasions of the San Francisco Bay and Delta,* is probably the most definitive source for information on invasive species in the San Francisco estuary including detailed species accounts for more than 200 invasive species. In addition to species accounts, this study reaches the following major conclusions regarding the impact of invasive species on the ecosystems and ecology of the Estuary:

- The Estuary is a highly invaded ecosystem with over 212 known and recognized invasive species present.
- Many of the Estuary's food webs and energy transfer processes are dominated by invasive species.
- Structural changes to specific habitats within the Estuary may be caused by invasive species.
- Invasive species contribute to the demise of endangered marsh birds and mammals.

Historically, invasive species have been transported into San Francisco Bay by boat and train for a variety of reasons. In the late 1800's gold rush and with the completion of the transcontinental railroad in 1869, many aquatic species were introduced into San Francisco Bay for food. In addition to the introduction of desired species, the transport of harvest species into the Bay accidentally brought other invasive species attached to the desired species, in sediments transported, or in water transported. The transport of coastal or estuarine water (as ballast) continues to be one of the most significant vectors for invasive species today. The transport of invasive species through ballast water, and other vectors for invasive species introductions are discussed below:

Ballast water

Cohen and Carlton (1995) estimate that hundreds of species are released into the San Francisco Bay each month via ballast water releases. Planktonic estuarine organisms from around the globe can be released through this mechanism (Carlton and Geller, 1993). Oceangoing vessels transport organisms through the uptake, transport, and subsequent discharge of water from ballast tanks. A great deal of information related to ballast water exchange and transport of invasive species is currently available, and a number of laws have been passed that attempt to deal with this problem including the 1996 National Invasive Species Act that created a national ballast management program. Cohen (1998) reports that ballast water is responsible for the introduction of the Asian clam (*Potamocorbula amurensis*), now the most abundant clam in the Estuary.

There are a number of mechanisms to control invasive species introductions from ballast water including ballast water exchange and treatment. Ballast water exchange is one method for helping reduce the number of coastal or estuarine species transported in ballast water. The basic concept is to require that ships exchange port water (usually lower salinity water) with open ocean water before returning to port. Typically estuarine or coastal species won't survive in the open ocean, and open ocean species will be less likely to establish in coastal areas, so less species with potential to occupy coastal port waters are introduced. Ballast water treatment comes in many forms including mechanical (filtration and separation), physical (sterilization by ultraviolet light, ozone, heat, electric current, or ultrasound) and chemical (biocides). Ships can treat ballast water using one method, or a combination, either in port or in the open ocean. While this method can be more effective than ballast water exchange, it is typically less cost effective (Buck, 2004)

In the San Francisco Bay, a combination of methods may produce the best results at limiting introductions of exotic species from ballast water. Cohen (1998) recommends the following actions for the reduction of invasive species introductions through ballast water:

- Sample and assess arriving ballast water
- Collect and analyze data on shipping activity and ballast discharges.
- Encourage ships to utilize appropriate ballast management measures.
- Prohibit the dumping of ballast sediments.
- Require ships to conduct open-ocean exchange of ballast water, or an equally effective alternative treatment, subject to safety concerns

- Encourage ships to assess the safety of exchange methods, to use the safest approach if there is uncertainty, and to make any needed retrofits.
- Support research into on-shore treatment, including approaches tailored to the Bay/Delta region.
- Monitor and participate in the assessment of voluntary federal ballast water guidelines.
- Assess the power of existing laws to prohibit or reduce the discharge of exotic species in ballast water, and use them.
- If existing law is not adequate for this task, pass laws that are.

While related to ballast water, a separate mechanism of introduction is hull fouling either on commercial or on private vessels. Many private vessels visit the Bay from foreign ports and no controls are currently present to control the organism attached to these vessels.

Bait worm shipments/Live bait

Shipments of various bait worms and associated kelps and unknown organisms mixed in with bait worms including snails, bivalves, amphipods, isopods, etc. is another potential transport mechanism. Packing material consisting of an East coast seaweed, *Ascophyllum nodosum*, is also dumped in the bay and has been detected and eradicated at Coyote Point in South San Francisco Bay. Releases of “red shiner” or other bait fish into freshwater locations of the delta can have adverse impacts on native species.

Herring-roe-on-kelp fishery

Macrocystis pyrifera collected in southern California has been placed in the San Francisco Bay as a substrate for herring spawning. *M. pyrifera* has become established in the Bay, and organisms associated or imported with the kelp may also be able to establish in the Bay.

Private party (aquaria, for food/sport)

Private party releases of fish and shellfish include the striped bass for food/sport, the release of turtles, fish, snails, etc from home aquaria, or releases from private recreational vessels. Nurseries (either aquatic or terrestrial) can be responsible for the release of invasive plants into the environment. Introductions by the aquaculture industry can occur during shipments of organisms from other countries that are then released via transplanting into local aquaculture facilities or inadvertent disposal in the marine environment. In addition, the intentional release or escape of cats and of farmed non-native red foxes has led to the spread of these predators into sensitive wildlife areas.

Restoration/Scientific Research

One of the most ironic introductions that has lead to serious ecosystem alteration was the intentional planting of Atlantic smooth cordgrass (*Spartina alterniflora*) in a Corps of Engineers

Dredged Material Demonstration Project in South San Francisco Bay in the 1970's. This introduction to test restoration planting methods has lead to one of the most profound ecological changes in the vegetative structure of tidal marshes.

Examples of species that may impact tidal marsh restoration

Given the large number of invasive species and the various degrees of knowledge concerning their impacts, it is very difficult to review the literature without focusing on a few of the most significant in terms their effects on tidal marsh ecology and restoration. The following list discusses those invasive or nuisance species, that in these authors opinion, have a high potential to undermine restoration efforts. Factors considered in this determination include the species' colonization or spread rates, potential to harm or displace special status species, potential to disrupt the natural food web, ability to cause structural ecosystem alterations, and in one case, may have an effect on the design of the restoration given potential human health threats. This list is not meant to be exhaustive and in some cases, these species are now naturalized and control may be unwarranted or successful. It is provided here as a basis for evaluating a range of species and the variation in our knowledge of both their biology as well as their control.

Invasive species:

Plants

- Atlantic salt-marsh cordgrass (*Spartina alterniflora* and its hybrids)
- Broadleaf peppergrass (perennial pepperweed) (*Lepidium latifolium*)

Invertebrates:

- Asian Clam (*Potamocorbula amurensis*)
- Australian-New Zealand boring isopod (*Sphaeroma quoyanum*)
- Chinese mitten crab (*Eriocheir sinensis*)
- European green crab (*Carcnius maenas*)
- Atlantic ribbed marsh mussel (*Arcuatula demissa*)

Mammals

- Norway rat (*Rattus norvegicus*) and Roof rat (*R. rattus*)
- Red fox (*Vulpes vulpes*)
- Feral cat (*Felis felis*)

Nuisance species:

Birds

- California gull (*Larus californicus*)
- Common raven (*Corvus corax*)
- American crow (*C. brachyrhynchos*)

Invertebrates

- Mosquitos (*Culex* sp., *Ochlerotalus* sp., and *Aedes* sp.)

What is the level of certainty of our knowledge?

Invasive species have had a major impact on the ecology of the San Francisco Bay. Tidal mudflats and shallow water habitats are almost entirely composed of introduced species, and native species are rarely found in abundance (Nichols and Thompson, 1985; Thompson and Shouse, 2002; Shouse and Thompson, 2003). In many cases, community structure and function within the Estuary is dominated by invasives creating "introduced communities." Also, in many locations throughout the Estuary, introduced species account for the majority of species diversity. Invasive species have achieved these levels of ecosystem dominance through a number of mechanisms including competition and exclusion of native species, alteration of physical habitat structure, and through the modification of food web structure (Nichols, Thompson and Schemel, 1990).

Our knowledge of most of these species relates to their impacts to native systems. A few examples demonstrate the extent of our understanding about these species:

<u>Atlantic salt-marsh cordgrass (*Spartina alterniflora* and its hybrids)</u>

Spartina alterniflora was first introduced into the San Francisco Bay in the early 1900's either through ballast water or sediment used as packing material for east coast oysters. In the 1970's, *Spartina alterniflora* was planted purposefully into the San Francisco Bay for shoreline stabilization, "restoration," or in wetland mitigation. Research done on the hybridization between exotic (*Spartina alterniflora)* and native (*S. foliosa*) cordgrass show that it is these hybrids that are actually driving the invasion and will ultimately replace both parental species (Ayres *et al*. 2003, 2004). Both the hybrid and the exotic form of *Spartina* have the ability to produce more pollen and yield up to twice the germination rate compared to the native *S. foliosa* (Anttila *et al*. 1997, 2000). This invasion poses an extreme threat to all established populations of native cordgrass, and according to Ayres *et al*. the hybrid will invade and dominate every salt marsh that is returned to tidal action in the central-south Bay (Ayres *et al*. 1999, 2002).

Due to its higher seed production and germination rate, *Spartina alterniflora* and its hybrids establish new colonies faster than the native cordgrass. Once established, they outcompete the native *Spartina*, growing 6 to 7 times faster (Callaway and Josselyn 1992). In addition, *Spartina alterniflora* and its hybrids can cause the displacement of native flora, changes in sedimentation, decreases in benthic invertebrate and algae populations, disturbance to the upper marsh and the loss of foraging sites for shorebirds and other animals. Because *Spartina alterniflora* has larger and more rigid stems, greater stem density, and higher root densities than native *Spartina* it may cause major structural changes in the Estuary. As of 2002, *Spartina alterniflora* and its hybrids have spread to over 3000 acres in South San Francisco Bay, and may eventually spread to over half of the intertidal flats within a couple decades (USFWS, 2003).

Collins (2002) reached the following conclusions regarding the impacts, potential spread, and geomorphologic alteration of the Bay:

- NIS (non-indiginous *Spartina*, including *Spartina alterniflora* and hybrids) cordgrass is unlikely to invade more than the upper half of the saline tidal flats and will tend to invade smaller proportion of the tidal flats in Far South Bay than in South Bay or Central Bay.
- NIS cordgrass will probably not dominate the saline high marsh above MHW (Mean High Water)
- The invasion of existing mid- and high-elevation marsh channel by NIS cordgrass will tend to isolate the headward reaches of first order channels from the rest of their channel networks.
- NIS cordgrass can cause second and third-order tidal marsh channels to retrogress, thus shortening and simplifying intertidal channel networks and the shoreline of the Estuary as a whole.
- NIS cordgrass can obstruct tidal flow and fluvial discharge in the upper tidal reaches of alluvial drainages.
- The upper tidal reaches of local streams can serve as refugia for non-hybrid *Spartina alterniflora* and as sources of new recruits for continued invasion around San Francisco Bay

Collins (2002) also addresses studies needs that could help determine the geographic extent and ecological impacts of the invasion. Studies are needed to determine: 1) The minimum elevation of NIS cordgrass in the lower intertidal under varied salinity conditions. 2) How marsh evolution, from tidal flat through low marsh to high marsh, is altered when the low marsh is dominated by NIS cordgrass. 3) How native plants and animals will adapt to the NIS cordgrass.

A great deal of uncertainty exists in how NIS cordgrass will impact the restoration process. Increased sedimentation rates and reduced mudflat areas are known impacts, but consequences for restoration are less clear. By trapping fine sediments and organic matter, it may also result in an increase in mercury methylation.

Current control methods for *Spartina alterniflora* (and hybrids) include hand-pulling and manual excavation, mechanical excavation and dredging, pruning, burning and mowing, covering/blanketing, flooding and draining, and the application of herbicides. Details on each method including benefits and drawbacks can be found in the 2003 San Francisco Esturay Invasive Spartina Control Program Final Programmatic EIR (REF).

Perennial pepperweed (*Lepidium latifolium*)

Perennial pepperweed is a creeping rooted perennial adapted to sites that are at least seasonally moist in riparian and wetland areas and is ranked a “B” level plant pest by California Dept. Food and Agriculture. It can establish on disturbed, bare soils, and seems well adapted to salt affected soils (Young *et al.*, 1995). Perennial pepperweed was reported in the Bay-Delta region as early as 1941, and was reported to be established and common throughout the Bay area by around

1960. In the South Bay, perennial pepperweed is found primarily along sloughs and is a dominant component of marshes adjacent to Coyote Creek (Grossinger *et al*. 1998).

Opportunities for further spread include high elevation tidal marshes, fresh-brackish marshes, brackish marshes with poor tidal circulation, along natural and artificial levees and berms within marshes, and on sandy beaches (Grossinger *et al*. 1998). Restored habitats, particularly diked areas with restored tidal action that may be somewhat muted, may be particularly susceptible to invasion by perennial pepperweed. In addition to becoming a dominant component of marsh communities, perennial pepperweed can compete with pickleweed, reducing habitat for the salt marsh harvest mouse and may outcompete rare native marsh plants *Lilaeopsis masoni* and *Cordylanthus mollis mollis*.

CDFG has tested burning, discing, and herbicide treatments as control measures for peppergrass. Restoration of full tidal action, herbicides, and hand-pulling have been used with some effectiveness in Contra Costa and Alemeda Counties, while mowing burning and discing have been ineffective and possibly counter productive (Grossinger *et al*. 1998). No fully effective method has been developed to date.

Studies on the susceptibility of restored tidal marshes from previously diked areas to perennial pepperweed invasion, effectiveness of control measures, and potential preventative measures would help restoration efforts. In addition, studies are needed on the competitive exclusion of native marsh plants by perennial pepperweed and the impacts of perennial pepperweed on the endangered salt marsh harvest mouse.

Asian Clam (*Potamocorbula amurensis*)

Introduced around 1986, the Asian clam (nicknamed “overbite”) has quickly become the most abundant clam in the estuary (Carleton *et al*. 1990; Nichols *et al*. 1990). A highly efficient filter feeder, the Asian clam ingests bacteria and small zooplankton as well as phytoplankton and has severely depleted phytoplankton populations in northern part of Estuary (Alpine and Cloern, 1992), altering food web structure and food availability for species higher in the food chain. The Asian clam may reduce native zooplankton populations making introductions of exotic zooplankton more likely (Kimmerer, 2004; Cohen, 1998). Since the introduction of the Asian clam typical summer phytoplankton blooms have been absent from the North Bay, presumably due to the Asian clam’s aggressive filtering that overwhelms phytoplankton net production and can influence the timing and extent of phytoplankton blooms in South Bay as well (Thompson, 1999). The Asian clam has also been shown to alter the vectors of contaminant movement through estuarine food webs (Linville et al. 2002).

The Asian clam has the potential to invade and dominate any restored tidal marsh or tidal mudflats in the South Bay, though its population numbers in the south bay undergo substantial inter-annual and decadal variation. Impacts to food web structure and abundance of zooplankton and phytoplankton would be expected. While this may alter prey availability for some desired species, it is unlikely to have major impact on the success of a restored marsh.

It is unknown if presence of the Asian clam would impact restoration activities, or if control measures could be developed for this species. Additional research on the impacts of the Asian clam on food web structure may help determine if any sensitive or desired species are being impacted by alterations caused by the clam. Because of its thicker shell (compared to *Macoma)*, it may have lower caloric value to foraging birds, causing some migratory birds to leave foraging grounds (Takehawa, pers. comm..). In addition, the role of the Asian clam in the effecting the bioaccumulation of legacy contaminants and mercury within food chains should be investigated. Also, local control methods may be able to be developed if in certain areas control of the clam could increase prey availability for species being impacted.

Australian-New Zealand boring isopod (*Sphaeroma quoyanum*)

A burrowing, filter feeding isopod native to Australia/New Zealand that has been in the San Francisco Bay for over a century. Today the isopod is common and frequent throughout San Francisco Bay. It burrows into all soft substrates including clay, peat, mud, sandstone, styrofoam docks, etc, and bores half-centimeter diameter holes that can lead to shoreline erosion. Talley *et al.* (2001) estimate that *S. quoyanum* infestation can lead to losses of greater than 100 cm of marsh edge per year.

Sphaeroma could impact restoration activities by weakening levees and other water control structures used in marsh restoration, or by increasing the vulnerability of marsh edges to collapse and retreat due to wave action. It is unlikely that control methods would need to be developed for this species, and control may be impossible. Additional research on the impact of burrows on levees, dikes, etc. could help predict potential impacts to restored marshes. Research on the differential recruitment of *Sphaeroma* on banks with different slopes, orientations, currents, or other factors might help in determining appropriate designs for levees within restoration sites.

Atlantic ribbed marsh mussel (*Arcuatula demissa*)

Arcuatula demissa was introduced into the San Francisco Bay around 1894, most likely from shipments of Atlantic oysters into the Bay. It is now one of the most common bivalves in the San Francisco Bay, including in salt marshes of the South Bay where it lies with its posterior margin protruding above the mud (called "endobyssate").

It has been reported that California clapper rail often get toes or beaks caught in the open valves of the mussel and can drown with incoming tide, or starve to death (Takekawa, 1993). Ironically, *Arcuatula* is also a major food source for the clapper rail. Because *Arcuatula* has potentially negative impacts on the California clapper rail, it may be seen as a species that should be precluded or controlled in restored environments. Unless a native bivalave were able to compete with *Arcuatula*, control may have a greater negative impact on the California clapper rail than allowing *Arcuatula* to persist.

Additional research should focus on the impact of *Arcuatula* on the California clapper rail, both its importance as a food source and as source of contaminants should the bivalve be found to bioaccumulate Hg or other compounds.

Chinese mitten crab (*Eriocheir sinensis*)

The Chinese mitten crab, *Eriocheir sinensis*, is a recently introduced species to the San Francisco Bay, presumably introduced through deliberate release to form a fishery or through ballast water releases (Cohen and Carlton, 1995). A native to coastal rivers and estuaries of Korea and China along the Yellow Sea, the Chinese mitten crab is a catadromous species with planktonic larvae that breeds in water with a salinity of approximately 25 ppt (parts per thousand). In the San Francisco Estuary, upstream migration occurs year-round with a peak in spring months, downstream migration primarily occurs in August-January with a peak in September-October (Veldhuizen and Stanish, 1999).

The Chinese mitten crab was first collected in San Francisco Bay in 1992, and populations have expanded rapidly since, with over one million mitten crabs collected in 1998 at Bay-Delta water transfer facilities. As of 1999, distribution of the mitten crab extended north of the Delevan National Wildlife Refuge in the Sacramento river drainage, east of Roseville in the American River drainage, south in the San Joaquin River draingage near San Luis National Wildlife Refuge, and south in the California Aqueduct to near Kettleman City and Taft (Veldhuizen and Stanish, 1999).

The mitten crab is well distributed in South Bay, throughout most of the sloughs and tidal creeks. They spend most of their lives in rivers and then migrate into estuaries to reproduce. Mitten crab burrows can cause accelerated bank erosion and slumping. Burrows can extend up to a half meter deep in mud banks. Potential impacts to San Francisco Bay ecosystems identified by the Chinese mitten crab Control Committee (2002) include:

- Weakening of levees and/or banks from mitten crab burrows, leading to increased maintenance/repair requirements, slumping and/or failure of banks/levees. Burrowing and slumping have been observed in San Francisquito and Stevens Creek.
- Mitten crab feeding behavior could cause a decrease in vegetation in agricultural fields and/or natural habitats.
- Water diversion/industrial/restoration activities could be disrupted by crabs blocking or clogging systems.
- Recreational and commercial fishing could be negatively impacted through the blockage or clogging of nets and traps, bait stealing, or damage to gear or catch.

- Native populations, community structure, and local biodiversity could be negatively impacted through predation, competition for resources, habitat alteration, or food-web disturbance
- Bioaccumulation and biomagnification of contaminants, disease transfer, and parasite spread could pose a health risk for the public or wildlife species that consume the crab either directly or through consumption of animals that prey or associate with the crab.

Population control measures for the Chinese mitten crab are poorly studied, and may not be effective. Current management strategies should include a plan for the prevention of further spread, detection of new populations, monitoring of existing populations and impacts, reduction of negative impacts, and development of population control strategies. Research needs include:

- Identification of natural and human induced spread including ballast water, ocean currents, recreational and commercial boat equipment, human transport and releases, and dredging.
- Establishment of standardized detection (including larvae), sampling, and monitoring techniques.
- Studies on biology, population studies and inter-annual variability, life history, environmental tolerances, critical habitats and impacts of the mitten crab including impacts on ecology, levees and agriculture, species at risk from mitten crabs.
- Studies on the erosion rate caused by crab burrows.
- Studies on the food web of crabs and whether or not their presence in the restored wetlands will mobilize or bioaccumulate Hg or Ag.
- Evaluation of impacts, current and potential, to recovery and restoration efforts.
- Develop methods for population control measures including values, risks, and options.
- Focused study on feasibility, value, and potential for a population control program at fish salvage, fish passage, and water diversion operations.

European green crab (*Carcinus maenas*)

The green crab is native to Europe, where it is abundant from Norway and the British Isles to the Atlantic coast of southern Spain. The green crab became established in San Francisco Bay in1989-90, potentially introduced from the eastern U.S. with packing material for lobsters or bait worms, or perhaps via ballast water, and has been spreading rapidly since. Green crabs are able to withstand a broad range of salinities and temperatures. The green crab, as an aggressive predator on other invertebrates, dramatically reduces native clams and shore crabs, and threatens regional shellfish production. Since its invasion of Bodega Bay, California in 1993, the abundance of native bivalve mulloscs and grapsid shore crabs have declined 90-95% as a direct result of green crab predation (Grosholz *et al*. 2000).

The green crab affects invaded ecosystems by reducing the abundance of native or desired species through aggressive predation. In Washington, the green crab may reduce populations of the desired commercial Dungeness crab (*Cancer magister*) through competition for habitat and food. The green crab also lowers shellfish abundance through aggressive feeding. These alterations in food web structure may be important in maintaining a prey population for desired species in restored ecosystems.

Control methods for the green crab could include chemical or biological controls; however, there is little research describing the effectiveness or practicability of these methods. Control and prevention methods for the green crab may be developed in Washington because of the green crab's potential to impact the Dungeness crab fishery. In the San Francisco Bay, research needs include a study of how green crab feeding alters food web structure in the South Bay and whether or not this has an impact on desired species in South Bay ecosystems.

Red fox (*Vulpes vulpes regalis*)

Red fox were brought to California in the 1800's for commercial farming and subsequently released or escaped (Jurek, 1992). The red fox is native to the Great Plains and should not be confused with the native but extremely rare and threatened Sierra Nevada red fox (*Vulpes vulpes necator*). In addition the smaller, native, less abundant and less aggressive grey fox (*Urocyon cinereoargenteus*) exists in some of the same habitats as the invasive red fox.

Red fox were first observed in the San Francisco Bay National Wildlife Refuge in the South Bay in 1986, and have been expanding their range ever since. Populations of red fox currently exist in all Bay counties and are regularly seen in the South Bay in tidal marshes, diked baylands, salt pond levees, landfills, agricultural lands, grasslands, golf courses, and urban areas (Goals, 2000). Dens have been located in levee banks and in salt marshes (Foerster and Takekawa, 1991). The red fox preys on clapper rail eggs, young, and sometimes adults, as well as other ground nesting birds such as least tern, snowy plover, Caspian tern, Forster's tern, black-necked stilt, and American avocet. Red fox may also prey on the salt-marsh harvest mouse, salt marsh wandering shrew, and California black rail. Red fox have been trapped and killed since 1991 as part of the San Francisco Bay National Wildlife Refuge predator management plan.

Between 1993 and 1996, red fox predated at least four of 257 western snowy plover nests. During 1991-96, plover and clapper rail nesting success increased, attributable to predator management on the Refuge (Harding *et al*., 1998). Red fox were responsible for the loss of all Caspian tern nests at two sites in the Refuge in the early 1990's (Mowry and Bair Island); while both tern colonies returned with some measure of success after predator management was initiated, neither colony returned to its former size and neither exists today (Strong *et al*., 2004). One of the South Bay's largest rookeries (Bair Island), which historically supported up to 500 heron and egret nests, was completely abandoned after red fox predation in 1991 (SFBBO, unpub. data).

The increase in urban sprawl (and associated landfills, golf course, etc.) and the decrease of larger predators such as coyote are some of the reasons for the increase in numbers of red fox and other “mesopredators” such as skunk and raccoon (Lewis *et al*., 1999). In a study of red fox in an extensive wetland area of Spain with large numbers of breeding waterbirds, red fox dens were found to be more common in areas closed to the public, without waterfowl hunting, but with a few standing buildings. Prey items at the dens consisted of 96% birds (including waterfowl, gulls, and rails; Ruiz-Olmo *et al*., 2003).

The design of the restoration matrix may determine predation pressure on some species. Modeling from a wetland site in England indicated that nest predation by red fox decreases with increasing width of “patch size” of habitat within the landscape, especially in areas <10 ha; linear strips of habitat were sensitive to width changes of just a few meters (Seymour *et al*., 2004). Thus creating larger pieces of habitats, and avoiding narrow strips within the landscape matrix may limit red fox predation in marsh habitats. In addition, marsh habitat adjacent to upland areas with increased flooding potential may make clapper rail more susceptible to red fox predation during extreme high tides or storm surges (Foin, 1997).

A further deterrent to red fox movement includes wire fencing along the ends of levees. This appears to discourage mammalian predators, including human disturbance, from areas used by nesting birds (Harding *et al*., 1998). However, fox allowed to remain in areas with large gull populations may help to maintain gull numbers (see below under California gulls; Ruiz-Olmo *et al*., 2003, Southern *et al*., 1985).

Long-term modeling indicates that effective red fox management could benefit more from: 1) decreasing juvenile survival, 2) decreasing reproduction, and 3) limiting immigration into the area rather than in the current predation management practice of trapping adults. However, to date no management techniques have been developed that address these issues in a restoration area with a large urban interface (Harding *et al*., 2001).

Long-term predator management is currently necessary for the control of red fox populations around the Bay as dispersal into the baylands from outside the wildlife refuge is inevitable. The reintroduction of coyote has been proposed as a method of controlling fox populations (Jurek, 1992), but coyote are also generalist predators and feed on birds and small mammals. In addition, the public would have to be convinced of the need to introduce a larger predator into the urban setting. Other predators may increase when red fox are removed; for example skunks have increased as predators on ground nesting birds as fox decrease in number with trapping effort (Neuman *et al*., 1991).

Predator management unfortunately is unpopular to some members of the public. Environmental education that informs the public about the harm that non-native and invasive predators cause to native wildlife is needed to garner support, and to prevent public outcry, litigation, and the proliferation of “feeding stations” around the perimeter of the restoration area.

Additional research that could help the restoration process includes research on local mammalian predator populations believed to be causing threatened or endangered species population declines, potential new management techniques and efficiency of known management techniques for a particular study area, and development of demographic models for these populations. These studies would increase local-level knowledge and would allow restoration planners to implement site-specific control measures to ensure predation does not undermine restoration efforts.

Feral cat (*Felis felis*)

Cats are known to have serious impacts on wildlife, especially small mammals and birds. Worldwide, cats are likely responsible for the extinction of more bird species than any other cause except habitat destruction. The damaging effects of cats on wildlife are particularly severe on oceanic islands, in "islands" of wildlife habitat in urbanized areas, and in other wild lands and open spaces near built-up areas (see references in Jurek, 1994). In the United States, cats currently contribute to the endangerment of populations of California least terns, piping plovers, loggerhead shrikes, marsh rabbits in Key West, and unique species of mice and woodrats on Florida's barrier islands (Humphrey and Barbour, 1981; Gore and Shafer 1993). Cats can outnumber and compete with native predators, feeding on many of the same animals as native predators. Large numbers of feral cats (as well as free-ranging house cats and dogs, Canis familiaris) can reduce the availability of prey for native predators, such as hawks (George, 1974). Even a few persistent individuals can have a large impact: in one study in New Zealand a single, free-ranging dog (not feral) killed up to 500 flightless kiwis (see review in Atkinson and Atkinson, 2000).

Although there is little information for restored areas specifically, feral cats can be major predators of native mammals and birds in marshes. Locally, California clapper rail, California least tern, California black rail, burrowing owl, and western snowy plover and other ground-nesting birds are particularly vulnerable to cat predation. Cats are common along salt pond levees, in salt marshes, and at edges of tidal sloughs (Foerster and Takekawa, 1991, Takekawa, 1993). A two-year study at the East Bay Regional Park District compared one park with no cats to one park where over 20 cats were fed daily. Almost twice as many birds were seen in the park with no cats as in the park with cats. Common ground-nesting birds were seen in the cat-free park, but were absent in the cat park. In addition, most of the mammals trapped in the cat-free park were native deer mice and harvest mice, whereas non-native house mice were far more common in the cat park. The house mice were likely supported by the cat food provided. (American Bird Conservancy, 2004).

Governmental agencies and conservation organizations have been attempting to eradicate or reduce feral cat populations on islands and mainland ecosystems by trapping, shooting, poisoning, and introducing pathogens. Municipalities and private group encourage responsible pet ownership and promoting pet sterilization to reduce cat populations. Groups opposed to euthanasia are using "neuter-and-release" programs to attempt to curtail population growth or to stabilize and protect local populations in "controlled colonies" (see references in Jurek, 1994). Feral cats are trapped as part of the NWR predator management plan, but the effectiveness of this trapping on cat populations is unknown since we have no knowledge of the size of the feral cat population and the percentage that are trapped (Foerster and Takekawa, 1991, Takekawa, 1993). Feeding stations at the urban interface (business parks and residential areas) around the Bay help populations of feral cats and other small-medium predators to proliferate. Again, a campaign to educate the public about the harm that non-native and invasive predators cause to native wildlife is necessary.

Norway rat (*Rattus norvegicus*) and roof rat (*R. rattus*)

Norway rats are common in marsh areas adjacent to urbanization such as near buildings, sewers and garbage. Roof rats are associated with thick vegetation, trees, and the upper regions of buildings. Both species of rats have caused major damage to wildlife, especially on oceanic islands with few native mammalian predators.

Nesting ducks and seabirds can be particularly susceptible to predation by Norway rats. Roof rats inflict heavy damage on nesting seabirds and shrub and tree-nesting landbirds (see review in Atkinson and Atkinson, 2000).

Around the Bay, both rats inhabit salt and brackish marsh and diked areas (Foerster and Takekawa, 1991). Although nothing is known about their overall numbers or distribution around the Bay, both rats are known predators on California clapper rail and other ground-nesting birds; they may also prey on salt marsh harvest mouse, salt marsh wandering shrew, and California black rail. Norway rats may eat up to one-third of all clapper rail eggs laid in the southern portion of the Estuary (BDOC, 1994). In the early 1980’s rats were responsible for predated a number of California gull nests in the then newly established gull colony in the south Bay. Rat predation appeared to increase when researchers entered the area (Jones, 1986). Rats are trapped as part of the NWR predator management plan, but the effectiveness of this trapping on rat populations is unknown (Foerster and Takekawa, 1991, Takekawa, 1993).

Most of the invasive species removal (especially for ubiquitous rats) programs have been done on islands, where non-native mammals have had a bigger impact and the rate of immigration after removal is low. However, these studies have recently been applied to mainland restoration areas. Rat poisoning in New Zealand has led to increases in reproductive success by native birds, increased seed and fruit production, and an increase in large invertebrates. Continued trapping was necessary in this study to control the influx of rats from outside the area and keep the predator levels to a minimum. In areas with native rodents, poisoning because a more difficult proposition, however, as non-target species may also be affected. In all cases, poisoning of secondary species (hawks, vultures, other mammals) must also be considered (Lovegrove *et al*., 2001). Limiting the amount of garbage accessible to rats may also help curtail their numbers, as well as limiting feeding stations.

Corvids

Corvids (family *Corvidae*) are a group of over 100 bird species including crows, ravens, jays, magpies, and nutcrackers. One of the most successful avian groups, they are represented on all continents except Antarctica. Two species, the common raven (*Corvus corax*) and American crow (*Corvus brachyrhynchos*), may pose a risk to San Francisco Bay restoration activities due to predation on shorebirds and other desired native species, both common and special status. The common raven and the American crow are known for being highly intelligent birds that easily adapt to human disturbance and human-altered ecosystems. Both species are generalist omnivores, feeding on roadkill, organic matter at landfills, grains, small mammals, amphibians, reptiles, birds, insects, eggs and nestlings. Researchers have documented both species preying on nests, including threatened and endangered species. In some locations, corvids have been cited as the primary predator of western snowy plover and California least tern.

Population trend information from the Breeding Bird Survey (BBS) and Christmas Bird Count (CBC) indicate that populations for the crow and raven have been increasing at a rate of 5.9 %/year and 4.6 %/year, respectively, in California during the past decade, and have increased substantially since the early 1900s with the development of irrigation and agriculture (Liebezeit and George, 2002). Without a doubt, most of these increases can be attributed to human activity. Increases in fragmented landscapes from habitat conversion and development, food sources such as dumpsters, landfills, crops and irrigated fields, ranching by-products, and water sources such as canals, reservoirs, and agriculture have all contributed to increases in corvid populations.

The importance of corvids as nest predators has been well documented in the literature, with over 50 studies that provide evidence for corvids as predators of threatened or endangered species in California or neighboring western U.S. states (Liebezeit and George, 2002). In the San Francisco Bay, corvid predation may be an important factor for populations of California least tern and western snowy plover. In many cases, predation by corvids may not be the most important factor in population declines, but cannot be ruled out as insignificant. For example, the primary cause of population decline for the western snowy plover is habitat degradation and expansion of recreational beach use, however, in certain locations (such as Point Reyes National Seashore) corvids are the primary nest predator and can be an important factor in population dynamics (Abbot and Peterlein, 2001).

In the Alviso and Eden Landing areas, ravens (as well as raptors) nest on PG&E towers above the marsh and salt ponds, giving the predators an overview of nesting birds below. This makes the plovers especially vulnerable to predation from ravens as the ravens could quickly learn where nests are by watching the adult plovers below (C. Strong, pers. obs.). Local control measures at Eden Landing Ecological Reserve include the removal of nests on PG&E towers adjacent to plover nesting sites, and lethal removal of adults if necessary (J. Krause, pers. comm.).

A number of management techniques have been explored to prevent predation of threatened and endangered species by corvids, including lethal removal (shooting, poisoning, trapping), behavior modification (repellents, sterilants, conditioned taste aversion), and habitat modification (nest exclosures, habitat restoration, perch/nest site removal, modification of anthropogenic food and water sources) (Liebezeit and George, 2002). While short-term solutions such as lethal removal and behavior modification may be necessary in some circumstances to avoid local population declines of threatened or endangered species, more effective methods for controlling corvid populations in the long run, and that may also benefit entire ecosystem function, are habitat restoration and modification of anthropogenic food and water sources. Because a number of landfills in the South Bay are in close proximity to restoration locations, management actions that deter corvids from eating garbage including installation of overhead wiring, use of chemical repellents, and covering waste with at least 15 cm of soil or a synthetic cover, could help reduce corvid population levels.

Additional research that could help determine management policy for San Francisco Bay restoration includes research on local corvid populations believed to be causing threatened or endangered species population declines, potential new management techniques and efficiency of known management techniques for a particular study area, and development of demographic models for corvid populations. These studies would increase local-level knowledge and would allow restoration planners to implement site-specific control measures to ensure corvid predation does not undermine restoration efforts.

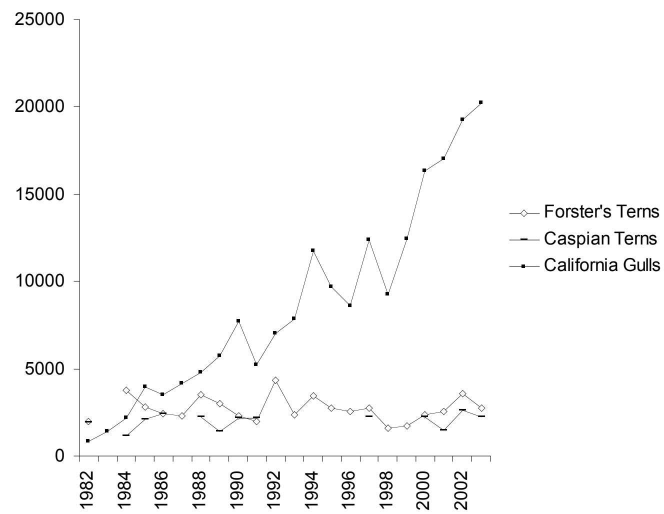
California gulls (*Larus californicus.*)

Although numerous gull species utilize the estuary during some part of the year, only the California gull lives year-round and nests in high numbers in the South Bay. (A few pairs of Western gulls, *L. occidentalis*, nest in the south Bay, and sizable colonies exist at Brooks Island, Alameda Naval Air Station, and Alcatraz Island.) California gulls appear to do well in environments that are too low in productivity to support other gulls species, likely related to their ability to thrive on a combination of small mammals, fish, birds, garbage and invertebrates. Unlike other gull species, California gulls will fly substantial distances from their breeding colony to forage (see references in Winkler, 1996).

California gulls have increased in the South Bay at an exponential rate, from about a dozen nests in 1980 to over 10,000 nests in 2003 (Figure 1; Strong, *in press*). This colonization in 1980 was a unique departure from their usual inland nesting habitat into an estuarine habitat (Jones, 1986). During the same time period, California gull populations have decreased dramatically at Mono Lake in eastern California due to water draw-downs from the lake. However, they have increased throughout much of the western U.S. due to an increase in available nesting habitat at reservoirs, and an increase in food availability in agricultural fields and refuse dumps (Winkler, 1996). While breeding bird surveys from 1966-2003 show no significant increases in California gull numbers throughout California or the western U.S. (Sauer *et al.,* 2004), Christmas bird counts over the last century show a steady increase (National Audubon Society, 2002). However, it should be noted that neither of these surveys focus on colonial waterbirds and the results could over or underestimate numbers significantly.

In the Bay, California gulls feed on the eggs and young of waterfowl, terns, shorebirds, and other gulls (C. Strong, pers. obs.), and have been seen feeding on small mammals within the tidal marshes of the estuary (J. Albertson, pers. comm.). California gulls are becoming increasingly common in the Salinas NWR area, and are predators on the western snowy plovers nesting there (Neuman, *et al.*, 2001). Western snowy plovers no longer utilize the extreme South Bay, possibly due to the large gull colony adjacent to the historic plover area (SFBBO, unpub. data).

Figure 1. Number of Caspian Terns, Forster's Terns, and California Gulls breeding in the San Francisco Bay estuary during 1982 to 2003 taken from monthly surveys at colony sites. Years with incomplete counts at primary colonies are not included. (Strong, *et al.*, in press).



Various methods have been used to reduce the size of gull colonies, including allowing vegetation encroachment over the nesting site, using monofilament to cover the nesting site, scaring tactics, and lethal control. In very large areas, eggs have been sprayed with oil or poison to prevent them from hatching, although this may need to be done for a number of years before becoming effective as generally, the gulls will relocate to renest nearby (Thomas, 1972). Vegetation allowed to remain or planted around the gull colony can attract mammalian predators, further reducing the gull colony (Morris *et al*., 1992). Red fox have been allowed to remain in areas near gull colonies to help control the gull populations (Ruiz-Olmo *et al*., 2003, Southern *et al*., 1985). Limiting large roosting areas near landfills may also discourage California gulls from utilizing an area (Thomas, 1972). Limiting the amount of garbage at dumpsters, in parking lots, and at landfills may also help reduce gull numbers (see above under Corvids).

Tidal restoration to the dry salt pond in Alviso (pond A6, or the Knapp property) will cause the disturbance and subsequent need for relocation of the largest gull colony in the estuary. Over 10,000 California gulls will then be competing for limited nesting space with Forster's terns, Caspian terns, American avocets, and possibly western snowy plovers. Depending on the timing of the creation of new island and levee habitat for new nesting areas, this could lead to severe habitat limitations for the tern and shorebird species in the newly restored areas as the gulls nest earlier, are larger, more abundant, and more aggressive. The creation of new nesting habitat does not necessarily mean the terns or shorebirds will utilize this new habitat; social attraction is often required to entice colonially breeding birds to new areas. This colony presents an opportunity to reduce the bay population of California gulls prior to the implementation of restoration. Management to reduce breeding success on this site from the current date until restoration of pond A6 would benefit all restoration sites.

Additional research for the San Francisco Bay restoration project includes research on local gull populations as described for Corvid species above. The identification of gull movement patterns and areas utilized for main feeding grounds would allow restoration planners to implement overall control measures to ensure predation does not undermine restoration efforts.

Mosquitos and West Nile Virus

A number of different mosquito species reproduce in South Bay marshes and wetlands including:

- Summer salt-marsh mosquito, *Aedes dorsalis*; prefers temporarily flooded tidal marsh pannes, heavily vegetated ditches and brackish seasonal wetlands in the San Francisco Bay.
- Winter salt-marsh mosquito, *Aedes squamiger*; prefers coastal pickleweed, tidal and diked marshes, and other brackish or saline habitats.
- Washino's mosquito, *Aedes washinoi*; prefers shallow ground pools and upland fresh or semi-brackish pools in close proximity to salt marshes or riparian cooridors.
- Western encephalitis mosquito, *Culex tarsalis*; breeds in all types of freshwater habitats.
- Winter marsh mosquito, *Culiseta inornata*; can be found in a wide variety of habitats including everything from rainwater pools and salt marshes to manmade ditches or containers.

Not all species of mosquitoes have the same potential to carry West Nile Virus (WNV), although all mosquito species have the ability to carry WNV. Goddard *et al*. (2002) determined that *Culex* species tend to be more adept at carrying WNV, and *Culex tarsalis* is one of the most efficient laboratory vectors of WNV tested in North America. In addition, *Culex tarsalis* has the highest probability of any mosquito tested in this 2002 study to amplify and maintain WNV in California (Goddard *et al*. 2002). *Culiseta inornata*, a widely distributed winter mosquito in California, also has a relatively high infection rate, and moderately high transmission rate for WNV. The only *Aedes* species tested in this study, *Aedes vexans*, had much lower transmission and infection rates for WNV that either *Culex tarsalis*, or *Culiseta inornata*.

Birds infected with WNV have been found in every county in California except San Benito County, and Del Norte County. San Mateo, Contra Costa, and Alameda Counties have reported birds with WNV in 2004, however, the only Bay Area county reporting mosquitoes infected with WNV is Solano County (USGS, 2004).

Restoration activities that contribute to the spread of WNV, or that increase the abundance of mosquitoes in Bay Area communities will likely be viewed as unacceptable by both the public and by mosquito and vector control agencies managed by Bay Area counties. Restoration design should incorporate mosquito abatement measures to ensure that mosquitos are kept at a tolerable threshold and that WNV is less likely to spread into Bay Area mosquito populations.

Restoration projects in San Francisco Bay have the potential to either create or eliminate mosquito breeding habitat. For example, by restoring tidal action to previously isolated marshes mosquito breeding habitat can be eliminated, while on the other hand, creation of isolated pools of water in the upper reaches of a restored marsh could create mosquito habitat. The Alameda County Mosquito Abatement District has the following recommendations for avoiding mosquito problems in salt marsh restoration projects:

- Delineate depressions, locate optimum drainage patters and determine level of land subsidence. These steps should be part of long term Adaptive Management.
- Maintain outboard levee system until after review by the Mosquito Abatement district, and until after the planned tidal system has been constructed.
- Inboard levee systems should be of sufficient height and strength to withstand wind-driven tides.
- Inboard and outboard levee systems should provide access (preferably roads) for monitoring, maintenance, and mosquito control. Predator gates should be installed.
- Outboard levee and slough breeches should be designed to reduce silt deposition problems.
- Water control structures should be considered to control tidal inflow and outflow.
- Dredged materials, if used, should not create isolated pools in the upper reaches of the marsh. These steps should be part of long term Adaptive Management.
- Pools above the mean high water line should be drained and should be exposed to daily tides.
- Discing or harrowing of cracked ground above mean high water line before levees are breeched can prevent mosquito production and allow reestablishment of native vegetation.
- Long-term maintenance should be recognized and funded.

Fish

The San Francisco Bay/Delta region is home to a number of different introduced fish species. In the Delta, these non-indigenous fish have had a great ecological impact significantly reducing native fish species populations. Bluegill, green sunfish, largemouth bass, striped bass, and black bass, through predation and competition for food and breeding sites, have eliminated the native Sacramento perch from the Delta, inland silversides may feed on the eggs and larvae of the Delta smelt, smallmouth bass have been associated with the decline of hardhead, and all bass species have been implicated in the global extinction of the thicktail chub in California.

It is clear from these examples that invasive fish species have had a great impact on fish assemblages in the Delta however the role of fish in South Bay restoration is unclear. While restoration projects would not result in the introduction of new species to the Bay, additional habitat for some species may be created, or restoration projects may have impacts on anadromous fish by altering fish passage. Alameda, San Leandro, Coyote, Upper Penitencia, Alviso, Stevens, San Francisquito and possibly San Lorenzo creeks, and the Guadalupe River all have anadromous fish populations.

If restoration activities are planned in South Bay rivers, sloughs, or creeks, fish passage should be a top priority, and alterations to any known spawning habitat avoided unless enhancement is possible. Additional research on the role of introduced fish species in South Bay tidal ecosystems would help determine if introduced fish species are impacting sensitive species, food web dynamics, or abundance of native fish. Many introduced fish species, particularly the stripped bass, have important economic roles so any control plans would need to consider economic as well as ecological impacts.

What predictive tools exist for gaining an understanding of this issue and what tools are needed to reduce uncertainty to an acceptable level?

Often the occurrence of an invasion is not noticed until it is too late to take action. In many instances, the scientific investigation focuses on the effect of the invasion rather than how to control or remove the invasive species. This is often a requirement of the regulatory agencies in that a justification is required in order to implement the sometimes temporary, but destructive, environmental impacts and to fund the costly control methods. In addition, persistence, coordination, and long-term funding is usually required. In only a few causes such as the *Caulerpa* invasion in a few coastal lagoons of southern California and the recent invasion and control of *Spartina alterniflora* in Bolinas and Tomales Bay has rapid eradication followed initial observations of the invader.

The same is true for nuisance species with the exception that they have usually been present in

the environment for a long period of time and it is usually a combination of human presence, urbanization, and proximity to suitable resources (including prey) that create conditions where these species can be detrimental to natural habitats and their occupants.
Controlling the effects of these invasive and nuisance species on the environment falls into two primary categories: institutional and scientific. Institutional controls relate to legislative action on non-indigenous species, regulatory controls on new introductions, and development and coordination of government agencies in control and eradication programs. Much has been written on institutional controls (Cohen, 2000; US Congress, 1993). On the other hand, institutional controls cannot be effective if there is not coordination between federal, state, and local agencies. Because such actions require funding, an equal information and awareness at all government levels, and effective policing and enforcement, it is rare that multi-governmental controls are effective. In the example of *Caulerpa* invasive of southern California lagoons, agencies have mobilized and developed standardized monitoring and eradication protocols that must be implemented whenever there is a permit action within a potentially susceptible lagoon. Consistent and directed enforcement of similar measures in the Bay area may have a role to play in some invasions or control of nuisance species especially if the San Francisco Bay Conservation and Development Commission and/or the Corps of Engineers coordinated on standardized approaches to condition their permitting actions.

In the scientific arena, many new tools are being developed to track the effects of invasions. In particular, genetic analysis has proven very useful in tracking *Spartina* invasions (Antilla *et al.* 2000, Ayres *et al.* 1999). Remote sensing and routine long-term monitoring are useful in discovering new invaders or monitoring expansion of nuisance species. While scientific knowledge of invasive species often focuses solely on the after affects of the invasion, some predictive tools have been developed. These predictive tools include modeling population and distributional trend analysis and ecosystem models (both conceptual and mathematical) that portray long-term changes resulting from either establishment or eradication of the species. Good examples of such analyses have been completed on *Spartina alterniflora* and its hybrids (Matsumoto, 2004; Collins, 2002). Likewise, the effects of the invasion of the Asian clam on the food webs of San Francisco Bay have also been documented (Nichols *et al.*, 1990).

The application of modeling to invasive species needs to be more thoroughly developed in order to more effectively communicate the importance of control. Graphic representations of the spread of a species or the diminishment of another native species are useful outcomes of population models calibrated with observations made in the field. It may be possible to include such modeling efforts into restoration experiments to test how sites where active controls are implemented differ structurally and functionally from those areas where controls have not been instituted. In addition, detailed observations and ecosystem modeling for sites where controls are being instituted now should be completed.

Control mechanisms need to be the focus of a considerable amount of research. Integrated pest management that includes use of mechanical, chemical, and biological controls needs to be conducted on those species with the greatest potential for adverse impacts to the restoration process. Good progress is being made on effective controls for *Spartina*. A similar effort should focus on other plant invaders. It is more difficult to control invasive animals as chemical control is often broad spectrum, affecting both natives and non-natives. In addition, predators introduction brings its own set of problems related to non-specific control. Genetic research which focuses on how to target species specific proteins with "designer-made" control agents may be a fruitful area of research for highly disruptive animal invaders.

What are the potential restoration targets and performance measures, linked to Objectives, for evaluating the progress of the restoration project?

In an ideal world, the complete eradication of invasive and the control of nuisance species from restored sites should be a primary performance standard for the restoration project. Unfortunately, 200 years of invasion of the San Francisco Bay estuary cannot be reversed quickly or economically. Therefore, the decisions as to restoration targets and performance measures must be species specific, and based on the level of impact each invader can have. Fundamental questions that must be answered for each of these species include:

$ Does the species cause significant adverse impact on the native, natural environment?
$ Will control and eradication result in a measurable improvement in the natural environment or can other mechanisms be used to ameliorate the impact of the species on the environment?
$ Are there control and eradication methods available, effective, cost-effective, and socially acceptable?
$ At what level must control be enactedBtowards complete eradication, limitations on distribution, or sustained, but low populations
$ Are there institutional mechanisms available to assure long-term control?

While invasion ecology has developed significantly over the years, scientists and project managers have not communicated very well on how to make decisions on what species might be most important to control and at when. Given the large number of invasive species present within the Bay (and likely to invade in the future), a triage approach which allows some to remain or not be controlled whereas others are actively controlled will have to be taken.

It is proposed that a decision matrix be developed that focuses on the appropriate level of control for each species as well as an evaluation of alternative measures (other than control) that might be set for the restoration project. An established risk assessment procedure, *Generic Nonindigenous Aquatic Organisms Risk Analysis*, developed by Orr (1993) and adapted to incorporate vector identification and management (Orr, 2003, in Ruiz and Carlton, 2003) should be the basis for this decision matrix. This risk assessment procedure is a process for evaluating the risks associated with biological invasions and for the consideration of management strategies. The purpose of the assessment is to focus scientific, technical, and other relevant information into the assessment.

For each organism evaluated through the risk analysis, information on the probability and consequences of establishment are organized so that mitigation, restoration, or control measures can be developed.

Organism Risk Assessment Model (Adapted from Orr, 2003)	
Probability of Establishment = (Xa)(Xb)(Xc)(Xd)	Consequences of Establishment = X + Y + Z
Xa = Association with pathway/vector: How is the organism associated with probable vector sources? Xb = Entry potential: Will the presence of this species within a certain pathway create conditions for establishment? Is the species introduced deliberately? Xc = Colonization potential: Once introduced, will the species establish? Xd = Spread potential: Once established, will the species be able to rapidly spread?	X = Potential economic impact: Will species impact crop or natural resources, impact subsidiary industries, tourism, etc.? Y = Potential environmental impact: Will this species result in the decline of threatened or endangered species, loss of biodiversity, etc.? Z = Perceived impact: How does the public and resource agencies view the threat and potential management of this species?

After completion of the organism risk assessment, a decision matrix for control and mitigation measures can be formed by placing organisms determined to pose a significant risk along one axis, and available mitigation or control measures on the other axis. To determine which risks (organisms) should be addressed through management, significant risks are compared with the available mitigation measures. When a particular organism presents a risk that coincides with an available mitigation measure, control efficiency is maximized. For risks that do not have available or potential mitigation measures such as well established aquatic animals, control may not as high a priority.

Because of the likelihood of repeated re-colonization from outside the project, it would be impossible to eradicate vertebrate predators from the estuary. However, restoration targets for nuisance predators should include a no-net increase of predation on special-status and breeding bird species in the Bay. Thus it will be necessary to determine pre-restoration levels of predation with reference/control/before studies as soon as possible.

In addition, design templates should also be tested as a means to control invasive or nuisance species. For example, since *Spartina* invasion is elevational dependent, it may be possible to create elevations that are too low or too high for it to invade a particular restoration site. Of course, some degree of stability would be required for this strategy to work as once sedimentation or sea level change resulted in a change in the surface elevation of the marsh, *Spartina alterniflora* could invade. Other experiments might focus on the dense planting of native vegetation or rapid response eradication as needed. This may be more effective in transition zone and upland areas where hybridization with native species is not a problem, e.g *Lepidium.* Other design considerations include minimization of pathways for travel by non-native predators; use of controlled inlets to restrict areas or control water levels when invasion seems eminent, or use of man-made materials on levees to avoid erosion problems that might occur from burrowing invertebrates.

Another design consideration relates to nesting island design. There is evidence that large colonies of nesting birds are more successful than smaller colonies, either because large colonies are better able to mob predators, or because the nests on the interior of the colony are protected from the "buffer" nests along the outside of the colony (O'Connell, 2003). Thus effort should be made to create nesting islands and insular levees that can support large numbers of colonially nesting birds rather than a series of small islands. In addition, more aggressive species (such as Caspian terns) may protect less aggressive species (such as plovers). Thus plovers could benefit from the creation of open salt pan habitat adjacent to tern nesting islands (Lauro *et al*., 2002).

Flooding and human disturbance should be minimized during the nesting season as both are known to flush adults from the colony, exposing eggs and young chicks to dessication and predation (Ahlund, 1989; O'Connell, 2003).

Highly fragmented areas should be avoided in restoration design, while increased large channel connectivity within marshes should be maximized. Both of these appear to limit red fox predation and benefit tidal marsh species such as the clapper rail (Foin, 1997).

Perches, including fence posts, signs, and towers, should be minimized within and around the restoration to the extent possible in order to limit avian predators from looking down into the marsh for prey. All garbage within the restoration site and to the extent possible, adjacent to the restoration site should be in enclosed containers at all times. Effort should be made to reduce the amount of landfill garbage available to predators, either by covering or other means.

Additional management recommendations include:

$ Limitations on building towers, boardwalks, planting trees, and predator perches on and adjacent to restoration area- especially in areas with nesting species
$ Continued control of predators including minimizing colonization from outside sources if possible
$ Design of restoration, to the extent possible, to limit predator movements between and within marshes and between adjacent habitats
$ Education of the public as to the problems caused by introduced and expanding predators on native wildlife; discouragement of "feeding stations" and all open garbage containers.

Restoration targets for nuisance predators should include a no-net increase of predation on special-status and breeding bird species in the Bay. Thus it will be necessary to determine pre-restoration levels of predation with reference/control/before studies as soon as possible.

Potential performance measures include:

$ Number of predators "taken" by Wildlife Services (should decline under active predator control and proper landscape design?)

$	Number of special-status species and breeding birds/eggs eaten by predators
$	Overall reproductive success of special-status species and breeding birds

Additional management recommendations include:

$	Limitations on building towers, boardwalks, planting trees, and predator perches on and adjacent to restoration area- especially in areas with nesting species (Issue 9?)
$	Continued control of predators
$	Design of restoration, to the extent possible, to limit predator movements between and within marshes and between adjacent habitats

What key questions essential to the success of the restoration need to be addressed through further studies, monitoring, or research?

Further research is needed in a broad area of basic research. Much scientific study has focused on the effects of invasion, more effort is needed on response to invasions as well as control mechanisms. As noted above, given the large number of invasive and nuisance species, it is not possible to undertake a comprehensive examination of all. Rather an initial evaluation using the approach suggested by Orr (2003) or some other means in order to determine those species that have the highest degree of risk to the restoration and have a higher certainty of control. While this paper presents a number of species as examples, it does not purport to have completed such an analysis. However, it is likely that several of the species discussed, notably *Spartina* and its hybrids, perennial pepperweed, Chinese mitten crab, red fox, and California gull might be among those deserving additional study. Such study might consist of the following:

$	What are the rates of invasion of newly restored habitats by non-indigenous species?
$	How does invasion by non-native species affect the ecological “assembly rules” of a newly restored habitat?
$	Assuming that *Spartina* hybrids and *Lepidium* cannot be controlled, what is the alternative future for the restoration project with these species as part of the dominant flora?
$	Can artificial transplantation of native species to a restoration site be effective in altering the influence of the non-native species?
$	Is there a Alow-level@ population size or distribution of an invasive species that can be sustained over time without adverse impact on the natural environment?
$	Are there other mechanisms in a restoration design that can limit invasion, i.e. hydrologic controls, topographic conditions, and/or sediment composition?
$	Are there biological controls that can be developed to effectively limit invasive species?
$	What monitoring tools are available to effectively detect invasive species prior to their becoming a problem in the environment?
$	How are the population dynamics of special-status species and breeding birds in marsh,

salt ponds, and adjacent habitats related to predation rates in marsh, salt ponds and adjacent habitats?

$ How do predator populations relate to movement corridors in marsh, salt ponds, and adjacent habitats and what is the immigration sites from outside the restoration area?

$ Where are breeding/feeding sites of red fox, rats, and feral cats found?

$ What are the important feeding sites for corvids and gulls and the movement patterns of gulls and corvids as they relate to important breeding sites of special status species and breeding birds?

Scientific knowledge can then be combined with agency actions to undertake control of species with a high risk for ecosystem damage. The level of control can be considered at three levels depending upon the species.

Action at the local level

Actions at this level direct control local populations through poisoning, trapping, or manual removal. While this is infeasible for most marine invertebrates, fish, and seaweeds, it can be useful for plants and terrestrial animals. In addition, design approaches can also be taken to limit invasion potential such as eliminating perches used by avian predators, reducing travel corridors used by terrestrial predators, or various methods to reduce mosquito habitat.

Action at the regional level

Some species can be controlled by taking regional approaches. For example, *Spartina densiflora* is currently limited to the north bay in a few locations and could be completely eradicated rather than allowing it to continue to spread slowly through the bay. Better management of landfills and sources of edible garbage may help to reduce gull populations. A regional monitoring and rapid response program could be implemented to detect and then undertake rapid eradication of newly arrived invertebrates, fish or seaweeds.

Action at the policy/political level

For most marine invertebrates, fish, and plankton, we have little potential to control them once they have arrived because they so quickly become integrated within the overall ecosystem. A major goal should be to prevent their arrival in the first place. Laws and regulations will need to be developed to effectively manage the mechanisms affecting their arrival to the Bay.

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References

Ahlund, M., and F. Götmark. 1989. Gull predation on eider ducklings Somateria mollossima: effects of human disturbance. Biological Conservation 48: 115-127.

Alpine, A.E. and J.E. Cloern. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. Limnology and Oceanography 37: 946-955.

American Bird Conservancy, 2004. Cats Indoors! Washington, DC. http://www.abcbirds.org/cats/states/california_intro.htm. 28 September 2004.

Anttila C.K., A.R. King, C. Ferris, D.R. Ayres, D.R.Strong. 2000. Reciprocal hybrid formation of Spartina in San Francisco Bay. Molecular Ecology 9: 765-771.

Anttila, C.K., and C.C. Daehler. 1997. Pollen Swamping of the Native California Cordgrass (*S. foliosa*) by Introduced Smooth Cordgrass (*S. alternaflora*) in San Francisco Bay. Proceedings of the Second International *Spartina* Conference. http://www.ncal.verio.com/~nsn/ pollenswamp.html.

Atkinson, I. A. E. and T. J. Atkinson. 2000. Land vertebrates as invasive species on islands served by the South Pacific Regional Environmental Programme. Pages 19-84 In: Invasive species in the Pacific: a technical review and draft regional strategy / technically. G. Sherley (ed.) South Pacific Regional Environmental Programme. Apia, Samoa.

Ayres D.R., K. Zaremba and D.R. Strong. In press. Extinction of a Common Native Species by Hybridization with an Invasive Congener. Weed Technology.

Ayres D.R., D.L.Smith, K. Zaremba, S. Klohr, D.R. Strong. 2004. Spread of exotic cordgrasses and hybrids (*Spartina* sp.) in the tidal marshes of San Francisco Bay. Biological Invasions. 6: 221-231.

Ayres, D.R., D.R. Strong, and P. Baye. 2003. *Spartina foliosa* – a common species on the road to rarity? Madroño 50: 209-213.

Ayres D.R., D.Garcia-Rossi, H.G. Davis, and D.R. Strong. 1999. Extent and degree of hybridization between exotic (*Spartina alterniflora*) and native (*S. foliosa*) cordgrass (*Poaceae*) in California, USA determined by random amplified polymorphic DNA

(PAPDs). Molecular Ecology 8: 1179-1186.

BDOC. 1994. Draft briefing paper on introduced fish, wildlife, and plants in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary. Bay-Delta Oversight Council, Calif. Resources Agency, Sacramento, 33 pp.

Buck, E.H. 2004. Ballast Water Management to Combat Invasive Species. Cograssional Research Service. Report to Congress, Order Code RL32344.

Carlton, J.T. and J.B. Geller. 1993. Ecological Roulette: The Global Transport of Non-indigenous Marine Organisms. Science 261: 78-82

Cloern, J.E. 1996. Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California. Reviews of Geophysics 34: 127-168.

Cloern, J.E. 1982. Does the benthos control phytoplankton biomass in south San Francisco Bay? Marine Ecology Progress Series 9: 191-202.

Cohen, A.N. 1998. Ships' ballast water and the introduction of exotic organisms into the San Francisco Estuary: Current status of the problem and options for management. San Francisco Estuary Institute, Richmond, CA.

Cohen, A.N., and J.T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. *Science* 279: 555-558.

Cohen, A.N., and J.T. Carlton. 1995. Biological Study. Non-indigenous Aquatic species in a United States Estuary: A case study of the biological invasions of the San Francisco Bay and Delta. U.S. Fish and Wildlife Service, Washington DC and the National Sea Grant College Program, Connecticut Sea Grant , NTIS No. PB96-166525.

Cohen, A.N., and B. Foster. 2000. The regulation of biological pollution: Preventing exotic species invasions from ballast water discharged into California coastal waters. Golden Gate University Law Review 30(4): 787-883.

Collins, J.N. 2002. Invasion of San Francisco Bay by smooth cordgrass, *Spartina alterniflora*, a forecast of geomorphic effects on the intertidal zone. San Francisco Bay Estuary Institute, Oakland. 50pp.

Foerster, K.S. and J.E. Takekawa. 1991. San Francisco Bay National Wildlife Refuge predator management plan and final environmental assessment. U.S. Fish and Wildlife Service, San Francisco Bay National Wildlife Refuge, Newark, CA. 54 pp.

Foin, T.C., E.J. Garcia, R.E. Gill, S.D. Culberson and J.N. Collins. 1997. Recovery strategies for the California clapper rail (Rallus longirostris obsoletus) in the heavily urbanized San Francisco estuarine ecosystem. Landscape and Urban Planning 38:229-243.

Goals Project. 2000. Baylands Ecosystem Species and Community Profiles: Life histories and environmental requirements of key plants, fish and wildlife. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project (P. R. Olofson, Ed.). San Francisco Bay Regional Water Quality Control Board, Oakland, California.

George, W.G. 1974. Domestic cats as predators and factors in winter shortages of raptor prey. *Wilson Bulletin* 86:384-396.

Goddard, L.B., A.E. Roth, W.K. Reisen, and T.W. Scott. 2002. Vector competence of California Mosquitoes for *West Nile Virus*. Emerging Infectious Diseases. Vol. 8 (12): 1385-1391

Gore, J.A. and T.L. Schaefer. 1993. Cats, condominiums and conservation of the Santa Rosa beach mouse. Abstracts of Papers Presented. Annual Meeting of the Society for Conservation, Tucson, Arizona, June, 1993.

Grosholz, E.D., G.M. Ruiz, C.A. Dean, K.A. Shirley, J.L. Maron, and P.G. Connors. 2000. The impacts of a non-indigenous marine predator in a California bay. Ecology 81: 1206-1224.

Grossinger, R., J. Alexander, A. Cohen, and J.N. Collins. 1998. Introduced tidal marsh plants in the San Francisco Estuary *Regional distribution and prioritites for control*. San Francisco Estuary Institue, Richmon, CA.

Harding, E.K., D.F. Doak, and J.D. Albertson. 2001. Evaluating the effectiveness of predator control:the non-native red fox as a case study. *Conservation Biology* 15(4):1114-1122.

Harding, E.K., D.F. Doak, J.D. Albertson, and J.E. Takekawa. 1998. Predator management in San Francisco Bay wetlands: past trends and future strategies. Final report. U.S. Fish and Wildlife Service, Division of Ecological Services, Sacramento, California.

Harvey, T.E. , R.L. Hothem, R.A. Keck, K.J. Miller, G.W. Page, and M.J. Rauzon. 1992 Status and trends report on wildlife of the San Francisco Estuary. USFWS, Sacramento, CA.

Humphrey, S.R. and D.B. Barbour. 1981. Status and habitat of three subspecies of *Peromyscus polionotus* in Florida. *Journal of Mammalogy* 62:840-844.

Hurt, R. 2004. Breeding status of the California Least Tern at Alameda Point, Alameda, California, 2003. Unpub. report, USFWS, Fremont, California.

Jones, P. A. 1986. Aspects of the reproductive biology of the California Gull (*Larus californicus*) in Alviso, California. Unpublished M.A. Thesis. San Francisco State University, San Francisco, California.

Jurek, R.M. 1992. Nonnative red foxes in California. Calif. Dep. of Fish and Game, Wildl. Manage. Div., Nongame Bird and Mammal Sec. Rep. 92-04. 16pp.

Jurek, R. M. 1994. A bibliography of feral, stray, and free-ranging domestic cats in relation to wildlife conservation. Calif. Dep. of Fish and Game, Nongame Bird and Mammal Program Rep. 94-5. 24 pp.

Kimmerer, W. 2004. Open Water Processes of the San Francisco Estuary: From Physical Forcing to Biological Responses. San Francisco Estuary and Watershed Science. Vol. 2, Issue 1 (February 2004), Article 1.

Lauro, B. and J. Tanacredit. 2002. An examination of predation pressures in piping plovers nesting at Breezy Point, New York. Waterbirds 25:401-409.

Lewis, J.C., K. L. Sallee, and R. T. Golightly, Jr. 1999. Introduction and range expansion of nonnative red foxes (*Vulpes vulpes*) in California. American Midland Naturalist 142: 372-381.

Liebezeit, J.R. and T.L. George. 2002. A summary of predation by corvids on threatened and endangered species in California and management recommendations to reduce corvid predation. Calif. Dept. of Fish and Game, Species Conservation and Recovery Program Rpt. 2002-02, Sacramento, California. 103 pp.

Linville, R.G, S.N. Luoma, L. Cutter, and G.A. Cutter. 2002. Increased selenium threat as a result of invasion of the exotic bivalve, *Potamocorbula amurensis* into the San Francisco Bay-Delta. Aquatic Toxicology 57: 51-64.

Lovegrove, T. G., C. H. Zeiler, B. S. Greene, B. W. Green, R. Gaastra, and A. D. MacArthur. 2001. Alien plant and animal control and aspects of ecological restoration in a small 'mainland island': Wenderholm Regional Park, New Zealand. Pages 155-163 in: M. N. Clout and C. R. Veitch (eds.) Turning the Tide: The Eradication of Invasive Species. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK.

Matsumoto, Yukari. 2004. The spatial patterns and growth rates of an invasive cordgrass (*Spartina alterniflora* and *Spartina alterniflora x foliosa*) in Alameda and San Bruno Marsh, CA. Masters Thesis. San Francisco State University. 103pp.

Morris, R.D., H. Blokpoel and G.D. Tessier. 1992. Management efforts for the conservation of Common Tern Sterna hirundo colonies: Two case histories. Biological Conservation 60: 7-14.

National Audubon Society. 2002. The Christmas Bird Count Historical Results [Online]. Available http://www.audubon.org/bird/cbc. 28 September 2004.

Neuman, K. K., L. E. Stenzel, and L. A. Henkel. 2001. Predator management at Salinas River National Wildlife Refuge: an analysis of the predator management plan. USFWS, Don Edwards San Francisco Bay National Wildlife Refuge. Newark, California.

Nichols, F.H. and J.K. Thompson. 1985. Persistence of an introduced mud flat community in south San Francisco Bay, California. Marine Ecology Progress Series. 24: 83-97.

Nichols, F.H., Thompson, J.K. and L.E. Schemel. 1990. Remarkable invasion of San Frnacisco Bay (California, USA) by the Asian clam *Potamocorbula amurensis*. II. Displacement of a former community. *Mar. Ecol. Prog. Ser.* 66:95-101.

O'Connell, T. J. and R. A. Beck. 2003. Gull predation limits nesting success of terns and skimmers on the Virginia barrier islands. Journal of Field Ornithology 74:66–73.

Orr, R. L., S.D. Cohen, and R.L.Griffin. 1993. *Generic Non-indigenous Pest Risk Assessment Process*. Report to the U.S. Department of Agriculture.

Orr, R. L. 2003. Generic Non-indigenous Aquatic Organisms Risk Analysis Review Process. In *Invasive Species: Vectors and Management Strategies*. Ruiz, G.M., and J.T. Carlton, eds. 2003. Island Press. Washington D.C.

Ruiz-Olmo, J., F. Blanch, and F. Vidal. 2003. Relationships between the red fox and waterbirds in the Ebro Delta National Park, NE Spain. Waterbirds 26:217-225.

Ryan, T.P. . 2000 California Gull. In Goals Project. Baylands Ecosystem Species and Community Profiles. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. P.R. Olofson, ed. San Francisco Bay Regional Water Quality Control Board, Oakland, CA.

Sauer, J. R., J. E. Hines, and J. Fallon. 2004. The North American Breeding Bird Survey, Results and Analysis 1966 - 2003. Version 2004.1. *USGS Patuxent Wildlife Research Center*, Laurel, Maryland.

Seymour, A. S., S. Harris, and P.C.L. White. 2003. Potential effects of reserve size on incidental nest predation by red foxes *Vulpes vulpes*. Ecological Modeling 175:101-114.

Shouse, M.K., F. Parchaso, and J.K. Thompson. 2003. Near-field receiving water monitoring of a benthic community near the Palo Alto water quality control plant in south San Francisco Bay: February 1974 through December 2000. U.S. Geological Survey Open-File Report 03-224.

Southern, W. E., S. R. Patton, L. K. Southern, and L. A. Hanners. 1985. Effects of nine years of fox predation on two species of breeding gulls. Auk 102:827-833.

Strong, C. M., L. Spear, T. P. Ryan and R. E. Dakin. 2004a. Forster's and Caspian tern colonies in the San Francisco Bay: population sizes and trends, 1982-2003. USFWS, Region 1, Portland OR.

Strong, C. M., L. Spear, T. P. Ryan and R. E. Dakin. *In press*. Forster's Tern, Caspian Tern, and California Gull Colonies in San Francisco Bay: Habitat Use, Numbers and Trends, 1982-2003. Waterbirds.

Talley, T.S., Crooks, J.A., and L.A. Levin. 2001. Habitat utilization and alteration by the invasive burrowing isopod, *Sphaeroma quoyanum*, in California salt marshes. Marine Biology 128: 561-573.

Takewawa, J. 1993. The California clapper rail: Turning the tide? Tideline (East Bay Regional Park District) 13(2):1-3,11.

Tershy, B. R., C. J. Donlan, B. S. Keitt, D. A. Croll, J. A. Sanchez, B. Wood, M. A. Hermosillo, G. R. Howald, and N. Biavaschi. 2001. Island conservation in north-west Mexico: a conservation model integrating research, education and exotic mammal eradication. Pages 293-300 in: M. N. Clout and C. R. Veitch (eds.) Turning the Tide: The Eradication of Invasive Species. IUCN SSC Invasive Species Specialist Group. IUCN, Gland, Switzerland and Cambridge, UK.

Thomas, G. J. 1972. A review of gull damage and management methods at nature reserves. Biological Conservation 4:117-127.

Thompson, J.K. 1999. The effect of infaunal bivalve grazing on phytoplankton bloom development in south San Francisco Bay: Stanford University, Standford, Calif., Ph.D. dissertation, 419 p.

Thompson, J.K., F. Parchaso, and M.K. Shouse. 2002. Near-field receiving water monitoring of a benthic community near Palo Alto water quality control plant in south San Francisco Bay: February1974 through December 2002. U.S. Geological Survey Open-File Report 02-394.

US Congress. 1993. Harmful Non-indigneous Species in the United States. Office of

Technology Assessment. OTA-F-565. Washington DC: US Government Printing Office. 391pp.

USFWS, 2003. Biological Opinion based on information provided in “San Francisco Estuary Invasive Spartina Project: Spartina Control Program.” Sacramento, CA Ref#1-1-03-F-0216.

U.S. Geologic Survey. 2004. West Nile Virus Maps. http://westnilemaps.usgs.gov/

Winkler, D. W. 1996. California Gull (*Larus californicus*). *In* The Birds of North America, No. 259 (A. Poole and F. Gill, Eds.). The Birds of North America, Inc., Philadelphia, Pennsylvania

Young, J.A., Palmquist, D.E., Blank, R.S., and C.E. Turner. 1995. Ecology and control of Perennial Pepperweed (*Lepidium latifolium L.*). California Exotic Pest Council, 1995 Symposium Proceedings. Reno, NV.