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Selected shorebirds: factors that control distribution and abundance in Pacific Coast estuaries and a case study of Elkhorn Slough, California

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ABOUT THIS DOCUMENT

This document was written by Kristen Ruegg, University of California, Berkeley. The following experts have generously reviewed and greatly improved this document.

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This document is part of a series of reports on key species that use estuarine habitats on the Pacific Coast. Coastal decision-makers are setting habitat and water quality goals for estuaries worldwide and exploring restoration projects to mitigate the major degradation estuarine ecosystems have undergone in the past century. These goals can be informed by an understanding of the needs of key species that use estuarine habitats. To inform on-going restoration planning as a part of ecosystem-based management at Elkhorn Slough, an estuary in central California, we have selected eight species / groups of organisms that are ecologically or economically important to estuaries on the Pacific coast of the United States. The first five sections of each review contain information that should be broadly relevant to coastal managers at Pacific coast estuaries. The final sections of each review focus on Elkhorn Slough.

Kerstin Wasson served as Editor-in-Chief for this series of reports, with editorial and production assistance from Erin McCarthy and Quinn Labadie. They conducted this work as staff of the Elkhorn Slough National Estuarine Research Reserve, owned and managed by the California Department of Fish and Game in partnership with the National Oceanic and Atmospheric Administration (NOAA). Grants from the Packard Foundation, Resources Legacy Fund Foundation, and the Estuarine Reserves Division of NOAA supported this project.

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The mission of the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve is conservation of estuarine ecosystems and watersheds, with particular emphasis on Elkhorn Slough, a small estuary in central California. Both organizations practice science-based management, and strongly support applied conservation research as a tool for improving coastal decision-making and management. The Elkhorn Slough Technical Report Series is a means for archiving and disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature.

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A. Background

Migratory shorebirds are a diverse group of aquatic bird species (Order Charadriiformes; suborder Charadrii) including oystercatchers, stilts, avocets, plovers, and sandpipers. The majority of shorebirds along the Pacific Coast of California are wintering birds or migrants stopping through on their way to and from their breeding grounds in eastern Siberia and much of Alaska and their wintering grounds as far south as southern South America (Morrison 1984). Fewer species are year round residents and / or breeding birds. There are several reasons to consider the potential influence of large-scale management alternatives on Pacific coastal migratory shorebird communities. For example, over the last several decades, many species of migratory birds have experienced precipitous population declines (Terborgh 1989, Askins 1990, Finch 1993). and loss of Pacific coastal estuary and wetland habitat may result in further population declines in some species (Moore 1993). Additionally, shorebirds are higher level predators in estuarine ecological communities, and significant changes in shorebird population size may have cascading effects on organisms at lower trophic levels (Daborn et al. 1993). Lastly, migratory shorebirds are a high profile group of species that generate considerable public interest as well as ecotourism dollars (Manion et al. 2000, Sekercioglu 2002) and as a result, decline in shorebird abundance and diversity may have substantial social and economic impacts on coastal communities.

This review will focus on Willets (*Tringa semipalmata*), Long-billed Curlews (*Numenius americanus*), Least Sandpipers (*Calidris minutilla*), and Marbled Godwits (*Limosa fedoa*) because they represent a broad range of the species found wintering and migrating within Pacific coastal estuaries: Long-billed Curlews are large, specialist feeders, Willets and Marbled Godwits are medium-sized, generalist feeders, and Least Sandpipers are small shorebirds foraging on smaller prey items (Figure 1). General information about each species is summarized in Table 1.

B. Trends in Distribution and Abundance

While reliable data on regional population trends are limited, historical accounts of relative abundance and distribution suggest that several species of North American shorebirds have declined over the last 150 years (Page and Gill 1994). For example, habitat alterations coupled with widespread hunting at the turn of the century is thought to have been responsible for the extirpation of some formerly widespread species such as the Eskimo Curlew (*Numenius borealis*) and significant declines in other species such as the Long-billed Curlew. Over the last 25 years, population trends based mostly upon Breeding Bird Survey (BBS) data (a system of roadside surveys designed to monitor populations of breeding landbirds) are more complex - while many shorebird species are experiencing decreases, others are appear to be increasing or remaining stable (Gill et al. 1995).

Qualitative and quantitative data on range-wide population trends for Long-billed Curlews, Marbled Godwits, Willets and Least Sandpipers show variation in patterns of abundance over the last century (Cooper 1994, Gratto-Trevor 2000, Lowther et al. 2001, Dugger and Dugger 2002) (Table 1). While range-wide populations of Marbled Godwits and Long-billed Curlews are thought to have declined since the1800s, no long-term population trends are known for Least Sandpipers or Willets.

Population trends for the four focal species at one intensely studied Pacific coastal estuary, Bolinas Lagoon, show conflicting patterns of abundance over the last several decades (PRBO 2008) (Figure 2). Species that were historically in decline, such as the Long-billed Curlew and the Marbled Godwit, appear to be increasing, while species that have historically been more stable, such as the Least Sandpiper and the Willet, show no clear trends (PRBO 2008) (Figure 2).

C. Factors Affecting Shorebird Abundance in Estuaries

Overall, the mobile nature of migratory shorebirds makes it difficult to pinpoint the cause for specific population trends. Predation by local mammalian and avian predators, toxins such as pesticides, plastics, and lead, collisions with structures such as power lines, and disturbance at nesting sites are all possible factors affecting shorebird abundance, but more research is needed to gauge their individual and combined importance.

The single most important factor that is thought to influence shorebird abundance is the availability of suitable habitat (Recher 1966). Habitat loss on the wintering grounds may lead to starvation and increased mortality (Morse 1980, Rappole and McDonald 1994, Goss-Custard et al. 1995), while habitat loss on the breeding grounds may negatively influence reproductive success (Myers 1983, Askins 1990, Sherry and Holmes 1993). Migratory stopovers provide an important link between breeding and wintering areas because the energy obtained at stopovers may be essential to successfully completing migration (Ricklefs 1974, Davidson and Evans 1988). The persistence of estuaries may be particularly important to species unable to shift to alternate foraging areas (Myers 1983, Senner and Howe 1984, Myers et al. 1987, Davidson and Piersma 1992). Given the multiple stressors encountered by migratory birds at breeding, wintering and migratory stopover sites, it is likely that specific population declines result from combinations of disturbances encountered throughout the annual cycle (Moore et al., 1993; Sherry and Holmes, 1993).

D. Factors Affecting the Shorebird Distribution within an Estuary

Food

The primary factor influencing the distribution of shorebirds within an estuary is the distribution and abundance of prey items (Wolff 1969, Goss-Custard 1970). This relationship has been documented at both large (tens of square kilometers; Goss-Custard 1970, Bryant 1979, Evans and Dugan 1984, Hicklin and Smith 1984, Goss-Custard and Yates 1992) and fine spatial scales (hundreds of square meters; Goss-Custard 1970, Wilson 1990). In some cases, the relationship is so close that the arrival and departure of shorebirds at an estuary is in sync with annual fluctuations in the invertebrate community (Schneider and Harrington 1981, Harrington 1983, Myers et al. 1990).

Tidal mudflat is the primary foraging habitat for many of the most abundant shorebirds (Recher 1966, Bengtson and Svensson 1968, Hickey et al. 2003, Strahlberg et al. 2006). Shorebirds mostly feed on benthic invertebrates found within the mudflats, such as copepods, clams, polychaetes and crabs (Gill et al. 1995). The four focal species in this review vary in regards to their feeding preferences and their distribution within tidal mudflats (Table 1):

1. Willets are generalists and can be found feeding on a variety of organisms throughout the mudflats. In addition to foraging for their food, Willets have also been known to steal prey from other birds (Gary Page, pers. comm.).
2. Least Sandpipers are surface-probers and feed mostly on small crustaceans and gastropods found in muddy, finer grained sediments.
3. Marbled Godwits are deep-probers that feed mostly on larger sand-dwelling prey.
4. Long-billed Curlews are also deep-probers that are thought to specialize on prey found within firm mud in high tidal areas, including invertebrates living in worm and clam tunnels. They are often found in salt marshes at higher tides.

When mudflats are inundated at high tide, many shorebirds will secondarily use sandy beaches, salt ponds, fresh water marshes and agricultural fields for additional foraging and / or resting (Burger et al. 1977, Gerstenberg 1979, Ramer et al. 1991, Long and Ralph 2001). Various physical parameters such as salinity, tidal height and sediment grain size influence prey availability and thus shorebird distribution within an estuary. These physical parameters will be reviewed below.

Salinity

Shorebirds are found associated with a broad spectrum of salinity levels from hypersaline ponds to freshwater marshes (Wolff 1969). The association of shorebirds with particular salinity levels is generally thought to be the result of the abundance of suitable prey species at particular sites rather then salinity tolerance per se (Wolff 1969, Goss-Custard 1970, Hicklin and Smith 1984, Colwell and Landrum 1995). Most shorebirds are found foraging in marine-brackish salinities associated with the intertidal mudflats, but many will secondarily forage and roost in hypersaline salt ponds and freshwater marshes and agricultural fields. All of the focal species in this review are known to use hypersaline salt ponds for roosting and or feeding during high tide (Cooper 1994, Gratto-Trevor 2000, Lowther et al. 2001, Dugger and Dugger 2002) and in late fall, Least Sandpipers, Marbled Godwits and Longbilled Curlews are also known to utilize agricultural fields at intermediate and high tides when mudflats are inundated (Long and Ralph 2001).

Tidal Height

Shorebirds primarily forage in intertidal mudflats when substrate is available (Recher 1966) and the availability of intertidal mudflats varies with changes in the tidal cycle. The ability of species to forage at various water depths depends upon their morphology - in general, species with longer legs and bills such as Willets, Long-billed Curlews and

Marbled Godwits are able to take advantage of higher water levels then species with shorter legs and bills such as Least Sandpipers (Cooper 1994, Gratto-Trevor 2000, Lowther et al. 2001, Dugger and Dugger 2002).

Substrate type

The distribution of benthic invertebrates and thus shorebirds within estuaries is determined in part by substrate type (muddier finer grain sediment versus, sandier, larger grain sediment; Quammen 1982, Grant 1984, Ramer et al. 1991). In general, small shorebirds such as sandpipers feed on invertebrates found in fine grained sediments, while larger shorebirds such as Willets, Godwits and Curlews eat larger, sand-dwelling organisms that are more abundant in sandier regions (Ramer 1985).

E. Predicted changes in estuary-wide abundance in response to restoration projects

The estuary-wide abundance of shorebirds is a function of their density and their distribution. Large-scale estuarine restoration projects could modify density, distribution or overall abundance. The goals of such restoration generally fall into two major categories: changes to water quality and changes to habitat extent. The types of responses expected from shorebirds to such restoration are reviewed below.

Changes to water quality

To the author's knowledge there are no studies demonstrating a clear relationship between water quality and the estuary-wide abundance of shorebirds. However, given the well documented relationship between shorebirds and prey availability (Wolff 1969, Goss-Custard 1970, Bryant 1979, Evans and Dugan 1984, Hicklin and Smith 1984), it seems logical to conclude that if changes in water quality were severe enough to influence the density and distribution of prey items, then this may in turn influence shorebird abundance.

Changes to habitat extent

Availability of foraging space is believed to be one of the most significant factors in determining the size of migratory bird populations (Recher 1966), but predicting the outcome of habitat changes is extremely challenging. One fruitful approach for understanding local patterns has been habitat-based modeling of population changes, such as applied to the South Bay salt pond restoration projects (Strahlberg et al. 2006). Another highly successful method for predicting the outcome of habitat alterations on population abundance is individual-based models (IBMs) that take into account the physiology and behavioral decision making of individual animals and from that predict how many birds will starve or run out of body reserves over the winter non-breeding season (Stillman et al. 2000, Durell et al. 2005). For example, the parameters of an IBM may include information on the energetics, consumption, and competitive behavior of a species as well as information on daily ambient temperature, day length, exposure time, prey density, and bird numbers at a particular site (Goss-Custard et al. 2006). These models have been shown to accurately predict the consequences of habitat alterations on species abundance in more than one species and site (Stillman et al. 2003, Goss-Custard et al. 2006). In Redshanks wintering in Cardiff Bay, Wales, an IBM predicted that the loss of intertidal feeding habitat resulting from a dam would increase the mortality of Redshanks by 3.65%; the actual observed increase in the rate of mortality was 3.17% (Goss-Custard et al. 2006). In addition, further simulations showed that mortality was most likely due to an increase in competition, and that restoration of 10% of the lost mudflat was needed to return mortality to its previous level. IBMs support the hypothesis that a decrease in mudflat foraging area will negatively influence shorebird populations and may result in mortality if habitat loss is severe enough.

In addition to reduction of mudflat area, changes in substrate composition within the mudflats may influence the extent of optimal foraging space for some shorebird species. In general, shorebird species with specialized bill morphologies or strong preferences for particular benthic invertebrates may be more susceptible to changes in mudflat composition than are more generalist species (Durell 2000). Of the four focal taxa in this review, the generalist habits of the Willet would make it the least likely to be affected by habitat changes within an estuary; given the known habitat use of Marbled Godwits, it remains unclear how habitat changes would influence their estuary-wide abundance or distribution. Alternatively, the substrate feeding preferences of Least Sandpipers and Long-billed Curlews make them more susceptible to changes in substrate composition - Least Sandpipers may decline with the loss of finer grain sediments, while Long-billed Curlews may decline with the loss of firm mud.

F. Status and trends of Elkhorn Slough populations

Seasonal patterns in abundance

Shorebird abundance at Elkhorn Slough varies seasonally. In general, abundance is greatest during spring and fall migration, at which time there can be as many as 20,000 individuals (Ramer et al. 1991), and lowest during the winter and summer (Senner and Howe 1984). According to an in-depth study of shorebirds at Elkhorn Slough from spring of 1999 to spring of 2000, abundance of Willets, Marbled Godwits, Least Sandpipers and Long-billed Curlews was greatest from late summer through winter (August - February) and lowest in late spring and early summer (May – June), when birds have left the region to breed elsewhere (Harvey and Connors 2002; see Figure 11.2, Connors 2003).

Spatial patterns of abundance

The distribution of Willets, Least Sandpipers, Marbled Godwits, and Long-billed Curlews from 1999-2000 is summarized in Figure 3 (Connors 2003). Over the course of the two year survey conducted by Connors (2003), Willets were most abundant at Parsons Slough (Figures 3 and 4) in all seasons and in the lower main channel in winter, the upper main channel in spring and mid to upper main channel in fall. In fall and winter, Marbled Godwits were most abundant in the main channel, Parsons Slough and North Harbor relative to other areas, but in spring their abundance in North Harbor and the lower main channel decreased relative to other areas. In winter and spring, Long-billed Curlews were most abundant in the mid-main channel relative to other areas, but in fall they were abundant in Parsons Slough. Least Sandpipers were abundant in the mid- to upper main channel and Parsons Slough year round. When these abundance figures are converted to densities (by dividing abundance by estimated intertidal mudflat area for each region), somewhat different patterns emerge (Connors 2003). For instance, while Parsons Slough hosts the greatest numbers of various shorebirds, their densities are actually fairly low – it is the vast extent of intertidal mudflats in this region that leads to high total numbers, not particularly valuable foraging grounds.

Factors affecting the distribution and abundance of shorebirds at Elkhorn Slough

At low tide, most shorebirds are found foraging in the intertidal mudflats. The use of alternate feeding and roosting sites can vary by species (Ramer et al. 1999, Long and Ralph 2001). At Elkhorn Slough, Connors (2003, 2008) found that Least Sandpipers and Marbled Godwits used muted tidal regions such as North Marsh, the salt ponds, and Moro Cojo Slough for feeding and roosting at high tide, whereas Willets and Long-billed Curlews typically did not (Figure 3).

Connors (2003) also found that species distributions on intertidal mudflats varied by particle size. For example, Long-billed Curlews, Marbled Godwits and Willets were associated with coarser-grained sediments found within lower slough and the North Harbor, while Least Sandpipers were associated with finer grain sediments found at the upper reaches of Elkhorn Slough. Connors hypothesized that associations between shorebird distributions and sediment size are likely a result of differences in the distribution of principle prey items, a pattern that has been shown in other species (Yates et al. 1993).

Temporal trends in distribution and abundance: Pre-1970s

While there are no published quantitative reports on shorebird abundance before the1970s, major changes to the Elkhorn Slough ecosystem occurred prior to this date that may have contributed to an increase in the shorebirds using this region. In particular, the area of mudflat has increased dramatically in the last 150 years as a result of extensive diking and draining to support human land use (Van Dyke and Wasson 2005). Further conversion of salt marsh to mudflat has occurred in the main channel most likely as a result of the opening of an artificially large and wide mouth to Elkhorn Slough built in 1947 to accommodate Moss Landing Harbor. In addition, freshwater inputs to Elkhorn Slough decreased due to the 1909 diversion of the Salinas River for agricultural use. These changes likely provided additional foraging grounds for shorebirds at Elkhorn Slough; and while global populations of shorebirds are thought to have declined during this period, the number of shorebirds in this region may have increased.

Temporal trends in distribution and abundance: 1970 - Present

Connors (2003) evaluated temporal trends in distribution and abundance of shorebirds at Elkhorn Slough in 1998 – 2000, replicating shorebird surveys originally done by Ramer (1991) in the late 1970s and comparing both data sets. Among Connors' main findings were that in the late 1990s larger shorebirds (Willets, Marbled Godwits, and Long-billed Curlews) were found in higher densities (but similar total numbers) in the lower sections of the main channel relative the middle sections, a pattern that did not exist in the late 1970s. Connors hypothesized that this may be due to a loss of intertidal habitat to erosion in the lower slough that may have led to greater shorebird densities and subsequent displacement of birds into less optimal foraging grounds.

Connors also found that since the late 1970s there was a shift in the distribution of small sandpipers from the mid- to the upper main channel. Mudflat area has increased in the upper slough due to conversion of marshes to mudflat. In addition, grain size has increased along the entire length of the main channel as a result of increased tidal velocities. Connors hypothesized that the increase in mudflat area in the upper main channel combined with the increase in sediment grain size throughout the main channel may account for the shift in the distribution of small sandpipers since the 1970s.

Examination of all the available monitoring data for the four species reveals significant interannual variation but few long-term trends (Figure 5). Monitoring data from the past five years suggests Willet abundance is increasing in Elkhorn Slough (S. Fork, unpublished data), but no such trends are evident for the other three species.

G. Predictions for Elkhorn Slough under different management alternatives

Overview

Four large-scale management alternatives for Elkhorn Slough were developed with the goal of decreasing rapid rates of subtidal channel scour and salt marsh conversion to mudflat habitat that have been documented over the past decades (Williams et al. 2008, Largay and McCarthy 2009). Changes to physical processes and water quality in response to these management alternatives vs. a "no action" alternative have been modeled and summarized (Williams et al. 2008, Largay and McCarthy 2009). To determine which management alternative best optimizes estuarine ecosystem health, the coastal decision-makers involved in this process of wetland restoration planning require at minimum some basic information about how species that play major ecological or economic roles are likely to respond to the different management alternatives. In the absence of detailed demographic data and rigorous quantitative modeling, it is impossible to obtain robust quantitative predictions about responses of these key species. Instead, the goal of the preceding review of factors affecting density and distribution of the species across their range and the evaluation of trends at Elkhorn Slough is to provide sufficient information to support qualitative predictions based on the professional judgment of experts. These predictions represent informed guesses and involve a high degree of uncertainty. Nevertheless, for these species the consensus of an expert panel constitutes the best information available for decision-making.

Biological predictions based on habitat extent

Our assessment of the management alternatives has multiple components. First, we predict how population sizes will respond to alternatives based only on extent of habitat of the appropriate tidal elevation. This assessment was based on the predictions of habitat extent at Year 0, 10, and 50 under the five alternatives (as summarized in Largay and McCarthy 2009 and shown in Table 2). Note that all alternatives involve major loss of salt marsh and concurrent gain of other habitat types at year 50; this is due to an assumption of 30 cm of sea level rise after 50 years, which largely overshadows effects of the alternatives. A significant change in habitat area was defined as an increase or decrease of 20% or greater over year 0, No Action (Alternative 1) acreages. Likewise, a significant change in population size of the species was defined as an increase or decrease of 20% or greater over the average population size of the past decade (1999-2008). For the habitat and species predictions, the geographic boundaries are all the fully tidal estuarine habitats of Elkhorn Slough excluding the Parsons complex (predictions do not include tidally restricted areas). For this first component, we made a very simplified assumption that population size is a linear function of area of habitat of appropriate tidal elevation. Thus for example a significant increase in habitat extent translates directly into a significant increase in estuary-wide population size.

For the migratory shorebird species considered here, we used intertidal mudflat area (part C of Table 2) as the basis for these habitat-based predictions, which are indicated with "H" and shown in blue on Figure 6. Since tidal mudflats are known to be by far the most important foraging habitat within estuaries for all four of these species, these habitat-based predictions are a reasonable starting point for understanding how estuary-wide abundance of the species would respond to the large-scale management alternatives. However, it is not known whether there is strong or weak correlation between tidal mudflat area within an estuary and estuary-wide abundance. It is possible that abundance of a particular shorebird species is near or at "carrying capacity" for the estuary, for instance if prey items or feeding territory size are limiting, such that greater densities of shorebirds cannot be sustained under current conditions. If so, then one would expect a strong correlation between habitat area and estuary-wide abundance of the shorebird – a doubling of tidal flat area might lead to a doubling of shorebird numbers, because prey numbers or foraging territories have doubled. On the other hand, it is possible that shorebird abundance is far below "carrying capacity" for the estuary, for instance because population numbers are constrained by predation on the breeding grounds or mortality during migration. In that case, a doubling of tidal mudflat area might lead to no change in estuary-wide abundance of the shorebird. In reality, the relationship between tidal mudflat area and estuary-wide abundance probably falls between these extremes. Comparative observations from multiple estuaries along this coast (Page et al. 1999) suggest that there is at least a loose relationship between aerial extent of tidal mudflats at an estuary and shorebird abundance at the estuary. This relationship of course must be curvilinear – shorebird numbers will not increase indefinitely at an estuary with increased habitat area, but at some point (when the entire migrating population uses the estuary as a stopover) must level off.

While we used intertidal mudflat area for habitat-based predictions, it is possible that salt marsh area also plays a role in the estuary-wide abundance of shorebird species, since they use it for roosting habitat. Long-billed Curlews in particular are often found in salt marshes at Elkhorn Slough at high tide (T. Newberry, pers. com.). The extensive loss of salt marsh under Alternatives 1 and 4 might have negative effects on shorebird abundance, but on the other hand, the salt marsh that will remain, fringing the estuary, might be ample. The relationship between salt marsh acreage and shorebird abundance is too poorly defined for us to incorporate it into the shorebird predictions.

Factors other than habitat extent that may be altered by management alternatives

Clearly the assumption of a strictly linear correlation between population size and extent of habitat of appropriate tidal elevation is overly simplistic and unlikely to accurately describe population response to the alternatives. Habitat quality or environmental conditions other than habitat extent are also important drivers of estuary-wide population size. Unfortunately, we lacked quantitative predictions for most parameters relevant to habitat quality for these species. In order to address this short-coming, we attempted to identify key aspects of each management alternative that might affect habitat quality or critical environmental conditions. Consideration of these aspects led to characterization of “best case” and “worst case” scenarios for each alternative, indicated by arrows in Figure 6. These arrows represent qualitative assessments; the exact length or location of the arrow has no quantitative significance. Each arrow is marked with a letter; abbreviations are described below. The description of the range of possible outcomes may be as important for decision-makers as the rough predictions of changes to population sizes based on habitat extent. This information will provide important guidance on future design or refinement of management alternatives. Identification of important parameters other than habitat extent which may be altered by the management alternatives may also lead to future physical modeling and predictions of these parameters, funding permitting, which would enable more robust biological predictions to be made in future iterations of this process, as management alternatives are refined. Here we review the factors invoked in the development of worst and best case scenarios for each of the alternatives.

The most important component of habitat quality for foraging shorebirds is community composition, biomass, and accessibility of the invertebrate prey base. However, no predictions are available for how small benthic infaunal invertebrates will respond to the large-scale management alternatives. We thus must rely on more indirect correlates. Least Sandpipers are known to be most abundant in muddy tidal flats with fine sediments, such as are found in portions of the estuary without strong marine influence. Data from Elkhorn Slough reveal that Least Sandpipers increase in abundance with distance from the mouth of the estuary (Figure 3b). It seems plausible that under Alternative 1 (and Alternative 4, which is fairly similar for the lower estuary), the proportion of the estuary which has strong tidal flushing and sandy sediments is likely to increase in years 10 and 50 as a result of continued increase in tidal prism. This increased marine influence (marked with +m in Figure 6) may lead to decreases in Least Sandpipers, as extent of muddy tidal flats with fine sediments decreases. Conversely, Alternatives 2 and 3 should decrease marine influence, leading to potential increases in appropriate habitat for and abundance of Least Sandpipers (scenarios marked with "-m" in Figure 6). The other three shorebird species show less clear patterns of abundance with sediment size or marine influence. These species are generally known to favor firmer mud or sandier sediments more typical of marine-influenced portions of the estuary, but data from Elkhorn Slough reveal that in general, densities near the mouth are not higher than densities in the mid-upper estuary (Figure 3a,c,d). We thus did not include changes in marine influence per se in making predictions for responses of these three species.

Another factor which may affect benthic invertebrate communities and thus shorebirds is water quality, in particular symptoms of eutrophication. Water quality predictions (by K. Johnson, summarized by Largay and McCarthy 2009) did not suggest that hypoxia would be common under any alternative. However, the modeling assumed good mixing in the water column. It is possible that stratification could occur under Alternatives 2-3, leading to prolonged hypoxia which would negatively affect benthic invertebrates. With lower tidal flushing, macroalgal mats might also accumulate. Thick, extensive algal mats are known to accumulate currently in subtidal areas of the estuary with muted tidal exchange (e.g., Bennett Slough, Whistlestop Lagoon), and benthic infauna can be reduced in abundance under such mats. Increased stratification and eutrophic symptoms (hypoxia or algal cover) might thus lead to decreases in shorebirds under Alternatives 2-3. (These scenarios are marked with "+e" for increased eutrophication in Figure 6.)

Other habitat conditions known to affect shorebirds include salinity and water depth. Salinity is not likely to change significantly under any of the management alternatives; given the absence of major riverine influence, salinities are likely to remain close to marine year-round in the tidal portions of the estuary under consideration here. Likewise, water depth is an important consideration for managed wetlands with permanent standing water such as salt ponds or lagoons, but not for the tidal portion of the estuary. Shorebirds can forage in different components of the intertidal depending on tidal height and this varies continually over the tidal cycle, but overall estimation of aerial extent of intertidal mudflats is a good proxy for foraging area of appropriate water depth.

Predictions for key species under different management alternatives

Each alternative is evaluated below. The assessment for each includes predictions based on extent of habitat of appropriate tidal elevation alone, summarized by the "H" and blue font in Figure 6, and consideration of other factors related to the management alternatives that might alter these predictions, leading to "best" and "worst" case scenarios shown by arrows in Figure 6. Least Sandpipers are treated separately, due to their preference for fine sediments, while predictions for the other three focal shorebirds are combined, because they are identical.

Alternative 1 – No action

By definition, there will be no significant change in estuary-wide population size of the shorebird species in Year 0. Based on habitat extent changes alone, we predict no change at Year 10, because acreage of mudflat habitat does not change significantly. At Year 50, we predict a significant increase for all species, because intertidal mudflat habitat extent increases significantly.

No other factors related to this alternative are well enough characterized to lead to deviations from these habitat-based predications for three of the focal species. For Least Sandpipers, increased marine influence over time, as tidal prism increases, may lead to lower numbers of birds than predicted by habitat alone (arrows marked "+m" in Figure 6), as extent of optimal habitat with fine sediments decreases.

Alternative 2 – Re-route of estuary mouth to create new inlet and decrease tidal prism

Based on habitat extent changes alone, we predict that the shorebird species will decline in abundance in all years under this alternative, because intertidal mudflat habitat area is decreased significantly (relative to Year 0, Alternative 1).

In the worst case scenario, the shorebird species might decline beyond what is predicted based on aerial extent of habitat alone, if symptoms of eutrophication increase markedly (arrows marked "+e" in Figure 6). This could occur if hypoxia or increased macrogalgal mats leads to decreases in benthic invertebrate prey. Design refinements of this alternative that would prevent water column stratification and algal mat accumulation would help support these species.

In the best case scenario, Least Sandpiper abundance might be greater than predicted based on habitat extent alone, because a greater proportion of the estuary might have the fine sediments that favor foraging by this species, due to decreased marine influence (arrows marked "-m" in Figure 6).

Alternative 3a – Low sill under Highway 1 bridge to slightly decrease tidal prism

Based on habitat extent changes alone, we predict no significant change in shorebird species abundance in any year, because extent of intertidal mudflats is not predicted to change significantly.

The factors that lead to best and worst case scenarios deviating from the above predictions, and the potential ways of mitigating the worst case scenario, are the same as described for Alternative 2.

Alternative 3b – High sill under Highway 1 bridge to strongly decrease tidal prism

Based on habitat extent changes alone, we predict decreased shorebird population sizes in Years 0 and 10, because a significant decrease in intertidal mudflat area is predicted in those periods. By Year 50, intertidal mudflat area is no longer significantly different than in Year 0 of Alternative 1, so we predict shorebird numbers in the estuary will not be significantly different either.

The factors that lead to best and worst case scenarios deviating from the above predictions, and the potential ways of mitigating the worst case scenarios, are the same as described for Alternative 2.

Alternative 4 – Decreased tidal prism in Parsons Complex

The predictions for this alternative are identical to those for Alternative 1 in Years 0 and 10. At Year 50, there is a significant increase in intertidal mudflat area at year 50 for Alternative 1, but it is (just barely) not significant for Alternative 4 (Table 2). So habitat-based predictions show no significant change at Year 50 for Alternative 4 (while they show an increase for Alternative 1).

As in Alternative 1, there is a potential decrease in Least Sandpiper population size related to increased marine influence in Years 10 and 50 (arrows marked "+m" in Figure 6.

For this document, we limited our predictions to the fully tidal areas of the estuary including the Parsons complex, because those are they areas for which habitat projections were available. However, it is worth noting that Alternative 4 would involve substantial loss of intertidal mudflat area within the Parsons complex, currently the area with highest abundance of many species of shorebirds.

Synthesis: ranking management alternatives for this taxon

For three of our focal species (Willet, Marbled Godwit, Long-billed Curlew), Alternative 1 appears to be the most favorable, since these species are abundant along the whole estuarine gradient, and would plausibly increase in abundance with the increased intertidal mudflat area projected for this alternative. Alternative 4 would be next most favorable, because habitat area remains constant, and, as with Alternative 1, there are no habitat quality changes of concern. Alternative 3a (low sill) would rank next; habitat area remains constant but habitat quality may decrease due to water quality degradation and increased algal mats. Alternative 3b and 2 rank last, respectively, due to their decreases in intertidal mudflat area coupled with potential concerns with decreased water quality. So from the perspective of these three focal species, the ranking is:
Alternative 1 > 4> 3a > 3b > 2.

Our fourth focal species, the Least Sandpiper, shows a somewhat different pattern. This species is most abundant in less marine-influenced portions of the estuary farther from the mouth. So while total intertidal mudflat area is greatest under Alternatives 1 and 4, the extent of mudflats with fine sediments might actually be lower in these alternatives, although this is difficult to predict. So some of the mouth-shrinking alternatives might be better for sandpipers. On the other hand, if water quality degrades considerably or algal mats increase, this would be a potential concern for sandpipers as for the other shorebirds. It is thus more difficult to rank Alternatives from the perspective of

sandpipers, but perhaps the intermediate alternatives would be most likely to favor their abundance, leading to a ranking such as:
Alternative 3a > 3b > 2 > 4 > 1.

External factors affecting population trends and importance relative to management alternatives

In addition to changes induced by the above management alternatives, abundance of these four shorebird species at Elkhorn Slough is likely to be strongly influenced by factors external to the estuary. Habitat loss on breeding grounds or decrease in tidal mudflat extent as sea level rises are examples of factors that could decrease Elkhorn Slough abundance of these species over the coming decades. If such factors decrease total population size of the species such that they are far below carrying capacity at Elkhorn Slough, then changes in habitat extent or condition resulting from the management alternatives are likely to be greatly overshadowed by these external factors. Present knowledge of demographic trends for these four shorebird species is too incomplete to assess whether local factors (i.e., the changes due to the management alternatives) vs. external factors will play a stronger role in determining local abundance of shorebirds at Elkhorn Slough.

Targeted restoration actions for these species at Elkhorn Slough

Targeted restoration actions could be undertaken to enhance migratory shorebird populations, regardless of which management alternative is implemented. About a third of formerly tidal wetlands in the estuary are now behind water control structures. In general, shorebirds are much less abundant at these sites than in fully tidal areas (Figure 3). So restoration of tidal exchange to some of them, particularly ones with very limited tidal exchange, would provide additional tidal flat foraging area. Since these areas have subsided substantially as a result of diking, return of tidal exchange would be likely to result in tidal mudflats and lagoons, thus good shorebird foraging habitat, not salt marsh. The Parsons complex serves as a highly successful example of this sort of restoration. From the 1950s-80s, this complex had very limited tidal exchange due to diking to allow for agricultural activities. In 1983, tidal exchange was restored, and by 1999, abundance of the four species of shorebirds was higher in this complex than in most other portions of the estuary (Figure 3), although densities there are not so high as along the main channel (Connors 2003).

While tidal flats are the most important foraging habitat for migratory shorebirds in the estuary, wetlands with restricted tidal exchange can be managed to provide valuable foraging and roosting habitat for shorebirds during high tide, when tidal flats are unavailable. North Marsh at Elkhorn Slough provides such habitat, with continual shallow water levels sustaining diverse and abundant shorebirds (Connors 2008). Other wetlands behind water control structures where return of full tidal exchange is not possible due to adjacent land uses could be managed with explicit consideration of appropriate water levels to serve as high tide refuges for shorebirds.

Importance of Elkhorn Slough shorebird abundance

Elkhorn Slough is one of forty-six sites recognized by the Western Hemisphere Shorebird Research Network (WHSRN) as critically important because it provides essential wintering and migratory stopover habitat along the Pacific Flyway. This estuary is considered a key site for Pacific coast shorebird conservation due to high abundance of various shorebirds (Page et al. 1999). As one of the largest estuaries on the California coast, Elkhorn Slough supports as many as 300 species of birds and 38 species of shorebirds (Senner and Howe 1984; Ramer et. al. 1991; Page et al. 1992), making it among the most species-rich sites for birds in the state of California. Elkhorn Slough has also been listed by Audubon California as an Important Bird Area in part because it is thought to provide habitat for >1% of the global population of threatened Long-billed Curlew populations, and >10% of the state's endangered, coastal-breeding population of Western Snowy Plovers (*Charadrius alexandrinus nivosus*) (Cooper 2004).

The relative contribution of Elkhorn Slough habitats to the overall population size and dynamics of migratory shorebirds is unknown, and may be relatively small for some species, whose populations are limited by factors on distant breeding grounds. But given the recognized importance of this estuary as wintering and migratory grounds for shorebirds, a precautionary approach in the face of uncertainty is warranted. A desirable target would be to maintain at least the current numbers of migratory shorebirds using the estuary so it can continue to provide a vital role in the Pacific Flyway. Some species, such as Western Sandpipers which were formerly the most abundant shorebird species at Elkhorn Slough, have declined in recent decades (B. Ramer, pers. com.). An overall goal of "no net loss" of migratory shorebirds from the estuarine wetlands of Elkhorn Slough is thus important and timely.

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A. Willet

B. Least Sandpiper

Photos by Paul Zaretsky

C. Marbled Godwit

Photo by Thomas Roundtree

D. Long-billed Curlew

Photo by Greg Hoffman

Figure 1. Photographs of the four focal species.

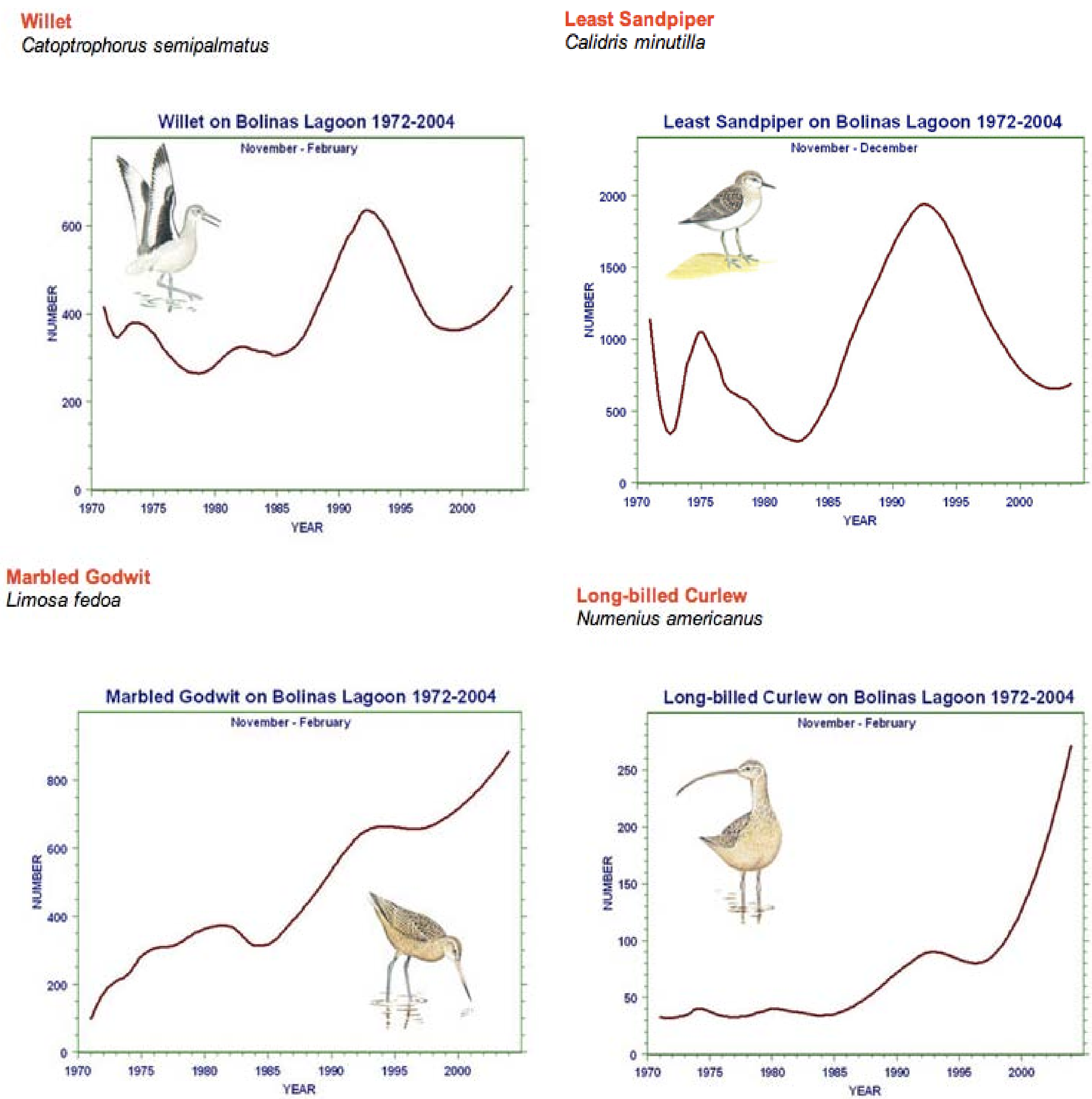


Figure 2. Population trends of the four focal species at Bolinas Lagoon. Figures from PRBO website: http:www.prbo.org/.

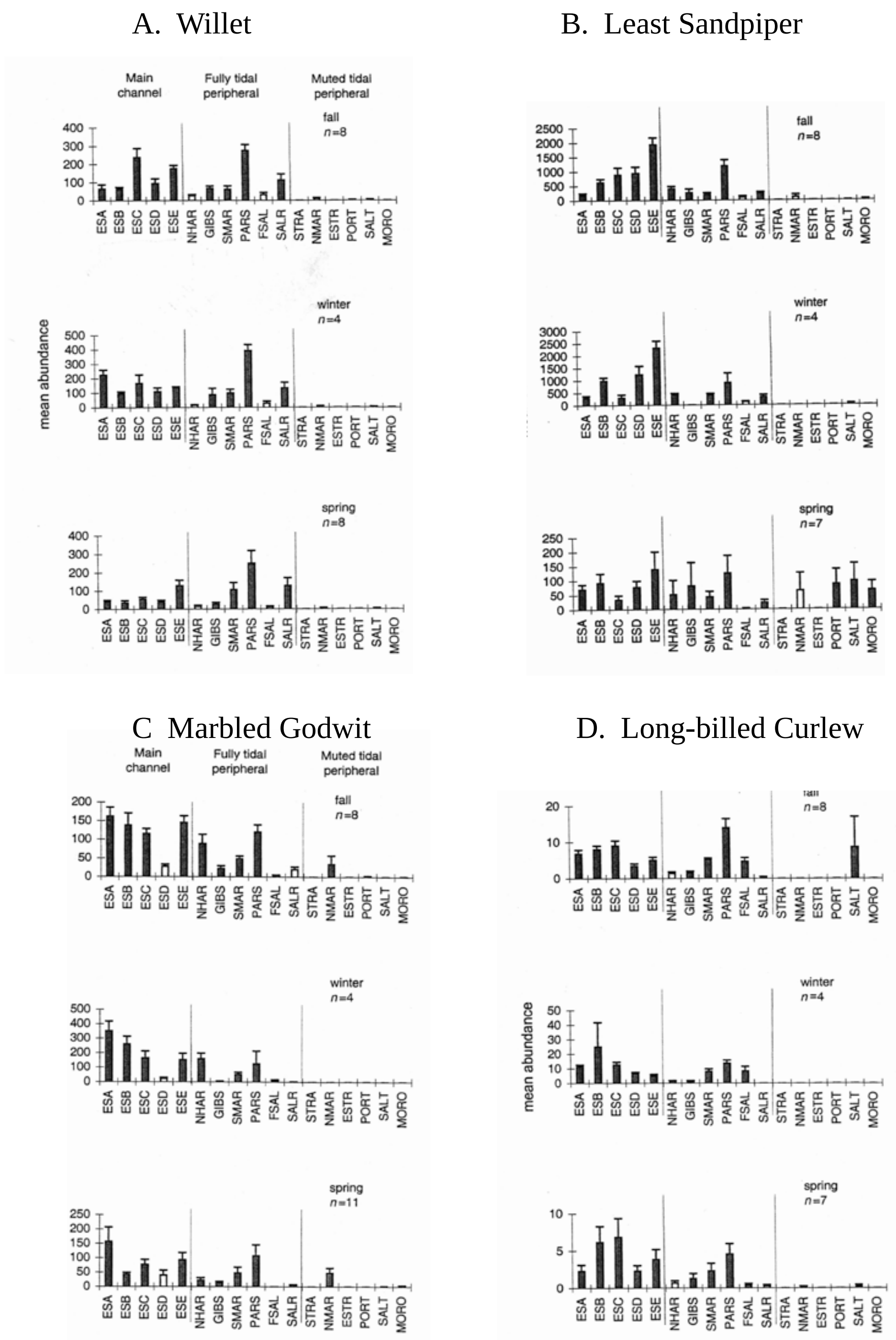


Figure 3. Mean abundance of Willets, Marbled Godwits, Long-billed Curlews, and Least Sandpipers at Elkhorn Slough based on spring 1999 through spring 2000 surveys. ESA = Elkhorn Slough Section A (mouth) through ESE = Elkhorn Slough Section E (head); NHAR = North Harbor; GIBS = Gibsons Landing; SMAR = South Marsh; PARS = Parsons Slough; FSAL = fully tidal salt ponds; SALR = Old Salinas River; STRA = Strawberry Marsh; NMAR = North Marsh; ESTR = Estrada Marsh; PORT = Porter Marsh; SALT = salt ponds; MORO = Moro Cojo Slough. Regions to the right of SALR are muted tidal regions; regions to the left of SALR, including SALR are fully tidal. See figure 4 for regions. Figure modified from Connors (2003).

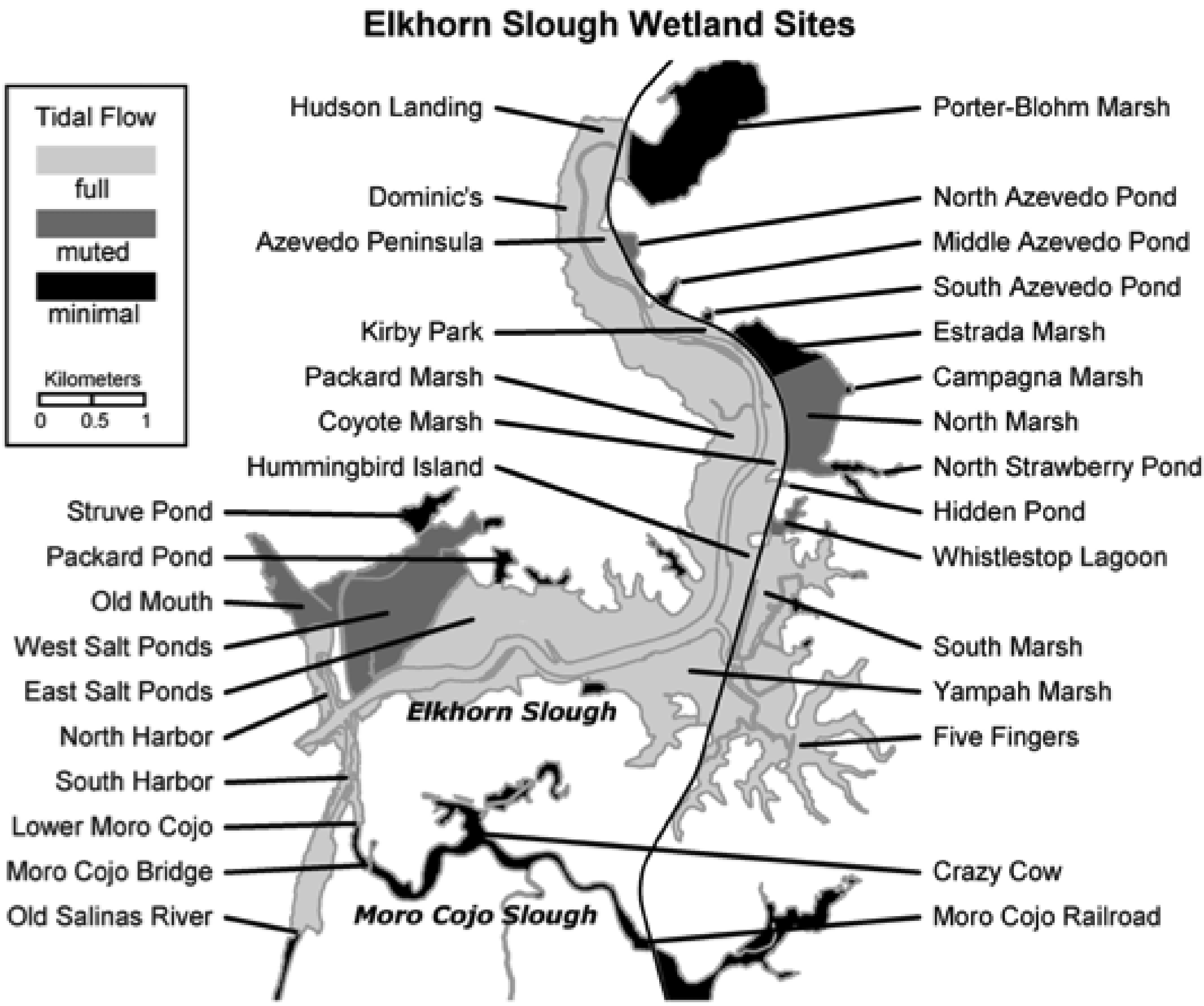


Figure 4. Map of Elkhorn Slough wetland habitats, shaded by amount of tidal exchange.

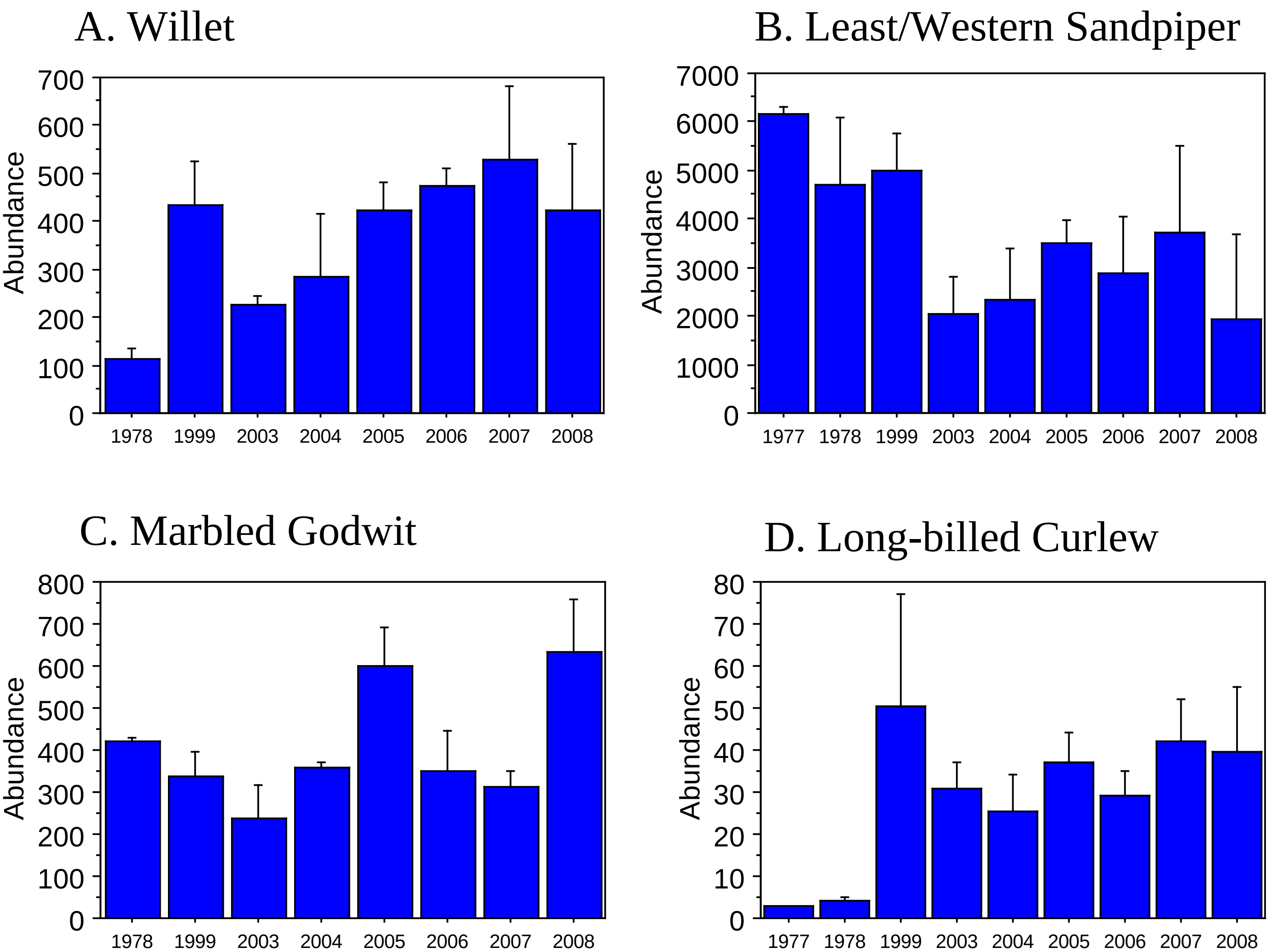
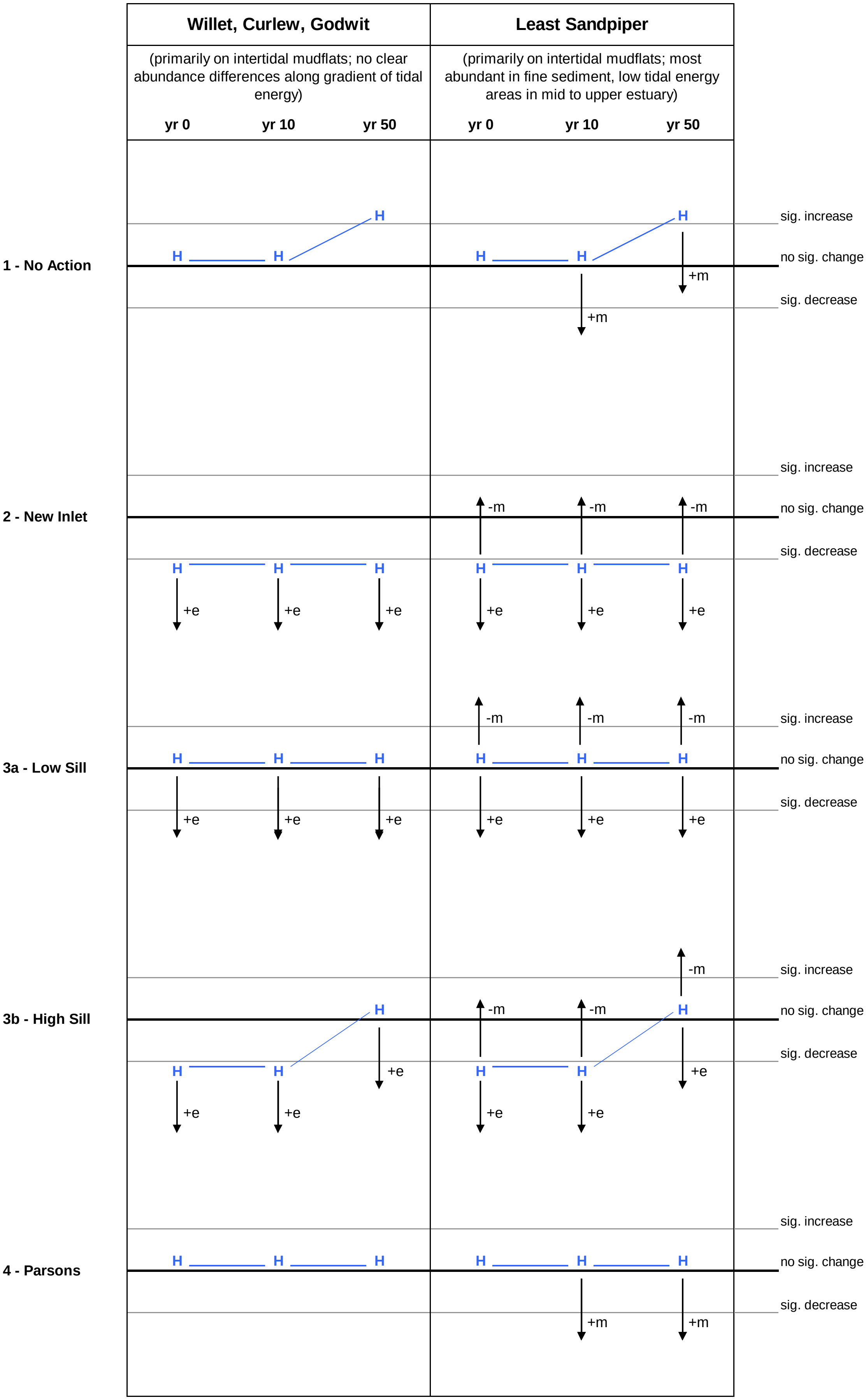


Figure 5. Abundance of focal shorebird species over time in Elkhorn Slough main channel. Counts for each species were taken along the main channel of Elkhorn Slough from the Highway 1 bridge to Kirby Park. Surveys were taken during fall migration (between September-November). All surveys for a given year were averaged. 1970s data are from a single survey for each species by B Ramer; 1999-2000 data are from numerous (3+) surveys by S Connors (with the exception of 2 surveys for Marbled Godwits); 2002-8 data are from ESNERR volunteer monitoring coordinated by S Fork, with 2 fall surveys per year. Western Sandpipers and Least Sandpipers were pooled into a single group because they could not always be distinguished.

Figure 6. Predicted response of selected shorebird species to management alternatives.



Legend for Figure 6

For each group of species, predictions made solely based on habitat extent are shown with a blue "H". These predictions make the simplified assumption of a linear relationship between estuary-wide population size and aerial extent of habitat of the appropriate tidal elevation. Thus a significant increase or decrease in habitat area translates to a significant change in population size.

The habitat predictions summarized in Largay & McCarthy 2009 were used for these projections. For all of these species, intertidal mudflat area was used as the basis for predictions.

A significant change in habitat area was defined as an increase or decrease of 20% or greater over year 0, No Action (Alternative 1) acreages. Likewise, a significant change in population size of the species was defined as an increase or decrease of 20% or greater over the average population size over the past decade (1999-2008).

For the habitat and species predictions, the geographic boundaries are all the fully tidal estuarine habitats of Elkhorn Slough excluding the Parsons complex (predictions do not include tidally restricted areas).

In addition to the habitat-based predictions, we illustrate a range of worst case and best case scenarios using arrows. These represent qualitative assessments of potential factors related to the management alternatives that might increase or decrease populations in ways other than predicted based on habitat extent alone; the exact length or location of the arrow has no quantitative significance. Each arrow is marked with a letter; legend for letters below. See text for more detail.

"+m" MARINE-INFLUENCED, SANDY HABITAT EXTENT WITH LOW RESIDENCE TIME increases as a result of increased tidal prism

"-m" MARINE-INFLUENCED, SANDY HABITAT EXTENT WITH LOW RESIDENCE TIME decreases as a result of decreased tidal prism

"+e" EUTROPHICATION symptoms such as hypoxia, water column chloropyll and macroalgal accumulation increase as result of lower tidal energy

Table 1 - Summary of attributes of 4 shorebirds commonly found in Pacific Coastal Estuaries. Information summarized from the Birds of North America reviews of species.

Common Name	Willet	Least Sandpiper	Marbled Godwit	Long-billed Curlew
Scientific Name	*Tringa semipalmatus*	*Calidris minutilla*	*Limosa fedoa*	*Numenius americanus*
Range	western populations breed in freshwater inland habitat of NA, winter from coastal N. CA south to Peru	breeds mainly subarctic tundra and far northern boreal forest over much of NA, winters coastal CA, south to N. SA	breeds in grasslands of northern US, and southern Canada, winters Pacific and Atlantic coasts of N., M., and S. America	breeds in Great Plains, Great Basin, and inter-montane valleys of w. US and SW Canada, winters along Coastal CA, south to Central America
Prey items	clams, snails, crabs, amphipods, aquatic insect and worms	benthic invertebrates (small amphipods, gastropods)	polychaetes, small bivalves, crabs and earthworms	burrow-dwelling mud crabs, ghoast shrimp and mud shrimp, some bivavles, marine worms and fish
Coastal feeding habitat preference	sandy and muddy tidal flats, sandy and rocky beaches, salt marsh	tidal flats (muddy areas), also salt marshes, fresh-water ponds, wet pastures, sandy and rocky beaches	tidal sand and mudflat and open sandy beaches	tidal mudflats, firm mud, high tidal areas
Coastal roosting habitat preference	rocky shore, mudflat, marsh, road dikes, sea beach	marsh vegetation near feeding areas	salt marshes, salt-pond dikes lagoon islands on salt grass, areas of bare ground within vegetation	high elevation salt marsh

Common Name	Willet	Least Sandpiper	Marbled Godwit	Long-billed Curlew
Feeding water level Preference	at depth of tarsus 5.7 - 7.0 cm or less	<2-4 cm, farther from waters edge than others	mostly 13-5 cm	<1 cm water
Optimal tidal height	no preference	unknown	no preference	prefers high tidal areas
Conservation Status	not listed	not listed	not listed, shorebird species of concern in Canada and US	Vulnerable in Canada, "highly imperiled" in U.S., total pop. size approx. 20,000
Population trends	no long term significant trends known	stable in west and central, may be declining in the east	significant declines since 1800's, possible increases from 1966 - 1996	significant declines in late 1800's, eastern populations still declining, while western pops. may be slight increase
Primary conservation Concerns	habitat degradation	habitat degradation	highly clumped distribution during migration and wintering, vulnerable to habitat degradation	habitat degradation

1

TABLE 2. Predicted habitat extent under management alternatives.

The numbers represent percent change from baseline conditions (Year 0, No Action alternative) as predicted by H.T. Harvey and Associates and summarized in Largay and McCarthy 2009. Habitats were defined based tidal elevation zones. The area of habitat considered excludes the Parsons Slough complex and all wetlands behind water control structures.

To facilitate perusal of trends, significant increases are coded with warm colors (20% or greater = orange, 50% or greater = red). Significant decreases are coded with cool colors (20% or greater = light blue, 50% or greater = dark blue).

HABITAT PREDICTIONS FOR SINGLE HABITAT TYPES

	A. Deep (>2 m) subtidal			B. Shallow subtidal			C. Intertidal mudflat			D. Salt marsh		
ALTERNATIVE	**yr 0**	**yr 10**	**yr 50**	**yr 0**	**yr 10**	**yr 50**	**yr 0**	**yr 10**	**yr 50**	**yr 0**	**yr 10**	**yr 50**
1 - No Action	0%	9%	42%	0%	8%	15%	0%	3%	22%	0%	-7%	-65%
2 - New Inlet	54%	65%	105%	53%	70%	108%	-39%	-36%	-32%	18%	6%	-40%
3a - Low Sill	9%	12%	20%	8%	22%	72%	-10%	-3%	14%	9%	0%	-55%
3b - High Sill	39%	28%	6%	39%	75%	182%	-34%	-28%	-16%	22%	18%	-36%
4 - Parsons	1%	6%	38%	0%	5%	10%	0%	3%	19%	-1%	-6%	-61%

HABITAT PREDICTIONS FOR COMBINED HABITAT TYPES

	E. Total mud (A+B+C)			F. Shallow mud (B+C)			G. Subtidal (A+B)			H. Intertidal (C+D)		
ALTERNATIVE	**yr 0**	**yr 10**	**yr 50**	**yr 0**	**yr 10**	**yr 50**	**yr 0**	**yr 10**	**yr 50**	**yr 0**	**yr 10**	**yr 50**
1 - No Action	0%	5%	25%	0%	4%	21%	0%	8%	32%	0%	-1%	-12%
2 - New Inlet	-8%	-1%	15%	-24%	-19%	-9%	53%	67%	106%	-17%	-20%	-35%
3a - Low Sill	-4%	3%	23%	-7%	1%	23%	8%	16%	40%	-2%	-2%	-13%
3b - High Sill	-9%	-3%	14%	-22%	-11%	16%	39%	45%	72%	-12%	-10%	-24%
4 - Parsons	0%	4%	22%	0%	4%	18%	1%	6%	27%	0%	0%	-12%