Abundance and Distribution of Wintering Shorebirds in San Francisco Bay, 1990-2008: Population Change and Informing Future Monitoring

Attachment A

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San Francisco Bay Shorebird Analysis

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EXECUTIVE SUMMARY

The results from three comprehensive surveys of wintering shorebirds in San Francisco Bay, conducted in November from 2006 through 2008, indicated stable or increasing populations for most species compared to equivalent surveys conducted from 1990 through 1992. These surveys were led by a broad partnership including PRBO Conservation Science, Audubon California, San Francisco Bay Bird Observatory, U.S. Geological Survey, and U.S. Fish & Wildlife Service. The number of individuals of 8 of 22 species increased throughout the Bay between the two time periods based on our criteria for change but apart from Willet and Least Sandpiper, those species that increased were the relatively less abundant ones (< 4000 individuals). The number of shorebirds observed in specific regions of the Bay changed considerably with the Central Bay (from the San Mateo Bridge north to Point San Pedro and Point San Pablo) exhibiting the most change; nine species increased, five decreased and the total number of shorebirds decreased. In the North Bay, seven species decreased and in the South Bay two species increased and two decreased. Although 19 of 22 species exhibited change in at least one region of the Bay, only the Least Sandpiper increased in all regions.

Given the increase in intertidal habitat in the Bay between survey periods and the increase in Least Sandpiper, possibly in response to increased acreages of tidal flat, the opposite response by Dunlin and Western Sandpiper, which frequently feed in close association with Least Sandpipers, may herald regional population declines. Numbers of Western Sandpipers were down Bay-wide but not sufficiently to meet both our criteria for a decline. These are the most abundant shorebirds in San Francisco Bay and we recommend monitoring their numbers carefully in the Bay and elsewhere in the region to clarify if they are declining.

Between the survey periods summarized here there have been major changes in the distribution and extent of some of the foraging habitats used by shorebirds. In particular, derelict salt ponds in the North Bay with little value to shorebirds have been breached creating mudflats. Salt pond levees have also been breached in the South Bay as part of the South Bay Salt Pond Restoration Project. While the process of restoring tidal marsh habitat in the Bay by breaching levees has created tidal flats and increased shorebird foraging opportunities over the short term of our study, over the long term the breaching will likely reduce the availability of shorebird foraging habitat as tidal marsh replaces tidal flats.

Shorebird populations were largely stable in this analysis, which suggests that overall San Francisco Bay has remained an important site for wintering shorebirds over the last 20 years. Whether this Bay-wide stability reflects stability in shorebird populations across a larger spatial extent is not known. A better understanding of the correlation between roosting shorebird counts, carrying capacity of available foraging habitat, and improved tracking of changes in shorebird foraging habitat in the Bay will be needed to fully evaluate future changes in the number of shorebirds wintering in San Francisco Bay.

It is unclear how environmental changes over the next 50 to 100 years will affect shorebird populations. The effects of climate change will likely reduce the availability of foraging habitat for shorebirds as mudflats and marshes struggle to keep pace with sea-level rise. Sea-level rise also threatens remaining salt ponds and ponds managed for shorebirds, most of which are protected by relatively low earthen dikes. Additional threats are posed by invasive hybrid *Spartina* which can colonize mudflats and reduce foraging opportunities for shorebirds.

It is possible, given our limited sample size of 6 years and the 14-year interval between survey periods, that some changes we describe are in error or that other species reported to be stable have actually changed. In order to improve our ability to detect shorebird trends in the Bay cost effectively (conducting comprehensive Bay-wide censuses annually is not likely to be economically feasible), we simulated sampling scenarios at various levels of reduced sampling effort. Based on our initial results, we recommend a sampling design in which a set of sites, selected randomly and weighted towards historic roost sites, would be counted annually with a survey once every 10 years of the remaining portion of the Bay to evaluate changes in the survey frame (e.g., new habitat and spatial shift in habitat). By conducting these annual surveys, we will have the ability to detect declines with reasonable certainty over shorter periods of time (e.g., 5 to 10 years) compared to periodic surveys. These annual Bay-wide surveys are needed to put project-specific trends into context. Given the expected changes in shorebird habitat due to restoration and management and the effects of climate change, it is ever more important to establish monitoring programs that can measure the impact of these effects.

Chapter 1

Change in Abundance and Distribution of Shorebirds in San Francisco Bay

Shorebirds have declined in many parts of the world largely because of wetland losses since the late 1800s (Page and Gill 1994, Brown et al. 2001, Stroud et al. 2004). Quantifying population trends and identifying their underlying causes are vital to the management and conservation of shorebird species. However, the clumped or uneven distributions of most shorebird species make trends difficult to measure (Howe et al. 1989) and widely separate breeding and wintering areas make underlying causes difficult to identify. In North America, most efforts to estimate shorebird population trends have focused on the Atlantic Flyway, and trends in the Pacific Flyway are not as well-documented (Howe et al. 1989, Bart et al. 2007).

Coastal areas within the Pacific Flyway are used by hundreds of thousands of shorebirds during winter (Page et al. 1999) with Western Sandpiper and Dunlin being the most numerous species. Within the Pacific Flyway, the San Francisco Bay Estuary has been identified as critical for migrating and overwintering shorebirds, accounting for more shorebirds during migratory and wintering periods than any other wetland along the Pacific coast of the conterminous USA (Page et al. 1999). Consequently, San Francisco Bay is recognized as a site of Hemispheric Importance by the Western Hemisphere Shorebird Reserve Network (Harrington and Perry 1995). During spring migration, over a million shorebirds are estimated to pass through San Francisco Bay and at one time; 589,000-932,000 have been documented on spring surveys, 340,000-396,000 on fall surveys, and 325,000 to 358,000 on early winter surveys conducted between 1988 and 1993 (Stenzel et al. 2002).

The San Francisco Bay and Delta is the largest estuary on the west coast of North America. Freshwater from the Sierra Nevada range enters the San Francisco Bay Delta via the Sacramento and San Joaquin rivers mixing with saltwater and passing through Suisun Bay then San Pablo Bay before flowing out to the Pacific Ocean through the Golden Gate. A variety of habitats including tidal mudflats, diked and undiked seasonal wetlands, managed and idle salt ponds, and tidal marshes support a diverse shorebird community. Shorebirds also use other features such as islands, levees, rip-rap shoreline, piers and other structures for roosting. The San Francisco Bay area, highly urbanized with > 6 million people, has undergone many changes over the last 200 years. In the late 1800s and early 1900s, >80% of the tidal marshes and 40% of the tidal flats were diked, channelized, and/or filled for agricultural crops, cattle grazing, salt production, urban infrastructure, or other uses (Goals Project 1999). During shorebird surveys of San Francisco Bay from 1988 to 1993, many areas in both the north and south regions were still functioning as commercial salt production ponds or hay fields. In the 14 years between the last winter shorebird survey in 1992 and a follow up series of surveys from 2006 to 2008, over 11,000 acres of former baylands had been created or restored to tidal action (SFBCDC 2008). The California Department of Fish and Game (CDFG), U.S. Fish and Wildlife Service (USFWS) and other agencies breached levees to restore tidal action to salt ponds and agricultural fields. They also changed the water management regimes of some salt ponds resulting in lower salinities and changed invertebrate and shorebird composition in the ponds (Takekawa et al. 2004).

The first comprehensive winter shorebird surveys of San Francisco Bay were conducted as part of a multi-state effort from 1988 to 1993, led by PRBO Conservation Science (PRBO), to document the important wetlands for migrating and wintering shorebirds in the Pacific Flyway (Page et al. 1999). As part of this project, three early winter counts of roosting shorebirds were made within San Francisco and San Pablo bays (hereafter San Francisco Bay or Bay) in November 1990, 1991, and 1992 (Stenzel et al. 2002). These surveys provided a baseline against which future numbers of shorebirds could be compared. From 2006 through 2008, comparable roost surveys were conducted to: (1) assess temporal and spatial changes in the population of shorebirds between sample periods (1990-92 and 2006-08); (2) assess the usefulness of periodic Bay-wide roost counts for detecting changes or shifts in shorebird abundance, and (3) examine alternative methods for monitoring changes in the abundance and distribution of wintering shorebirds in San Francisco Bay using reduced effort. These surveys were led by a broad partnership including PRBO, Audubon California, San Francisco Bay Bird Observatory (SFBBO), U.S. Geological Survey (USGS), and USFWS.

METHODS

Study Site

For our study we divided San Francisco Bay into North, Central, and South bay regions (Fig. 1). The North Bay included the region between the Carquinez Bridge and points

San Pedro and San Pablo, the Central Bay between the Bay and the San Mateo bridges, and the South Bay from the San Mateo Bridge south. These regions were further divided into 10 subregions (A-J; Fig. 1). Regions and subregions varied in extent and composition of available shorebird habitat as follows:

North Bay- Subregion A, on the north and west shores of San Pablo Bay, was characterized by extensive tidal flat, salt marsh, hay fields, other undeveloped diked baylands, and a 9,000-acre inactive, salt pond complex within the Napa-Sonoma Wildlife Area that CDFG began restoring in 1994. After the 543-hectare Pond 3 within this restoration area was breached in 2002, invertebrate species richness and shorebird use at low and high tides increased (Takekawa et al. 2004). The number of foraging shorebirds also increased at Tolay Creek after CDFG and USFWS opened 176 ha of diked agricultural bayland to tidal action in 1997 (Takekawa 2002). Subregion B, on the eastern shore of San Pablo Bay, contained some residential and industrial development, and less extensive tidal marshes and tidal mud flats than subregion A.

Central Bay- Subregion C, from Point San Pablo to Bay Bridge on the east side of the Bay, is heavily developed with high-density residential areas, marinas, and other commercial enterprises. Extensive rip-rap creates a rocky shoreline with small amounts of interspersed tidal marsh and mudflats. The heavily urbanized Area D, from the Bay Bridge to San Leandro, includes the Oakland International Airport, Oakland harbors, and other residential and industrial development. The majority of the shoreline is rocky with some sandy beaches and tidal marshes. Subregion E, from San Leandro to the San Mateo

Bridge, includes the Hayward shoreline and consists of tidal marshes, wastewater treatment ponds, and managed wetlands located behind a rip-rapped shoreline. Subregion I, from the San Mateo Bridge along the western shore to the Bay Bridge, is heavily used for residential and commercial purposes. The shoreline is mostly rocky with some fringing marshes. Subregion J, on the western shore from the Bay Bridge to Point San Pedro, includes the heavily urbanized San Francisco waterfront and the less developed shores of west Marin County. The hardened shorelines in the south are composed of rock, sea walls, and piers. The northern portion of subregion J consists of mostly rocky shoreline, marinas and some sandy beaches and marsh.

South Bay- Subregion F, from the San Mateo Bridge to the Dumbarton Bridge on the eastern shore, is characterized by large tracts of active and derelict salt ponds some of which are managed for wildlife. The shoreline is bordered by large tracts of tidal marsh or levees with fringing marshes and extensive tidal flats at low tide. Subregion G, encompassing all area south of the Dumbarton Bridge, is similar to subregion F but has more residential development on the western shore. Subregion H, on the western shoreline from the Dumbarton Bridge to the San Mateo Bridge, is characterized by large tracts of tidal marsh and extensive areas of salt ponds that are in disuse or are managed for wildlife. The northern portion of subregion H is primarily residential development fronted by a rocky shoreline. Overall, subregions F-H in the South Bay contain over 15,000 acres of salt ponds that have been managed or restored under the South Bay Salt Pond Restoration Project since 2004. Portions of the Alviso and Eden Landing complexes received controlled tidal exchange with San Francisco Bay through water control structures in 2004 and 2005 to reduce pond salinity. In March 2006, three Alviso ponds (A19, A20, and A21) were breached to allow tidal exchange with the Bay. This resulted in lowered salinity and altered hydrology in the breached ponds relative to those used for continued salt production in the Newark and Mowry complexes. As a result of the breaching and changes in pond management, the number of shorebirds increased in the Alviso and Eden Landing complexes.

Data Collection

We conducted annual Bay-wide censuses of roosting shorebirds in San Francisco Bay from 2006 to 2008 for comparison with a similar survey effort from 1990 to 1992 (Stenzel et al. 2002). During 2006-08, we surveyed 320 sites covering intertidal and non-tidal habitat including marshes, managed and non-managed salt ponds, other diked wetlands, water treatment facilities, rip-rapped shorelines, piers, and other manmade structures where shorebirds were likely to roost. In each year during the two time periods, censuses extended over a 3-6-day period in November (Table 1). Counts were made in November when the majority of overwintering birds had arrived and when counts were less likely to be aborted because of inclement weather than counts later in the winter. Censuses were conducted during high tide (approximately 5 feet higher than MLLW at the site) when most shorebirds were mainly stationary at roosts, and consequently easier to count than when feeding and moving on lower tides. Sites were surveyed by teams of professional and amateur ornithologists led by someone experienced at identifying species of shorebirds in large mixed-species flocks. Observers included staff from PRBO, SFBBO, USGS, USFWS, Audubon California, and over 100 volunteers recruited from other agencies, organizations, and the public. Training sessions were held to familiarize volunteers with survey methods, data recording, species identification, and methods of estimating shorebird numbers. Most sites were covered by persons on foot but some were accessed by boat, and in San Pablo Bay, aerial surveys supplemented ground counts where pedestrian access was limited.

As a precaution against double-counting birds, team leaders in adjacent survey areas discussed flock movements when necessary to reduce the likelihood that some flocks of birds were recorded by more than one census team. In addition, to avoid double-counting birds from one day to the next, sites within the same Bay region were conducted on the same day (e.g., all sites in the North Bay were surveyed on day 1, sites in the South Bay on day 2 and sites in the Central Bay on day 3).

Observers were instructed to identify all individuals to species except for Long-billed Dowitchers (*Limnodromus scolopaceus*) and Short-billed Dowitchers (*Limnodromus griseus*) which were recorded as dowitcher species. In some cases, observers estimated the number of birds in a flock and then estimated the proportion of each species present. These proportions were used to directly estimate numbers for each species. Because of poor lighting, quick or distant views, similarity of species, or other factors, it was not possible to identify all shorebirds to species. In such circumstances, surveyors identified individuals as belonging to various groups containing two or more species (e.g., Western/Least sandpiper or unidentified *Calidris* sandpiper). These unidentified individuals were allocated to species based on the ratio of identified individuals from within the site, the adjacent site, or the entire subregion following Page et al. (1999).

Data Analysis

We summarized shorebird detections using two methods: (1) we summed detections for all sites to provide overall totals for the 2006-08 survey period, but (2) for comparison of shorebird abundance and distribution between the two time periods, we used only detections from the 224 sites surveyed in all 6 years plus 13 additional sites with shorebirds in 2006-08 that were not believed to be available for roosting in 1990-92 (e.g., agricultural/pastoral lands that were opened to tidal action). For each site covered during the later, but not in the earlier period, we determined its past potential as shorebird roosting habitat based on our knowledge of the site. Only the 13 sites, considered as unsuitable in 1990-92 but suitable in 2006-08, were included with the 224 covered on all surveys in the analysis comparing the two periods. Of these 13 sites, eight were located in subregion A, two in subregion E and three in subregion G (Table 2). New sites added in 2006-08 that likely contained suitable roosting habitat in the past were not included in the second analysis because they may have contained shorebirds that went uncounted during 1990-92 and thus could induce a positive bias in change estimates. We found no evidence that suitable roosting sites from the early period became unsuitable during the later period.

We calculated the change in the abundance of each species by dividing the sum of the individuals observed at the 237 sites in 2006-08 by the sum those at the 224 sites covered in 1990-92. To determine whether a change in shorebird numbers or distribution was statistically significant between the two time periods, we used the two-tailed Wilcoxin rank sum test. The sum of individuals counted for each species in each year were ranked 1 through 6 among years. The Wilcoxin test statistic was calculated by summing the ranks for each time period and using the higher number of those two numbers. The highest possible level of significance, given our sample size of 6 years, was P = 0.1. Because statistical significance may not convey biological significance, we also invoked another criterion for quantifying a potentially biologically meaningful population change: a ≥33% change in the average number of shorebirds between the two periods. The second criterion corresponds to a 3.5% annual change in shorebird abundance following the guidelines set forth by the Program for Regional and International Shorebird Monitoring (PRISM) for a biologically meaningful rate of decline (Bart et al. 2005). Both criteria had to be met for us to consider a change between periods to be potentially meaningful.

RESULTS

At all sites surveyed in 2006-08, we found a total of 327,000 to 355,000 shorebirds of 29 species. In addition to the species in Table 3, American Golden Plover (*Pluvialis dominica*), Pacific Golden Plover (*Pluvialis fulva*), Pectoral Sandpiper (*Calidris melanotos*), Ruff (*Philomachus pugnax*), Sharp-tailed Sandpiper (*Calidris acuminata*), Surfbird (*Aphriza virgata*), and Wilson's Snipe (*Gallinago delicata*) were found on the 2006-08 surveys. Three small calidrid sandpipers, Western Sandpiper (*Calidris mauri*), Dunlin (*Calidris alpina*), and Least Sandpiper, accounted for 65% of the shorebirds on the 2006-08 surveys (Table 3). Three large species, American Avocet (*Recurvirostra americana*), Willet (*Catoptrophorus semipalmatus*), and Marbled Godwit (*Limosa fedoa*) accounted for another 22% of the total. Dowitchers accounted for 6% and Black-bellied Plovers (*Pluvialis squatarola*) for 4% of the total. Every other species accounted for ≤1% of the total.

In 2006-08, 35.4% of the shorebirds were found in the North Bay, 11.9% in the Central Bay, and 52.7% in the South Bay. However, all species were not distributed similarly among the three Bay regions. For some species, the total from one Bay region exceeded the sum of the other two Bay regions: for example, Semipalmated Plover (*Charadrius semipalmatus*) and American Avocet in the North Bay; Black Oystercatcher (*Haematopus bachmani*), Spotted Sandpiper (*Actitis macularia*), Whimbrel (*Numenius phaeopus*), Black Turnstone (*Arenaria melanocephala*), and Sanderling (*Calidris alba*) in the Central Bay (Table 3).

Within the 237 sites that were selected to measure change between the two periods (1990-92 and 2006-08), the total shorebirds were not significantly different based on our criteria for change. However, a Bay-wide change was detected in 9 of 22 species and 8 of these species were more abundant in 2006-08 (Fig. 2, Table 4). The only species exhibiting a potential decrease in total number was the Snowy Plover (Table 4); however, this species was likely undercounted. During independent January surveys conducted specifically for the Snowy Plover by SFBBO over the same winters (2006-08), 89-131 plovers were counted compared to only 30-62 on our surveys (USFWS unpublished data).

More species exhibited a change within a Bay-region than Bay-wide. Within the 237 sites, 19 of 22 species met our criteria for change within one or more Bay regions. The greatest change was observed in the Central Bay where nine species exhibited an increase and five a decrease between the two survey periods (Fig. 3, Table 4). Eight species increased and none decreased in the North Bay (Fig. 3, Table 4) and two species increased and two decreased in the South Bay (Fig. 3, Table 4). The Least Sandpiper was the only species that increased in each Bay region (Table 4). Black Oystercatcher and Greater Yellowlegs increased in the North Bay, Central Bay, and Bay-wide. Species increasing solely in the North Bay were Black-bellied Plover, American Avocet, and Sanderling. Species increasing solely in the Central Bay were Killdeer, Black-necked Stilt, Spotted Sandpiper, Willet, Marbled Godwit and Black Turnstone; all also increased Bay-wide except Black-necked Stilt and Marbled Godwit. The Long-billed Curlew increased in the South Bay and Bay-wide. Semipalmated Plover increased in the North Bay and decreased in the Central Bay, but did not change Bay-wide. Species decreasing only in the Central Bay were Ruddy Turnstone, Western Sandpiper and dowitchers. Dunlin decreased in both the Central and South bays but not Bay-wide. Species not exhibiting change based on our criteria were Lesser Yellowlegs, Whimbrel, and Red Knot.

DISCUSSION

This study provides the only data documenting spatial and temporal changes in shorebirds using San Francisco Bay over the last 20 years. Our results indicate stable or increasing Bay-wide populations for most species. We found 8 of 22 species increased Bay-wide between the two time periods based on our criteria but most of these species were in low overall abundance (< 4000 individuals). However, Willet and Least Sandpiper were the two exceptions, each exceeding 25,000 individuals on the 2006-08 surveys and the Least Sandpiper increased in all Bay regions. The only species that met our criteria for a Bay-wide decrease was the Snowy Plover. However, this species which occurs in low numbers primarily in the South Bay can be difficult to detect in dry salt ponds and flocks were likely missed during surveys. Because of its small population size, flocking behavior and, most of all, its inconspicuousness, we cannot assume that the proportion of the population recorded over the years remained constant. We therefore have low confidence in the result that the Snowy Plover has decreased since 1990-92.

While change in the number of shorebirds within specific regions of the Bay was observed, evidence suggesting a spatial shift among Bay regions was found only for the Semipalmated Plover which decreased in the Central Bay and increased in the North Bay. Dunlin and Western Sandpiper may have also shifted from the Central and South bays to the North Bay but their increase in the North Bay did not meet our criteria for change. Overall, the trend for shorebirds was for an increase in the North Bay where eight species and the total number of shorebirds increased. A decrease in total shorebirds is suspected in the Central Bay but did not meet our criteria for change (change in means between the two periods was <33%).

Assuming that shorebird populations in San Francisco Bay are not limited by roost site availability, the spatial and temporal changes in shorebird populations we observed could reflect changes in foraging habitat in the Bay, shifts in the spatial distribution of shorebirds at scales larger than San Francisco Bay, or changes to a species' population as a whole. Between the two survey periods summarized here there have been major changes in the distribution and abundance of some of the foraging habitats used by shorebirds. In particular, derelict salt ponds in the North Bay with little value to shorebirds have been breached creating mudflats. While the process of restoring tidal marsh habitat in the Bay by breaching salt pond levees has created tidal flats and increased shorebird foraging opportunities over the short term of our study, over the long term the breaching will likely reduce the availability of shorebird foraging habitat as tidal marsh replaces tidal flats (Stralberg et al. 2008).

Of the species found to have increased Bay-wide, the largest changes were found in Willet (37.4%), Long-billed Curlew (100.4%), and Least Sandpiper (171.2%), each having increased by over 1,000 individuals Bay-wide. The Least Sandpiper, the only species to have increased significantly in each Bay region, also exhibited the largest Bay-wide change increasing by over 21,000 individuals. In contrast to the Least Sandpiper, Bay-wide numbers for Dunlin and Western Sandpiper were down in 2006-08 although not to levels to meet our criteria for change. Given the increase in intertidal habitat in the

Bay between survey periods and the increase in Least Sandpiper, possibly in response to increased acreages of tidal flat, the lack of a similar response by Dunlin and Western Sandpiper, which frequently feed in close association with Least Sandpipers, may herald regional population declines. We recommend monitoring numbers of these two species carefully in San Francisco Bay and elsewhere in the region to clarify if they are declining.

Despite the importance of San Francisco Bay for wintering shorebirds in the western hemisphere, the results presented here reflect changes at only one, albeit large, estuary and may not reflect Pacific Flyway-wide population changes. Shorebird populations were largely stable in this analysis, which suggests that overall San Francisco Bay has remained an important site for wintering shorebirds over the last 20 years. However, whether this Bay-wide stability reflects stability in shorebird populations across a larger spatial extent is not known. A better understanding of the correlation between roosting shorebird counts, carrying capacity of available foraging habitat, and improved tracking of changes in shorebird foraging habitat in the Bay will be needed to fully evaluate future changes in the number of shorebirds wintering in San Francisco Bay.

It is unclear how environmental changes over the next 50 to 100 years will affect shorebird populations. Additional salt pond breaches will likely occur over the next few decades and will provide foraging habitat for shorebirds as mudflats are formed. But, as these ponds are colonized by marsh vegetation, they will become less valuable to shorebirds as foraging habitat (Stralberg et al. 2008). Looking further into the future, the effects of climate change will likely reduce the availability of foraging habitat for shorebirds as mudflats and marshes struggle to keep pace with sea-level rise. The future of shorebird foraging habitat will depend in great part on the availability of suspended sediment in the Bay. In a sediment-starved estuary, we may see mudflat erosion. Sea-level rise also threatens remaining salt ponds most of which are protected by low earthen dikes. Additional threats are posed by invasive hybrid *Spartina* which can colonize mudflats and reduce foraging opportunities for shorebirds.

Despite the extensive effort to document shorebird use of San Francisco Bay, interpretation of our results requires some caution. First, although one of the goals of this study was to assess temporal and spatial changes in the population of shorebirds between the two time periods (1990-92 and 2006-08), the data from the earlier period were originally collected to document the important wetlands for migrating and wintering shorebirds in the Pacific Flyway. As a result, some sites covered in 2006-08 were not included in the earlier period and vice versa. We attempted to rectify this problem by comparing only sites covered in both time periods and including some sites in the later time period that were unavailable in 1990-92 (i.e., new habitat). Furthermore, our estimates are based on only 6 years of data aggregated into 2 sets of 3 years. Under the criteria used by the Wilcoxin test, shorebird abundance in all 3 years of one group had to be larger or smaller than the abundance of shorebirds in all 3 years from the other group to be statistically significant ($P = 0.1$). Therefore, a species that had 2 high years and 1 low year, followed by 2 low years and one high year would not have exhibited a statistically significant change. Furthermore, the non-parametric test we employed does not account for the magnitude of the difference in counts. This protects against the effect of a single large count in a small dataset driving the statistical analysis but lacks biological interpretation. Thus, considering both the statistical output as well as the observed change estimates is useful when drawing inference from these data. Certainly, more regular monitoring would have increased our ability to quantify population trends but would have required a substantial increase in effort. Consequently, we present the results of simulations to guide the design of more regular surveys requiring reduced annual effort for monitoring shorebirds in San Francisco Bay in the future in Chapter 2.

In conclusion, San Francisco Bay remains an important site for wintering shorebirds as our surveys have shown stable to increasing populations Bay-wide. Willet, Long-billed Curlew and Least Sandpiper increased the most Bay-wide. Considerable change was indicated within specific Bay regions. The Central Bay exhibited the most change with nine species increasing and five species decreasing. The North Bay exhibited increasing numbers of eight species and the South Bay which held over half the total number of shorebirds exhibited the least amount of change with two species increasing and two decreasing. The Least Sandpiper was the only species that increased in all Bay regions. The overall trend of increasing shorebirds may reflect the creation of new habitat (e.g., salt ponds breached or managed for wildlife). Shorebird habitat in San Francisco Bay is threatened by climate change in the form of sea level rise, salinity shifts, invasive plants, and other threats. More research and monitoring are needed to track shorebird populations and assess the impacts of environmental change and wetland management actions.

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TABLES AND FIGURES

Table 1. Dates of the early winter San Francisco Bay shorebird censuses.

1990	1991	1992	2006	2007	2008
2-Nov	17-Nov	7-Nov	5-Nov	8-Nov	13-Nov
3-Nov	19-Nov	8-Nov	6-Nov	9-Nov	14-Nov
4-Nov	20-Nov	9-Nov	7-Nov	10-Nov	15-Nov
5-Nov	21-Nov	15-Nov		11-Nov	
	23-Nov				
	24-Nov				

Table 2. Sites considered new roosting habitat (not suitable roosting habitat in the 90s and not surveyed in the 1990s.

Site Code	Site name
A48	Napa Floodplain FCP
A53	Ringstrom Bay Unit
A54	Wingo Unit
A56	American Canyon Wetlands
A59	Carl’s Marsh
A63	Tolay Creek south of Hwy 37
A69	Sonoma Baylands restoration
A80	Guadalcanal Village restoration
E13	Oro Loma Marsh
E14	Robert’s Landing marsh North
G46	South Bay Pond A19
G47	South Bay Pond A20
G48	South Bay Pond A21

Table 3. Results of the San Francisco Bay shorebird survey using all sites, 2006-08. % is percent composition for the entire Bay based on the total number recorded during all three years.

	Total				Percent			
Species	2006	2007	2008	Mean	N. Bay	C. Bay	S. Bay	%
Black-bellied Plover	14028	16230	10481	13580	20.7	17.5	61.8	4
Snowy Plover	68	60	36	55	0.0	6.1	93.9	0
Semipalmated Plover	3267	1970	1485	2241	53.1	6.6	40.3	1
Killdeer	959	1159	620	913	24.6	41.6	33.8	0
Black Oystercatcher	58	80	76	71	10.3	89.7	0.0	0
Black-necked Stilt	5456	4984	3504	4648	17.1	8.9	74.0	1
American Avocet	31734	34191	28676	31534	53.2	6.1	40.8	9
Spotted Sandpiper	64	75	86	75	7.6	91.1	1.3	0
Greater Yellowlegs	614	575	1109	766	45.4	20.4	34.2	0
Willet	28006	25083	22642	25244	22.4	24.5	53.1	7
Lesser Yellowlegs	39	75	38	51	9.9	3.9	86.2	0
Whimbrel	103	84	77	88	1.9	64.0	34.1	0
Long-billed Curlew	3122	2558	2989	2890	32.4	13.8	53.8	1
Marbled Godwit	14186	20998	17718	17634	24.7	29.7	45.6	5
Ruddy Turnstone	20	76	40	45	0.0	8.1	91.9	0
Black Turnstone	311	282	355	316	8.4	87.9	3.7	0
Red Knot	671	637	131	480	0.0	8.6	91.4	0
Sanderling	539	684	605	609	17.8	69.7	12.5	0
Western Sandpiper	103179	101354	105355	103296	31.5	8.5	60.0	30
Least Sandpiper	37776	37891	36336	37334	26.6	14.8	58.6	11
Dunlin	88366	57578	103707	83217	47.2	7.7	45.2	24
dowitcher spp.	22878	20698	15816	19797	36.0	10.8	53.2	6
other species	52	58	104	71	43.5	26.6	29.9	0
Total	355496	327380	351986	344954	35.4	11.9	52.7	100

Table 4. Percent change in mean counts from 1990-92 to 2006-08 at 237 sites. Changes meeting the p ≤ 0.10 and the 33% change criteria are indicated in bold. ∞ indicates zero counts on the 1990-92 surveys.

Species	**N. Bay**	**C. Bay**	**S. Bay**	**Total**
Black-bellied Plover	**192.8**	-11.7	-19.8	-1.0
Snowy Plover		-52.4	**-49.3**	**-49.5**
Semipalmated Plover	**1217.2**	**-81.0**	16.5	108.3
Killdeer	223.4	**216.7**	112.1	**178.8**
Black Oystercatcher	∞	**8650.0**		**9750.0**
Black-necked Stilt	99.4	**236.8**	-32.3	-17.3
American Avocet	**111.8**	-32.7	-7.7	25.7
Spotted Sandpiper	∞	**430.0**	-33.3	**436.4**
Greater Yellowlegs	**294.6**	**151.0**	14.2	**78.5**
Willet	34.5	**119.3**	18.1	**37.4**
Lesser Yellowlegs	250.0	166.7	15.8	24.5
Whimbrel	-16.7	42.0	11.3	28.3
Long-billed Curlew	18.4	47.6	**315.6**	**100.4**
Marbled Godwit	-10.9	**129.9**	-18.5	4.5
Ruddy Turnstone		**-88.8**	100.0	-18.9
Black Turnstone		**227.5**	52.4	**244.1**
Red Knot	-100.0	4.9	-52.2	-49.3
Sanderling	**983.3**	-22.4	219.4	5.1
Western Sandpiper	23.4	**-72.3**	-29.2	-26.0
Least Sandpiper	**327.6**	**84.9**	**152.5**	**171.2**
Dunlin	59.0	**-58.2**	**-37.3**	-13.6
dowitcher spp.	58.3	**-47.0**	-14.0	-5.3
Total	**46.4**	-32.3	-18.1	-6.1

Figure 1. Map of San Francisco Bay showing 3 Bay regions and A-J sub-regions surveyed for shorebirds.

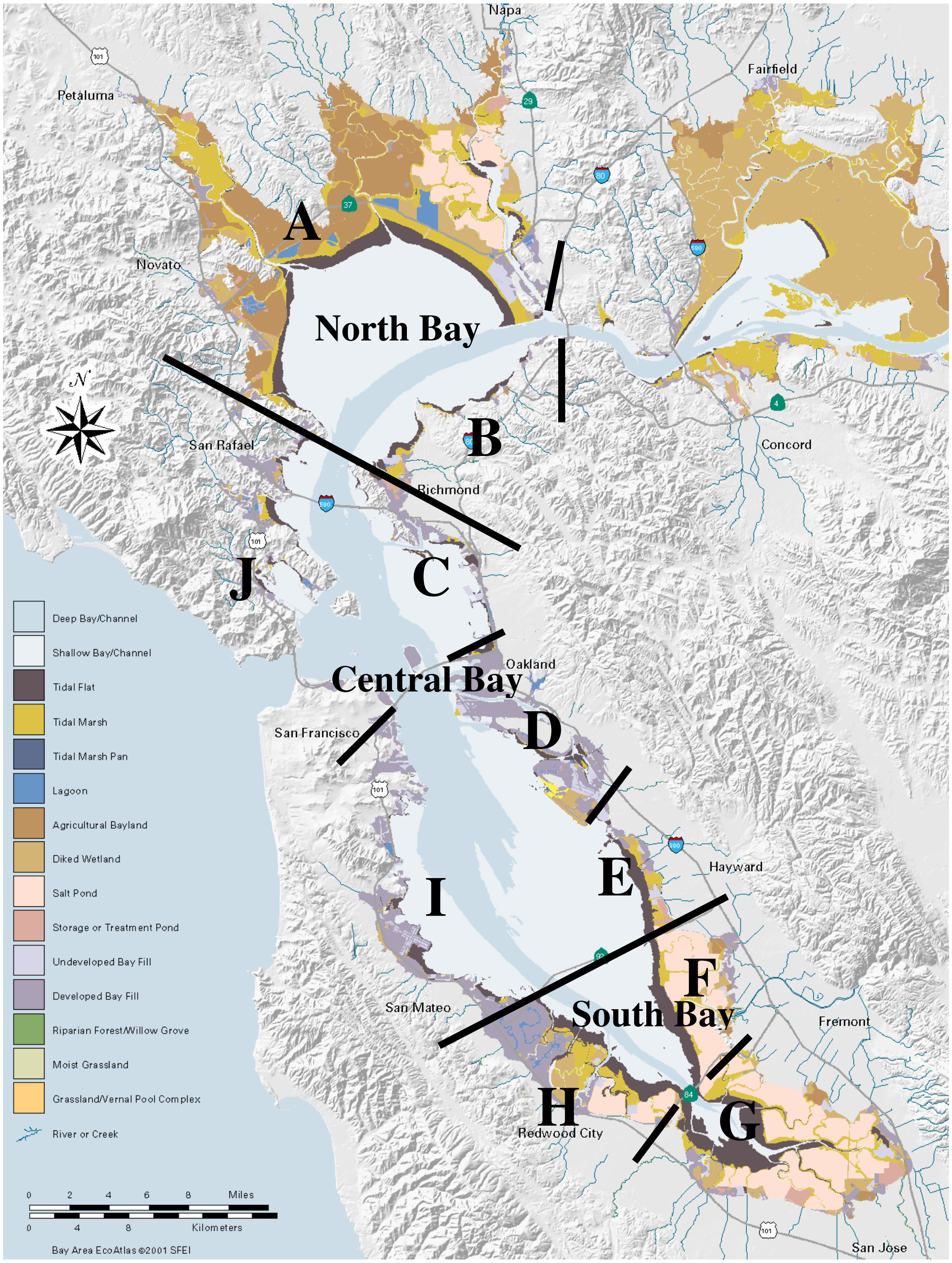


Figure 2. Total number of shorebirds counted in San Francisco Bay winter census in 1990-92 and 2006-08.

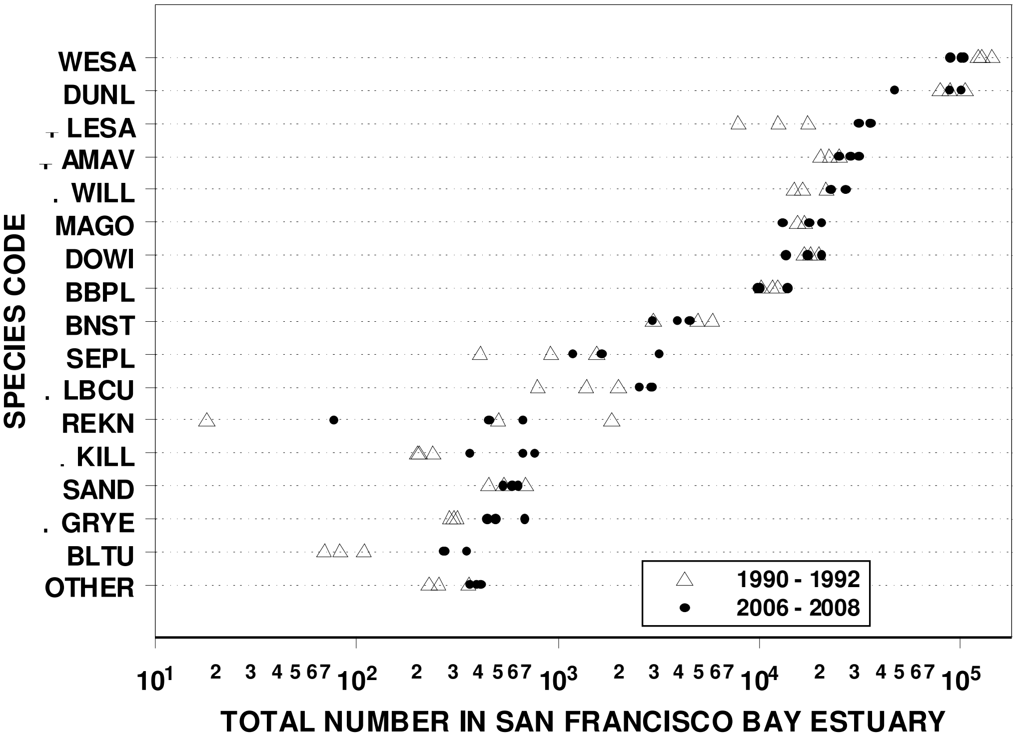


Figure 3. Total number of shorebirds counted in San Francisco Bay winter census in 1990-92 and 2006-08 by species and by Bay region.

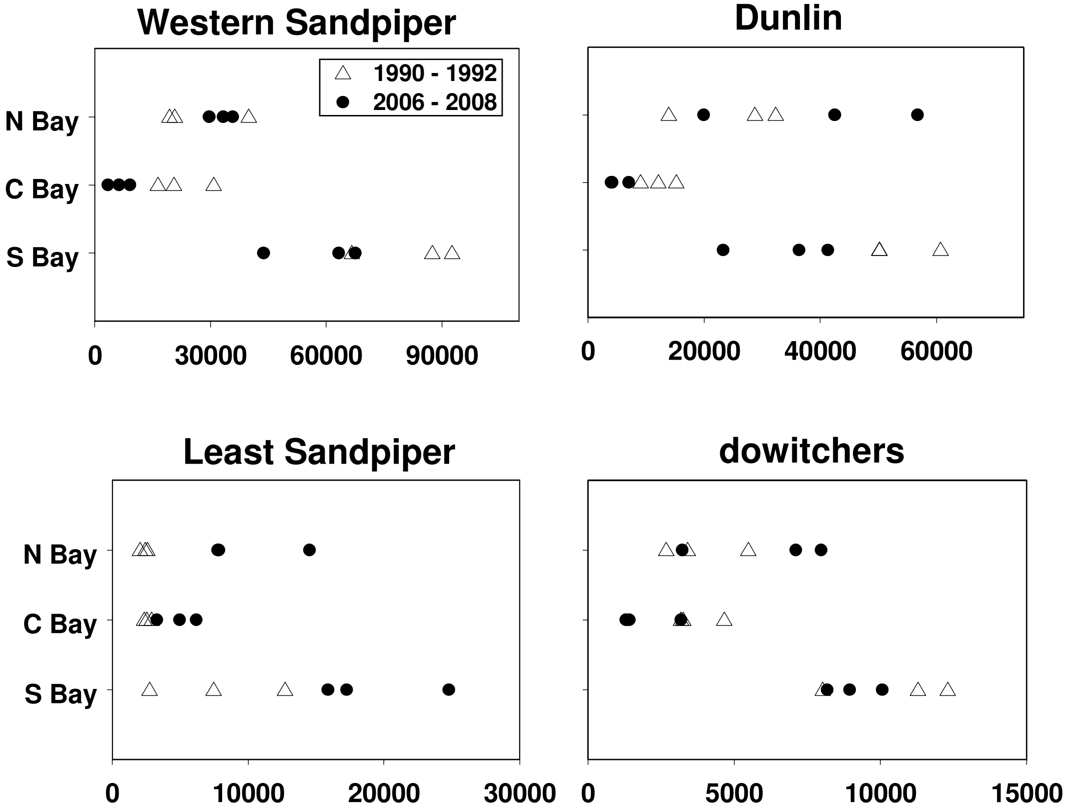
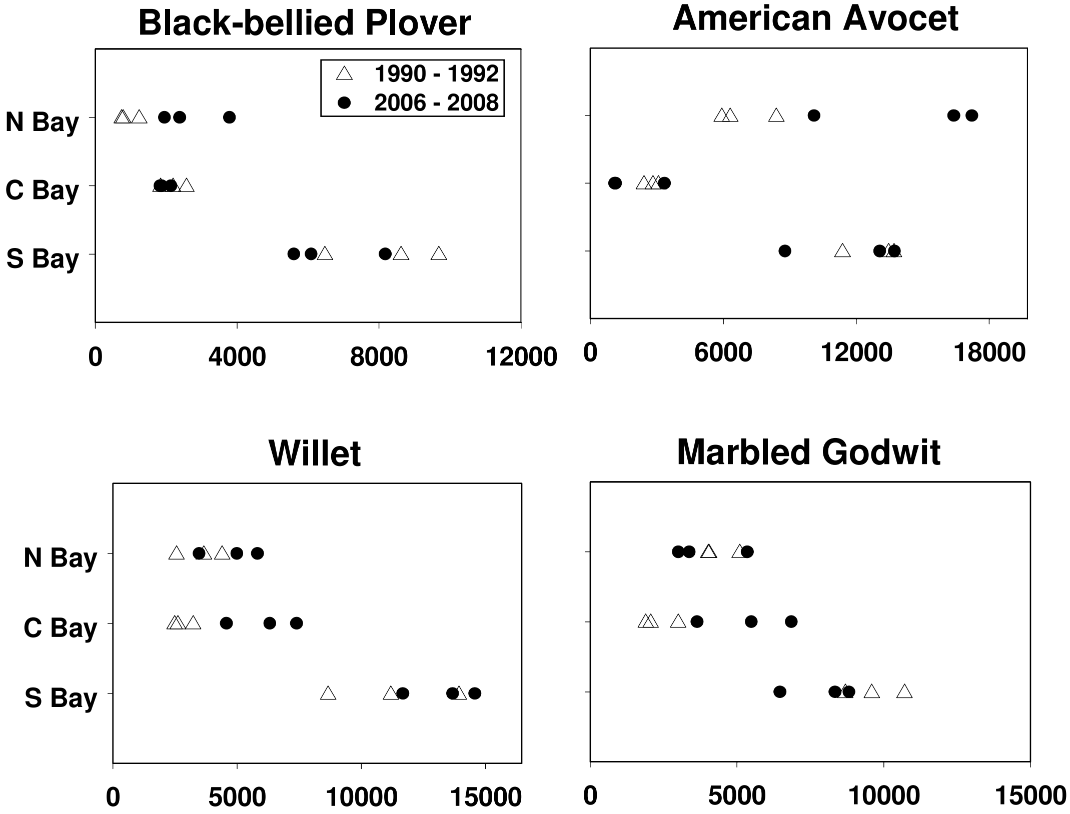


Figure 3. Cont'd



Black-bellied Plover

American Avocet

Willet

Marbled Godwit

Figure 3. Cont'd

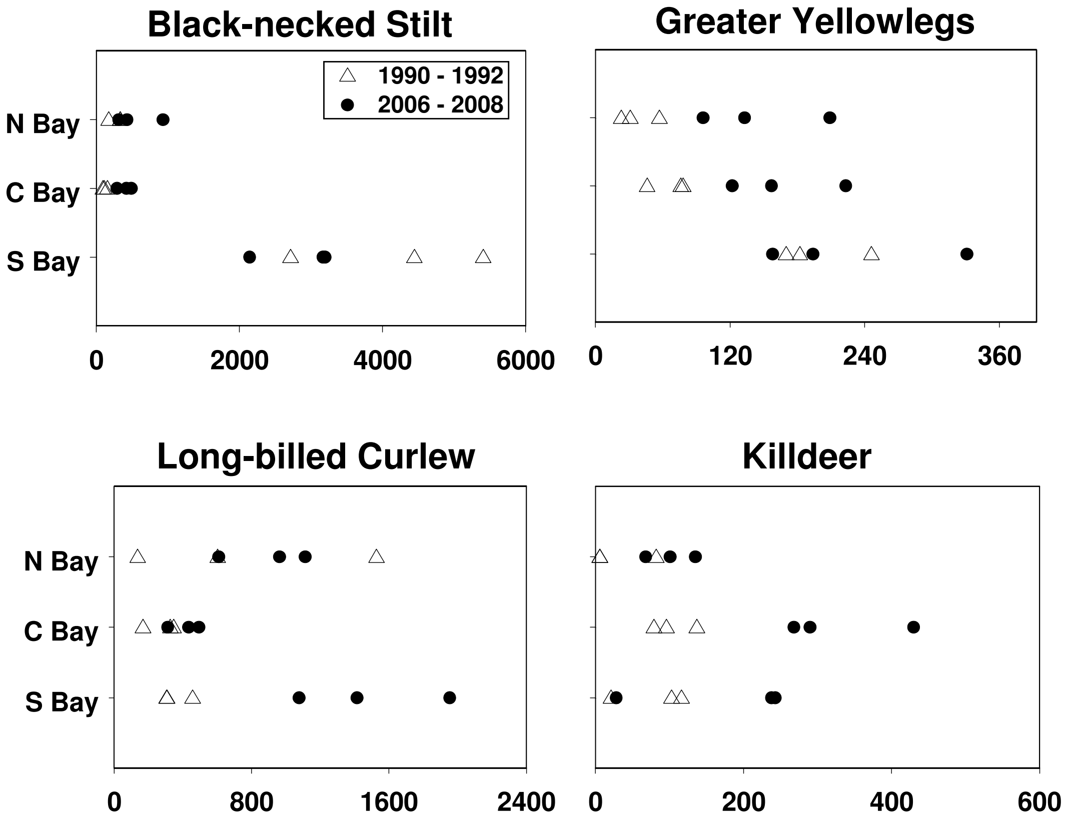
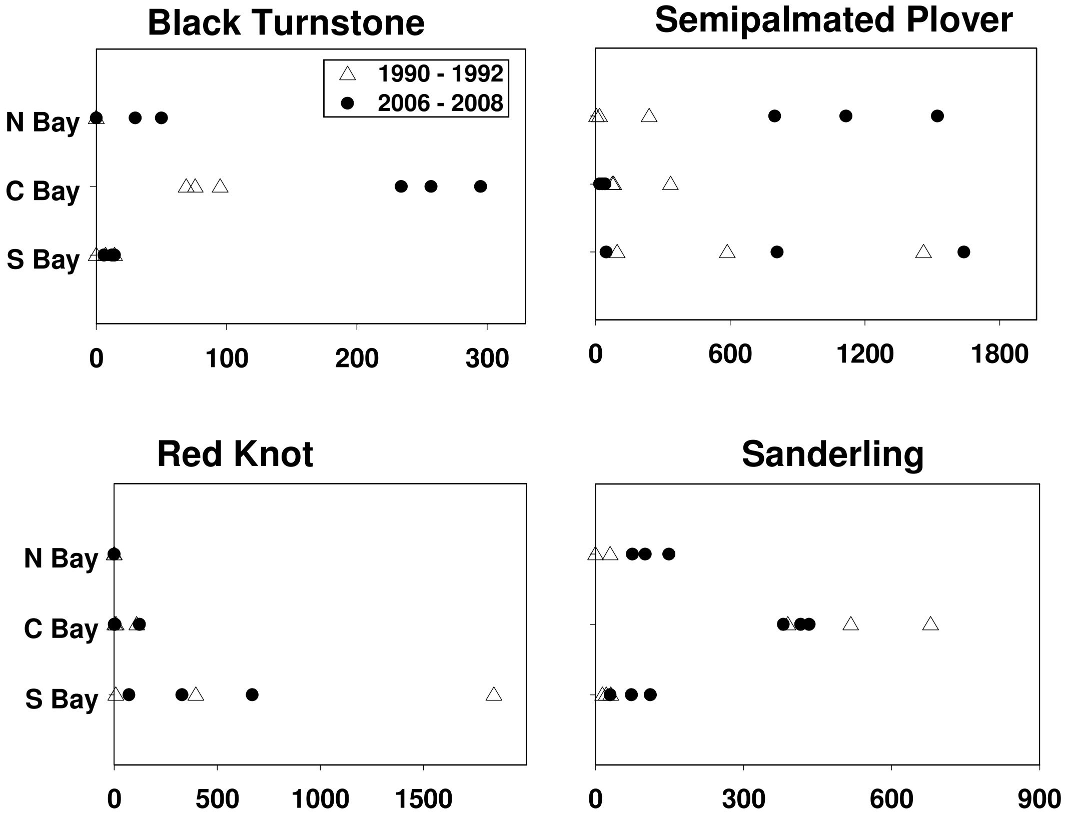


Figure 3. Cont'd.



Chapter 2

Using Simulations to Inform Shorebird Monitoring in San Francisco Bay

Long-term monitoring programs for large-landscapes require sampling designs that are logistically feasible, and that minimize bias and variance in estimates of population size or population change (Braun 2005). Although a complete enumeration of all birds from a region (i.e. comprehensive count) or population of interest is desirable, such comprehensive data are often unable to be collected. Thus both spatial and temporal sampling is predominantly used to estimate the population within a selected region over a period of time. However, whether assumed-to-be complete counts or sampling is used to estimate the population, subsequent estimates of population change and inference may be influenced by frame bias and selection bias.

Frame bias results when the total region over which a species occurs has not been adequately defined in which case declines in the observed sample may be either a real decline or movement of birds to a region not captured by the sampling frame (Bart et al 2005). Frame bias can exist in either a comprehensive count of a population or a sampled population if the entire region in which the population of interest occurs has not been properly defined or if the distribution of habitat changes over time. Selection bias occurs when some areas within the sampling frame cannot be included due to restricted accessibility (e.g. private land, large road-less areas). Thus, in light of these sources of potential bias, we face the question: are declines or increases observed in the limited sampling areas an unbiased measure of population trends across all areas? Simulations are a powerful quantitative tool for understanding ecological systems and potential sources of bias in wildlife monitoring programs. Given the availability of at least some data from a region, they can provide insights about the ability of sampling designs to detect changes in the distribution and abundance of a population over time, variability of parameter estimates on inference, and model fit (Gelmen and Meng 1996, Manly 2007).

The San Francisco Bay estuary provides habitat for over 1 million shorebirds (Charadriformes) annually (Page et al. 1999, Stenzel et al. 2002), and has been designated a site of "Hemispheric Importance" by the Western Hemisphere Shorebird Reserve Network. Comprehensive November surveys of roosting shorebirds in the San Francisco and San Pablo bays (hereafter, San Francisco Bay or Bay) were completed in 1990-92 and 2006-08 (see Chapter 1 for details). These surveys consisted of counts in variably sized "census" units and it was assumed that all birds were counted within each census unit. The comprehensive counts yielded an estimate of the total birds in the Bay and contributed to our understanding of the value of the estuary to wintering shorebirds but they required substantial logistical support to complete. Furthermore, these survey periods were 14 years apart thus providing limited data to detect trends and annual variation in the population, particularly as related to spatial and temporal trends in shorebird habitat. Moreover, conducting comprehensive surveys annually to track long-term trends and habitat associations of shorebirds using the Bay may not be logistically feasible. Consequently, alternative sampling-based approaches to monitoring wintering shorebirds in the Bay are needed.

We utilized spatially-referenced data from the comprehensive shorebird counts (1990-92, 2006-08) to simulate spatially and temporally explicit sampling scenarios at various levels of reduced sampling effort in the Bay. Overall, we provide data to inform the development of a sampling design that could accurately capture changes in the abundance of shorebirds using the Bay without having to conduct comprehensive counts. Specifically we assessed: (1) How much can we reduce sampling effort and still accurately (±20%) detect changes in shorebird abundance? (2) What is the best sample selection framework to identify where to survey roosting shorebirds? and (3) How frequently should surveys be completed to accurately detect 20-year population trends?

METHODS

Data Compilation

We used 224 count locations that were searched for roosting shorebirds in all 6 years of the November shorebird roost counts, 1990-92 and 2006-08 (Fig. 1). These represented 85% of the total sampling areas searched at least one time in each of the 2 time periods and >90% of the total birds counted during the comprehensive counts. We considered these data to represent the "true" number of birds present in the estuary during each of the 6 years of monitoring. The 224 count locations were located within 3 general regions of the Bay: (1) San Pablo Bay (SPB); (2) the Central Bay (CB); and (3) the South Bay (SB; see Chapter 1 for detailed descriptions of these 3 regions).

For our simulation study, we also considered only a subset of the species identified during the comprehensive counts. We selected 8 species or species-groups (species) that represented birds that were fairly common in the Bay and represented a variety of body sizes (Table 1). Because of the limited amount of rocky coastline habitat in the Bay, the suite of species we considered in these simulations did not include rocky shoreline dependent species (e.g. Black Oystercatcher). For each species, we calculated the finite rate of population change as:

$$\Delta_i = \frac{\sum_{j=2006}^{2008} count_j}{\sum_{j=1990}^{1992} count_j}$$

Where Δ_i indicates the change in the abundance of species, *i*, between 1990-92 and 2006-08; $\sum_{j=2006}^{2008} count_j$ is the sum of the counts of species, *i*, across all sampling locations in each year, *j*, between 2006 and 2008; and $\sum_{j=1990}^{1992} count_j$ is the sum of the counts of species, *i*, across all sampling locations in each year, *j*, between 1990 and 1992. Values of $\Delta_i > 1$ identified an increase in the abundance of species, *i*, while values of $\Delta_i < 1$ identified a decrease in the abundance of species, *i*, between the 2 time periods.

Simulations

For all simulations, we generally considered a repeated survey framework (Duncan and Kalton 1987). In each iteration of a simulation, a sample of locations was selected and then those same locations were used to subset all 6 years of the survey data as if those same locations were surveyed in all 6 years of sampling. We considered 3 levels of sampling effort, measured by the percentage of the total number of sampling locations surveyed, to evaluate how much we could reduce sampling effort within each year and still generate an estimate of change ±20% of the observed change based on 100% effort (i.e. all 224 locations surveyed): (1) 75%, (2) 50%, and (3) 25%. In combination with reduced effort, we considered 4 approaches to drawing samples to determine where we should survey: independent random sample (IRS); stratified random sample (SRS); generalized-random tessellation sample (GRTS); and stratified generalized-random tessellation sample (SGRTS). We used 3 approaches to stratification. First we sampled each of 3 distinct areas of the bay (SPB, CB, and SB) as strata and ensured that at least 25%, 50% and 75% of the sampling locations within each of the strata were sampled. Second, we stratified by weighting the drawing of a sample location proportional to the natural-logarithm of the total number of shorebirds observed at each sample location in the years 1990-92. Stratifying based on historical data of where the birds were typically found is represented by this approach and is common in ecology (Krebs 1999). Also, several studies have identified high roost-site fidelity in the Bay (Warnock and Takekawa 1996) and other coastal estuary systems (Colwell et al. 2003, Conklin and Colwell 2007, Peters and Otis 2007). High consistency of site use should reduce the year to year variance in the data and subsequently in estimates of population change. As well, high site fidelity suggests that spatial shifts in the distribution of birds are not very likely. Changes in the spatial distribution of birds can result in both selection and frame bias. Due to the very high degree of clustering of roosting shorebirds, we considered the natural log-total as the continuous stratification weight to even the sample selection probabilities. We also considered both stratification approaches together.

Using these criteria, we defined a total of 24 scenarios and employed the spsurvey package in program R (© 2008 The R Foundation for Statistical Computing) to implement simulations. For each scenario, we conducted 1000 iterations. For each iteration of each simulation in each effort scenario for each species, we calculated Δ_i and the squared-error of Δ_i (the squared difference between the simulation estimate of Δ_i and the "true" Δ_i). Therefore, each scenario for each species resulted in a distribution of 1000 Δ_i s, and 1000 squared-errors of Δ_i .

Comparing Scenarios

We compared effort and sample selection scenarios using measures of bias, variance, and overall accuracy, both within and among species groups, and across all species together. We calculated the bias of each scenario for each species as the squared difference between the observed change and the median change estimate from the distribution of 1000 change estimates. We quantified variance as the difference between the 25th and 975th ranked values of the 1000 simulated estimates of change (i.e. the width of the 95% CI of change based on the percentile method). Lastly, we measured the overall accuracy of each scenario based on the mean of the distribution of 1000 squared-errors (mean squared error = MSE). Although species specific differences were of interest, we primarily wanted to evaluate which effort and sampling scenarios performed the best across all the species considered in our analysis. We simply averaged the bias, variance, and MSE across the 8 species-species groups to quantify the overall performance of each scenario.

Power Analysis

Although our first set of simulations compared spatial sampling designs and effort level with spatially comprehensive surveys at 100% effort, we were unable to assess the effectiveness of alternative temporal sampling designs (e.g. annual surveys, every other year surveys). We were only able to assess the relative value of alternative spatial sampling designs using two sets of 3 years (1990-92 and 2006-08) of surveys separated by 14 years. We conducted a second set of simulations to determine the power of different temporal sampling designs to detect population trends. We used the criteria of being able to detect a 50% population decline over 20 years with 80% power at the $p = 0.05$ significance level. This is a fairly strict criteria, so we also evaluated the power to detect a 50% decline over 20 years at $p = 0.15$ significance level (Butcher et al. 1999)

For each simulation, we drew a sample using one of the spatial sampling designs at a specified effort level (see "Simulations" above). We partitioned data at the selected sites from the full dataset. We then simulated a 20 year dataset by bootstrap sampling the 6 years of data at each survey location and applying ~3.5% decline in abundance per year (Efron and Tibshirani 1993). For each simulated 20-year dataset, we fit an over-dispersed Poisson regression model with random effects using Markov Chain Monte Carlo (Gilks et al. 1996) in the MCMCglmm package in program R v2.8.1. Our model consisted of a continuous fixed-effect of year and 2 random effect variance terms accounting for correlation among sites and among years. We conducted 100 iteration in each simulation and calculated the proportion of the iterations where the upper value of the 95% credible interval (equivalent of 95% CI) or 85% credible interval of the trend estimate was < 0 as our measure of power to significantly detect trend at the $p = 0.05$ and the $p = 0.15$ significance level, respectively.

RESULTS

Between the two time periods 5 of the 8 species showed evidence of an increase in abundance while *Calidris* sandpipers, dowitchers, and stilts decreased. Overall change values ranged from 20% declines to 60% increases (Fig. 2). Yellowlegs (Mann-Whitney $U = 0$, $p \approx 0.10$) and whimbrel (Mann-Whitney $U = 0$, $p \approx 0.10$) were the only species that had statistically significant changes; both were increases.

Overall, our simulation results across all species were predictable based on sampling theory. By increasing overall sampling effort, from 25% to 75% of the total sampling locations, bias, variance, and the overall MSE of our estimates of change were reduced (Fig. 3). Averaged across sampling regimes and species, MSE was reduced from 0.44 (min = 0.13, max = 1.02) at 25% effort to 0.08 (min = 0.05, max = 0.13) at 50% effort to 0.03 (min = 0.01, max = 0.04) at 75% effort. Generally, increasing sampling effort from 25 – 50% of the total effort resulted in a larger increase in accuracy than an increase from 50 – 75% (Fig. 3).

There were noticeable differences in the bias and variance among our sampling designs. Sampling designs that weighted sampling effort towards areas of historic abundance of roosting shorebirds tended to be slightly more biased than other designs, whereas they exhibited much lower variance in their estimates than designs without a weighted stratification by historic data. These patterns were consistent among all sampling efforts and species. The strength of the variance component in the calculation of the overall accuracy (accuracy = MSE = variance + bias^2) was apparent as overall, designs with high variance but low bias tended to have much higher MSE when compared with the slightly more biased but less variable sampling designs (Table 3; Fig. 3).

Overall, the level of effort and stratification using historical data had a greater influence on the performance of each sampling design at each effort level than sampling using GRTS versus IRS. However, GRTS exhibited greater bias in the weighted sampling than IRS, suggesting that by trying to both achieve a spatially-balanced design while also being constrained by weighted sample locations may result in slight bias, given the distribution of roosting shorebirds evaluated here. However, stratified sampling designs using historical 1990s data to weight the selection of locations resulted in the lowest MSE observed when using either the GRTS algorithm or random sampling.

Overall, patterns among species were consistent with those averaged across all species we evaluated (Table 3). The only notable difference across species was that, on average, yellowlegs and whimbrel had larger bias and variance, given the sampling effort and sampling design, than the other species groups. However, these species were substantially less abundant than the other 6 species (see Table 3 in Chapter 1).

The power analyses suggested that in order to meet the criteria of having 80% power to detect a 50% decline in 20 years at the $p = 0.05$ or $p = 0.15$ significance level using an over-dispersed Poisson regression model and a stratified 25% sampling effort, surveys should be conducted annually (Table 4). Reducing sampling from every year to every other year reduced power for all species from on average across species, 0.89 to 0.06 at 25% survey effort. Sampling every five years performed poorly a well compared to annual sampling. Power to detect trends was >0.80 for all species using annual surveys at 25% effort.

DISCUSSION

The effort-intensive, comprehensive November surveys of roosting shorebirds conducted from 1990-92 and again from 2006-08 provide an accurate measure of wintering shorebird use of the Bay. These data also provide a unique opportunity to assess sampling design and survey methodology for long-term monitoring of wintering shorebird populations in the Bay. Our *post-hoc* analysis using subsets of the full data set suggested a properly designed sampling framework for shorebirds in the Bay could meet our accuracy standards while also reducing the overall effort needed to accomplish the surveys. Consequently, this creates an opportunity to conduct the surveys more regularly, preferably annually, to better understand annual variability in the Bay shorebird numbers, link shorebird populations in the Bay with specific management actions, and identify spatial and temporal variation in wintering shorebird populations at scales larger than the Bay if combined with monitoring data from other regions in the Pacific Flyway.

Overall, the populations of shorebird species that we evaluated were relatively stable in the Bay between the two time-periods and the observed changes were fairly small.

However some spatial shifts were detected in the populations of some species (Table 4 in Chapter 1). Our simulations identified the possibility for bias in estimates as a result of spatially shifting populations, if samples are weighted too much on the historical data of a species' distribution, and if that species tended to be highly aggregated. In our analysis, samples (whether drawn randomly or using the GRTS algorithm) with weighted stratification based on the historical data tended to have slightly larger bias than samples without this stratification. This bias was likely induced by spatial shifts in the population, combined with samples that were weighted towards areas where there were already high numbers of birds based on historic data. However, based on the MSE criteria, the weighted designs were most accurate and provided good estimates of change at very low sampling effort. In future simulations, we will be evaluating the sensitivity of the sampling design and change estimates to different weighting structures related to historic data.

The value of using these historical data for testing sampling designs was not surprising given that many species of shorebirds tend to exhibit high roost site fidelity and that overall the spatial distribution of shorebirds has been relatively stable across the Bay. However, spatial patterns of shorebirds around the Bay are likely to change as the result of changes in the distribution of habitat in this landscape created by large scale restoration projects, and over a longer term, rising sea levels. Any ongoing monitoring program for shorebirds in the Bay will have to accommodate changes in the sampling frame (e.g., new habitat, lost habitat) within the bay and the in the broader landscape to prevent frame and selection bias. Wide-ranging species like shorebirds may respond to changing habitat availability on the landscape over much larger scales than even the Bay. Understanding how trends in the Bay compare to species population trends over wider geographical regions is needed to help understand whether trends in the Bay reflect Pacific Flyway population trends or more localized trends in populations within the Bay only.

Our simulations were limited to the general survey design used to collect the data. All survey locations were sampled once in each of the 6 sampling years in this repeated survey design (Duncan and Kalton 1987). Sampling the same areas repeatedly is convenient and provides data on how changes in habitat will affect birds at specific locations, but may not reflect the change in the population as a whole if the sample is not representative of that whole population. Drawing a new sample of survey locations every year can avoid this potential bias, yet may be logistically implausible and makes linking habitat changes with species response more difficult. One alternative is a split panel design where one sample is a repeated sample while a second set of sites are selected at random each year (Duncan and Kalton 1987).

Lastly, our power analyses suggested that annual surveys would be needed to be able to detect 50% declines in shorebird populations over a 20-year time period with 80% power when surveying with 25% effort whether using the $p = 0.05$ or $p = 0.15$ significance level. Annual surveys were a substantial improvement over sampling every other year or every fifth year, Reducing the sample size by half (i.e. annual surveys to every-other year surveys) resulted in a 96% decline in power. These data provide quantitative support of the need for annual surveys in addition to their qualitative appeal for facilitating continued volunteer engagement in the monitoring program.

CONCLUSION AND RECOMMENDATION

Our simulation analysis suggests that using a properly stratified sampling design, effort to survey roosting shorebirds in San Francisco Bay could be reduced by up to 75% and still achieve reasonably accurate (±20%) estimates of population change and meet power criteria to detect 20-year trends. We suggest the use of historical data to guide the distribution of sampling, given our results and the high roost site fidelity of shorebirds; however, we caution that by not monitoring areas where the birds have been absent or found only in small numbers previously could yield biased trend estimates overtime. This is a mixture of both frame and selection bias. Thus, the weighting used to stratify the sampling distribution needs to be evaluated carefully and strategies to adequately cover areas not captured in the initial sampling design over time are needed to prevent biased trend estimates. Based on our data and initial simulation results, we recommend that any long-term monitoring program of shorebirds in the Bay consider a sampling design in which one set of sites would be selected randomly, weighted towards historic roost sites, and counted annually. The remaining region of the Bay would be surveyed every 10-years to evaluate changes in the survey frame (e.g. new habitat and spatial shift in habitat) that could bias trend estimates. These every 10-year updates would help inform the sampling frame for the following 10 year period. Ultimately, finding efficient ways to monitor shorebird populations annually in the Bay are needed for their conservation and management. Simulations using our historical data provide a critical first step in developing a robust monitoring protocol.

TABLES AND FIGURES

Table 1. Species-species groups used in simulations to assess sampling scenarios for November roost counts of shorebirds in San Francisco Bay.

Species-Species Group	Reference Name
American Avocet	Avocet
Black-necked Stilt	Stilt
Willet	Willet
Greater Yellowlegs, Lesser Yellowlegs	Yellowlegs
Long-Billed Curlew, Marbled Godwit	Curlew-Godwit
Whimbrel	Whimbrel
Least Sandpiper, Western Sandpiper, Dunlin	Calidris
Long-billed Dowitcher, Short-billed Dowitcher	Dowitchers

Table 2. Definition of 8 sampling regimes used to draw samples for simulations of sampling scenarios for November roost counts of shorebirds in San Francisco Bay.

Sampling Regime	Code
Generalized Random-Tesselation Stratified Sampling	GRTS
Generalized Random-Tesselation Stratified Sampling with additional stratification by San Pablo Bay, Central Bay, and South Bay	SGRTS
Generalized Random-Tesselation Stratified Sampling with additional stratification weighted by the abundance of shorebirds in the 1990-92 sample years.	GRTSW
Generalized Random-Tesselation Stratified Sampling with additional stratification by San Pablo Bay, Central Bay, and South Bay and weighted by the abundance of shorebirds in the 1990-92 sample years.	SGRTSW
Independent Random Sampling	IRS
Stratified Random Sampling with stratification by San Pablo Bay, Central Bay, and South Bay	SIRS
Stratified Random Sampling with stratification weighted by the abundance of shorebirds in the 1990-92 sample years.	IRSW
Stratified Random Sampling with stratification by San Pablo Bay, Central Bay, and South Bay and weighted by the abundance of shorebirds in the 1990-92 sample years.	SIRSW

Table 3. Summary of bias, variance (var), and mean squared error (mse) for each species-species group in each simulation scenario for November roost counts in San Francisco Bay.

[a]bias = (observed change – median of simulated change)^2

		Avocet			**Stilt**			**Curlew-Godwit**			**Dowitchers**		
Sampling	**Effort**	**bias[a]**	**var[b]**	**mse**	**bias[a]**	**var[b]**	**mse**	**bias[a]**	**var[b]**	**mse**	**bias[a]**	**var[b]**	**mse**
GRTS	25	0.0013	1.9885	0.2898	0.0021	2.8372	0.5681	0.0015	3.3244	0.8097	0.0000	1.5637	0.1694
GRTS	50	0.0000	1.0642	0.0685	0.0001	1.1669	0.1023	0.0005	1.6633	0.1808	0.0000	0.8342	0.0436
GRTS	75	0.0000	0.5885	0.0234	0.0003	0.7364	0.0351	0.0000	0.8796	0.0524	0.0001	0.4240	0.0118
SGRTS	25	0.0003	1.8756	0.2569	0.0064	2.5350	0.5298	0.0029	3.1629	0.7387	0.0002	1.5396	0.1627
SGRTS	50	0.0002	1.0995	0.0712	0.0004	1.3061	0.1260	0.0002	1.6919	0.1954	0.0000	0.7742	0.0399
SGRTS	75	0.0002	0.5912	0.0240	0.0000	0.7675	0.0367	0.0000	0.9659	0.0626	0.0000	0.4649	0.0146
GRTSW	25	0.0550	0.9349	0.1006	0.0311	1.0794	0.1084	0.1093	1.4867	0.1881	0.0321	0.7705	0.0635
GRTSW	50	0.0447	0.3918	0.0408	0.0146	0.1692	0.0236	0.0955	0.5124	0.0963	0.0278	0.2531	0.0312
GRTSW	75	0.0195	0.2068	0.0184	0.0061	0.0545	0.0060	0.0126	0.3269	0.0383	0.0092	0.1093	0.0087
SGRTSW	25	0.0380	1.0054	0.1052	0.0288	1.1932	0.0913	0.0847	1.4548	0.2122	0.0338	0.7314	0.0687
SGRTSW	50	0.0339	0.3133	0.0551	0.0174	0.2366	0.0179	0.0966	0.4685	0.0907	0.0280	0.2232	0.0330
SGRTSW	75	0.0184	0.1787	0.0213	0.0059	0.0538	0.0063	0.0094	0.2945	0.0455	0.0079	0.0880	0.0104
IRS	25	0.0001	2.0056	0.3021	0.0028	2.6104	0.5221	0.0004	3.3097	0.8705	0.0003	1.6300	0.1889
IRS	50	0.0007	1.0628	0.0746	0.0001	1.2118	0.1130	0.0013	1.5960	0.1708	0.0003	0.8839	0.0495
IRS	75	0.0000	0.5793	0.0221	0.0001	0.7743	0.0400	0.0000	0.9766	0.0617	0.0001	0.4672	0.0144
SIRS	25	0.0001	1.8861	0.2484	0.0017	2.3454	0.4428	0.0008	3.4959	0.9143	0.0019	1.6129	0.1730
SIRS	50	0.0000	1.0231	0.0675	0.0000	1.3595	0.1296	0.0001	1.7419	0.1826	0.0000	0.8134	0.0468
SIRS	75	0.0000	0.5435	0.0194	0.0001	0.7703	0.0392	0.0000	0.9124	0.0571	0.0000	0.4591	0.0135
IRSW	25	0.0454	1.0660	0.1025	0.0232	1.3314	0.1302	0.0773	1.5789	0.2079	0.0286	0.7971	0.0625
IRSW	50	0.0251	0.5346	0.0316	0.0131	0.4821	0.0272	0.0380	0.7415	0.0707	0.0154	0.3672	0.0227
IRSW	75	0.0038	0.1824	0.0031	0.0024	0.0645	0.0025	0.0010	0.3144	0.0061	0.0015	0.1147	0.0023
SIRSW	25	0.0304	1.0643	0.1021	0.0148	1.4040	0.1315	0.0706	1.6371	0.2095	0.0265	0.8504	0.0594
SIRSW	50	0.0190	0.4848	0.0395	0.0112	0.5587	0.0237	0.0345	0.7522	0.0714	0.0147	0.3633	0.0226
SIRSW	75	0.0007	0.1326	0.0054	0.0023	0.0591	0.0026	0.0010	0.2604	0.0128	0.0016	0.0818	0.0027

[b]var = (975th ranked simulated estimate of change – 25th ranked simulated estimate of change)^2

Table 3. cont’d.

		Calidris			Whimbrel			Willet			Yellowlegs		
Sampling	**Effort**	**bias**[a]	**var**[b]	**mse**	**bias**[a]	**var**[b]	**mse**	**bias**[a]	**var**[b]	**mse**	**bias**[a]	**var**[b]	**mse**
GRTS	25	0.0005	1.5047	0.1456	0.0014	4.4527	1.7536	0.0001	2.8746	0.5338	0.0000	2.2674	0.1221
GRTS	50	0.0000	0.7179	0.0365	0.0001	1.7026	0.2022	0.0002	1.4470	0.1298	0.0005	1.2886	0.0432
GRTS	75	0.0001	0.4538	0.0131	0.0004	0.9651	0.0610	0.0000	0.8161	0.0430	0.0003	0.6767	0.0129
SGRTS	25	0.0000	1.3642	0.1336	0.0024	4.7511	3.4265	0.0014	2.6499	0.5128	0.0002	2.2623	0.1188
SGRTS	50	0.0000	0.8127	0.0401	0.0001	1.6137	0.1879	0.0000	1.3901	0.1360	0.0004	1.0874	0.0348
SGRTS	75	0.0002	0.4385	0.0129	0.0002	0.9706	0.0638	0.0000	0.8372	0.0464	0.0000	0.6378	0.0109
GRTSW	25	0.0301	0.7297	0.0552	0.0213	1.5472	0.1778	0.0734	1.3629	0.1585	0.1941	0.9633	0.1476
GRTSW	50	0.0187	0.2776	0.0228	0.0286	0.4974	0.0375	0.0390	0.3860	0.0644	0.1695	0.3096	0.1358
GRTSW	75	0.0053	0.0766	0.0053	0.0333	0.2208	0.0323	0.0067	0.1723	0.0144	0.0871	0.1835	0.0859
SGRTSW	25	0.0250	0.6875	0.0618	0.0258	1.6533	0.1789	0.0609	1.2743	0.1640	0.1427	1.0845	0.1974
SGRTSW	50	0.0171	0.2156	0.0264	0.0288	0.5633	0.0380	0.0511	0.4085	0.0505	0.1358	0.3873	0.1695
SGRTSW	75	0.0050	0.0744	0.0058	0.0333	0.1769	0.0325	0.0057	0.1623	0.0159	0.0859	0.1726	0.0871
IRS	25	0.0000	1.4323	0.1408	0.0075	5.0053	5.2314	0.0000	2.5760	0.4955	0.0000	2.4438	0.1293
IRS	50	0.0006	0.8612	0.0455	0.0000	1.9233	0.2476	0.0010	1.4068	0.1357	0.0000	1.3095	0.0416
IRS	75	0.0000	0.4759	0.0147	0.0001	1.0022	0.0643	0.0000	0.8424	0.0424	0.0000	0.7177	0.0141
SIRS	25	0.0001	1.4565	0.1475	0.0023	4.2660	1.9910	0.0001	2.5285	0.4559	0.0006	2.3727	0.1200
SIRS	50	0.0000	0.7934	0.0412	0.0000	2.1920	0.3218	0.0001	1.4378	0.1226	0.0000	1.2592	0.0319
SIRS	75	0.0001	0.4490	0.0131	0.0003	0.9610	0.0598	0.0000	0.8272	0.0425	0.0000	0.7293	0.0121
IRSW	25	0.0183	0.7620	0.0590	0.0285	1.7770	0.2123	0.0434	1.4714	0.1520	0.1648	1.0715	0.1257
IRSW	50	0.0093	0.3718	0.0181	0.0315	0.7842	0.0524	0.0234	0.6058	0.0491	0.1282	0.4638	0.0904
IRSW	75	0.0012	0.1203	0.0013	0.0316	0.2604	0.0246	0.0014	0.1688	0.0029	0.0404	0.1738	0.0412
SIRSW	25	0.0175	0.8363	0.0549	0.0068	1.7294	0.2407	0.0385	1.4007	0.1588	0.1027	1.2073	0.1703
SIRSW	50	0.0078	0.3754	0.0210	0.0341	0.6806	0.0546	0.0243	0.6982	0.0440	0.0898	0.5561	0.1282
SIRSW	75	0.0008	0.0568	0.0022	0.0316	0.1930	0.0276	0.0010	0.1418	0.0048	0.0412	0.1862	0.0404

[a] bias = (observed change – median of simulated change)^2

[b] var = (975th ranked simulated estimate of change – 25th ranked simulated estimate of change)^2

Table 4. Summary of power (probability) to detect a 50% decline in abundance over 20-years at the p = 0.05 significance level using 25% effort and a stratified-weighted GRTS sampling for surveys conducted annually, every other year (EOY) and every fifth year (FFY). The p = 0.15 significance level was also used for all species.

Species	**Annual**[a]	**EOY**[b]	**EFY**[c]
Avocet	0.89	0.05	0.00
Stilt	0.89	0.01	0.00
Willet	0.94	0.02	0.00
Yellowlegs	1.00	0.07	0.00
Curlew-Godwit	0.80	0.04	0.00
Whimbrel	0.88	0.03	0.00
Calidris	0.88	0.04	0.00
Dowitchers	0.83	0.04	0.00
All - p = 0.05	0.99	0.06	0.00
All - p = 0.15	1.00	0.63	0.00

Figure 1. Distribution of 224 sampling locations used in simulations to assess sampling frameworks for wintering shorebirds in the San Francisco Bay.

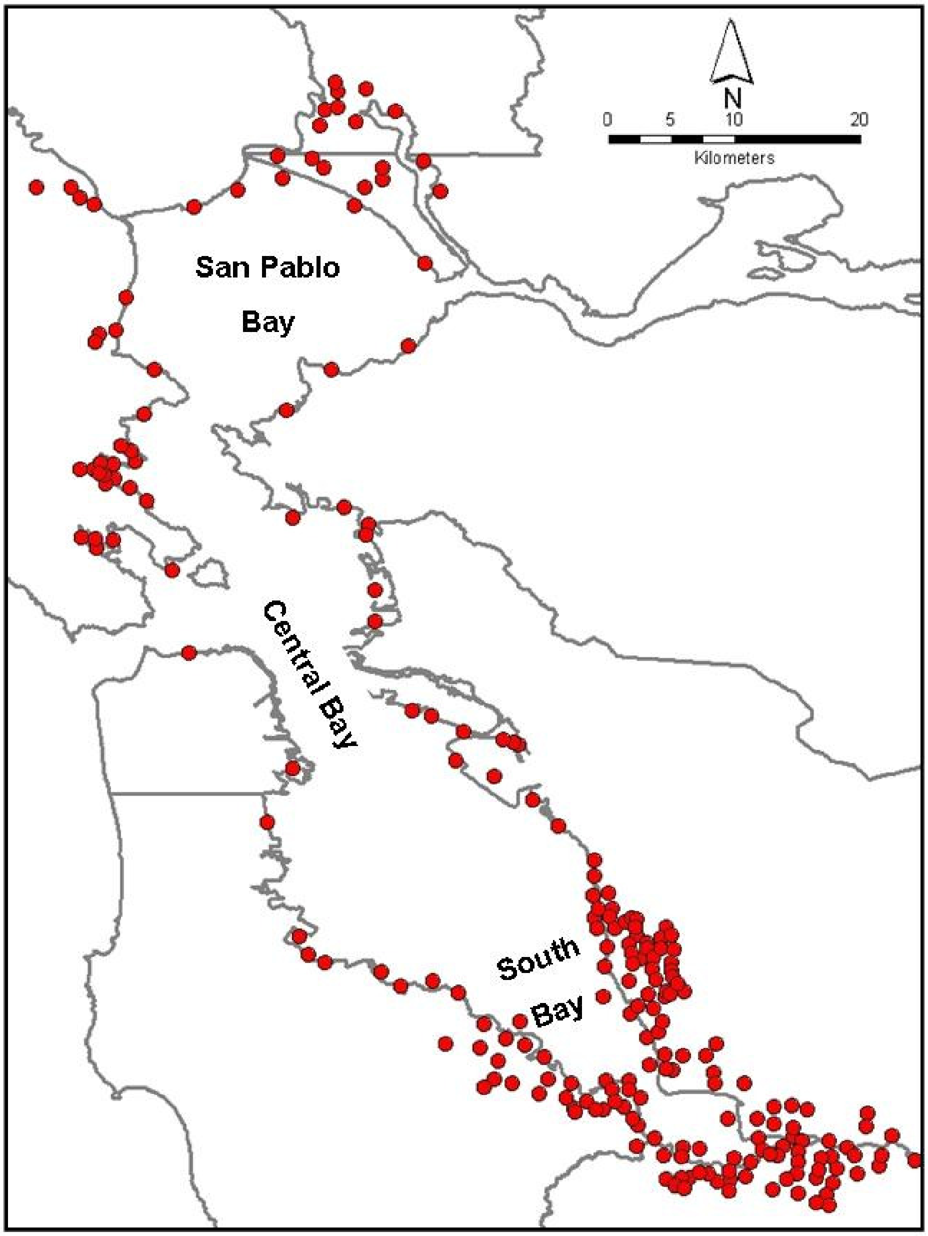


Figure 2. Observed change in the abundance of roosting shorebirds in each species-species group between 1990-92 and 2006-08 based on the complete set of 224 survey locations in the San Francisco Bay. Hollow diamonds indicate a significant change ($p = 0.10$) based on the non-parametric Mann-Whitney U test.

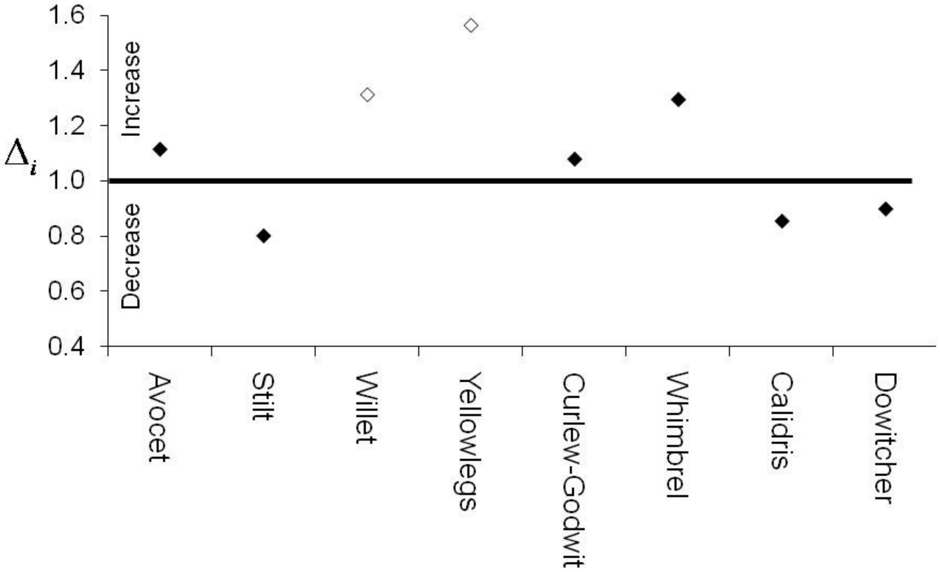
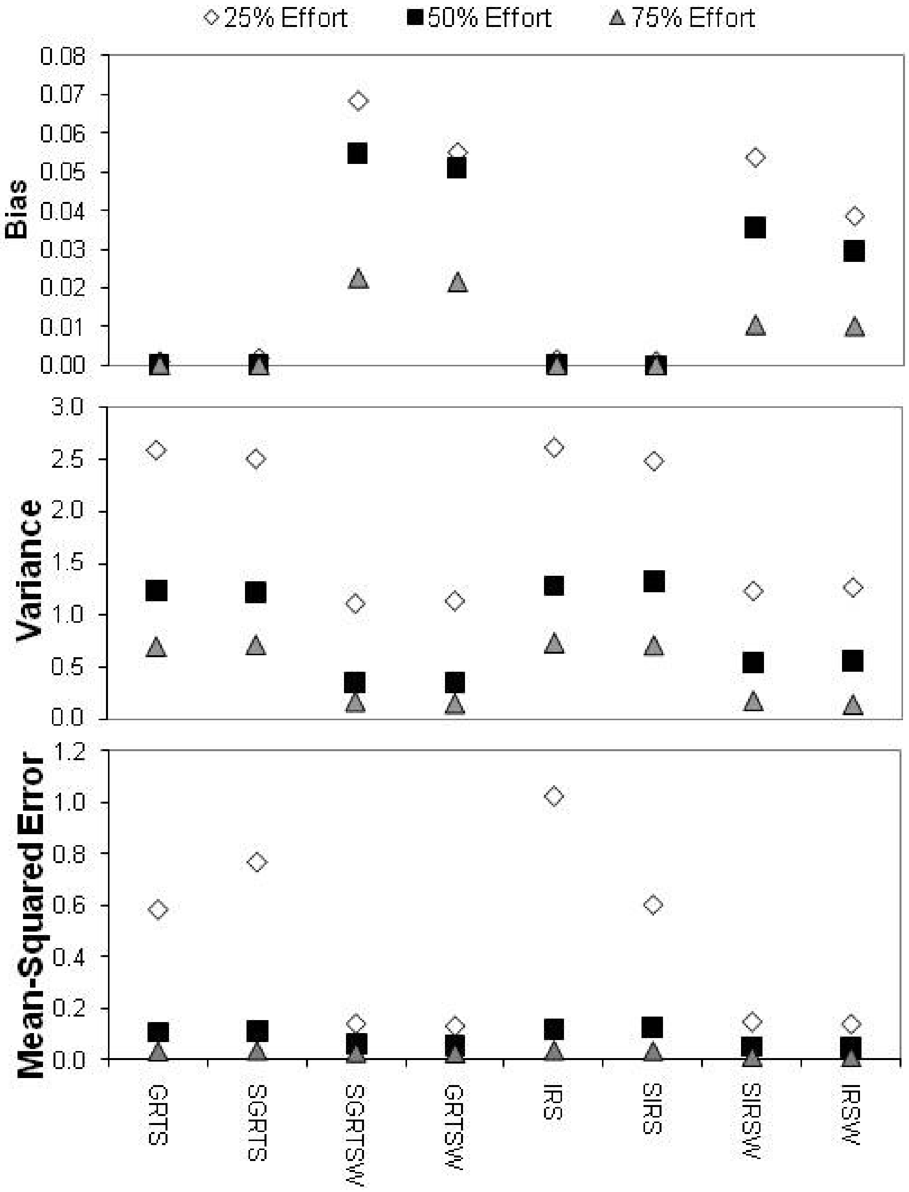


Figure 3. Average bias, variance, and mean-squared error across all 8 species-species groups for each sampling regime and effort level evaluated using November shorebird roost count data from the San Francisco Bay, 1990-92 and 2006-08. See Table 2 for sampling scenario codes


◇25% Effort
■50% Effort
▲75% Effort
Bias
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Variance
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Mean-Squared Error
1.2
1.0
0.8
0.6
0.4
0.2
0.0
GRTS
SGRTS
SGRTSW
GRTSW
IRS
SIRS
SIRSW
IRSW

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