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RESEARCH

# Breeding Waterbird Populations Have Declined in South San Francisco Bay: An Assessment Over Two Decades

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## ABSTRACT

In south San Francisco Bay, former salt ponds now managed as wildlife habitat support large populations of breeding waterbirds. In 2006, the South Bay Salt Pond Restoration Project began the process of converting 50% to 90% of these managed pond habitats into tidal marsh. We compared American Avocet (*Recurvirostra americana*) and Black-necked Stilt (*Himantopus mexicanus*) abundance in south San Francisco Bay before (2001) and after approximately 1,300 ha of managed ponds were breached to tidal action to begin tidal marsh restoration (2019). Over the

18-year period, American Avocet abundance declined 13.5% (2,765 in 2001 vs. 2,391 in 2019), and Black-necked Stilt abundance declined 30.0% (1,184 in 2001 vs. 828 in 2019). Forster's Tern (*Sterna forsteri*) abundance was 2,675 birds in 2019. In 2019, managed ponds accounted for only 25.8% of suitable habitats, yet contained 53.9%, 38.6%, and 65.6% American Avocet, Black-necked Stilt, and Forster's Tern observations, respectively. Conversely, tidal marsh and tidal mudflats accounted for 42.9% of suitable habitats, yet contained only 18.4%, 10.3%, and 19.8% of American Avocet, Black-necked Stilt, and Forster's Tern observations, respectively. Using a separate nest-monitoring data set, we found that nest abundance in south San Francisco Bay declined for all three species from 2005–2019. Average annual nest abundance during 2017–2019 declined 53%, 71%, and 36%, for American Avocets, Black-necked Stilts, and Forster's Terns, respectively, compared to 2005–2007. Loss of island nesting habitat as a result of tidal marsh conversion and an increasing population of predatory California Gulls (*Larus californicus*) are two potential causes of these declines. All three species established nesting colonies on newly constructed islands within remaining managed ponds; however, these new colonies did not make up for the steep declines observed at other historical nesting sites. For future wetland restoration, retaining more managed ponds that contain islands suitable

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for nesting may help to limit further declines in breeding waterbird populations.

## KEY WORDS

American Avocet, Black-necked Stilt, California Gull, Forster's Tern, habitat use, nesting islands, managed ponds, population change, tidal marsh restoration

## INTRODUCTION

San Francisco Bay is one of the most important sites for waterbirds along the Pacific Flyway, supporting more than 1 million waterbirds annually (Page et al. 1999; Takekawa et al. 2001; Stenzel et al. 2002; Warnock et al. 2002). Often recognized for its importance to staging and wintering waterbirds, San Francisco Bay also supports large numbers of breeding shorebirds and terns. Over the last few decades, San Francisco Bay has supported the largest breeding populations of American Avocets (*Recurvirostra americana*) and Black-necked Stilts (*Himantopus mexicanus*) and nearly 30% of the breeding population of Forster's Terns (*Sterna forsteri*) along the Pacific coast (Stenzel et al. 2002; Rintoul et al. 2003; Strong et al. 2004; McNicholl et al. 2020). Once uncommon breeders in San Francisco Bay (Sibley 1952; Gill 1977; Rintoul et al. 2003), these three species benefitted from the conversion of approximately 14,000 ha of tidal marsh in south San Francisco Bay to commercial salt ponds between the 1860s through the 1950s (Goals Project 1999). As part of the South Bay Salt Pond (SBSP) Restoration Project, many of these salt ponds have since been transferred to government ownership, have been taken out of salt production, and are now managed as pond habitat for wildlife or are being converted to tidal marsh. In addition to providing abundant invertebrate and fish food resources (Takekawa et al. 2006), these former salt ponds provide nesting habitat in the form of islands and levees. More than 90% of Forster's Tern nests, >70% of American Avocet nests, and ~20% of Black-necked Stilt nests in south San Francisco Bay occur on islands within managed ponds (Strong et al. 2004; Ackerman and Herzog 2012; Hartman et al. 2016a; Ackerman et al. 2020).

In 2001, Rintoul et al. (2003) conducted a comprehensive breeding survey to examine the abundance, distribution, and habitat use of American Avocets and Black-necked Stilts in San Francisco Bay south of the San Mateo Bridge. Through this effort, the populations of American Avocets and Black-necked Stilts in south San Francisco Bay were estimated to be 2,765 and 1,184 birds, respectively. Since 2001, south San Francisco Bay has experienced considerable landscape and management changes (<http://www.southbayrestoration.org>). First, most salt ponds were transferred to government management in 2003 and are now managed as ponds for wildlife habitat within the US Fish and Wildlife Service's Don Edwards San Francisco Bay National Wildlife Refuge and the California Department of Fish and Wildlife's Eden Landing Ecological Reserve. Second, the breeding population of California Gulls (*Larus californicus*), a key predator of waterbird eggs and chicks (Herring et al. 2011; Ackerman et al. 2014b, 2014c; Takekawa et al. 2015; Peterson et al. 2017), has increased from an estimated 16,998 gulls in 2001 to 45,026 gulls in 2019 (Burns et al. 2018; Tarjan and Burns 2019), likely exerting higher predation pressure on breeding waterbirds (Ackerman et al. 2014b, 2014c). Finally, the SBSP Restoration Project is implementing a large-scale plan to convert 50% to 90% of former salt ponds into tidal marsh habitats within the next 50 years (USFWS and CDFG 2007). Since 2006, the SBSP Restoration Project has reconnected approximately 1,300 ha of former salt ponds to the bay, beginning the process of tidal marsh restoration. Restoring former salt ponds to tidal marsh is expected to benefit some plants and animals that depend on tidal marsh habitat, as well as buffer against storm surge, and potentially improve water quality and protect inland areas from sea level rise (USFWS and CDFG 2007; Goals Project 2015). However, the loss of managed pond habitat, and islands therein, may negatively affect thousands of waterbirds that rely on these productive wetland habitats for foraging, roosting, and nesting (Warnock and Takekawa 1995; Takekawa et al. 2001; Warnock et al. 2002; Strong et al. 2004; Hickey et al. 2007; Ackerman et al. 2009; Stralberg et al. 2009; Demers et al. 2010; Bluso-Demers et al. 2016; Hartman et al. 2016a).

To address this, the SBSP Restoration Project was designed to follow an adaptive management framework, whereby waterbird populations are monitored during each phase of managed pond conversion to tidal marsh, allowing managers to adjust plans to achieve the SBSP Restoration Project's goal of maintaining existing waterbird populations in south San Francisco Bay. To help achieve this goal, and to maximize waterbird use of reduced managed pond habitat, nesting islands were constructed within managed ponds during Phase 1 of the SBSP Restoration Project and the construction of additional islands are planned for future phases of the project. New islands have been constructed in the Ravenswood (30 islands at Pond SF2 in 2010) and Alviso (16 islands at Pond A16 in 2012) complexes of the Don Edwards San Francisco Bay National Wildlife Refuge, and at the Eden Landing Ecological Reserve (six islands at Ponds E12 and E13 in 2015; Figure A1). However, despite these many large-scale landscape changes, breeding waterbird population trends in south San Francisco Bay have not been investigated in the past decades.

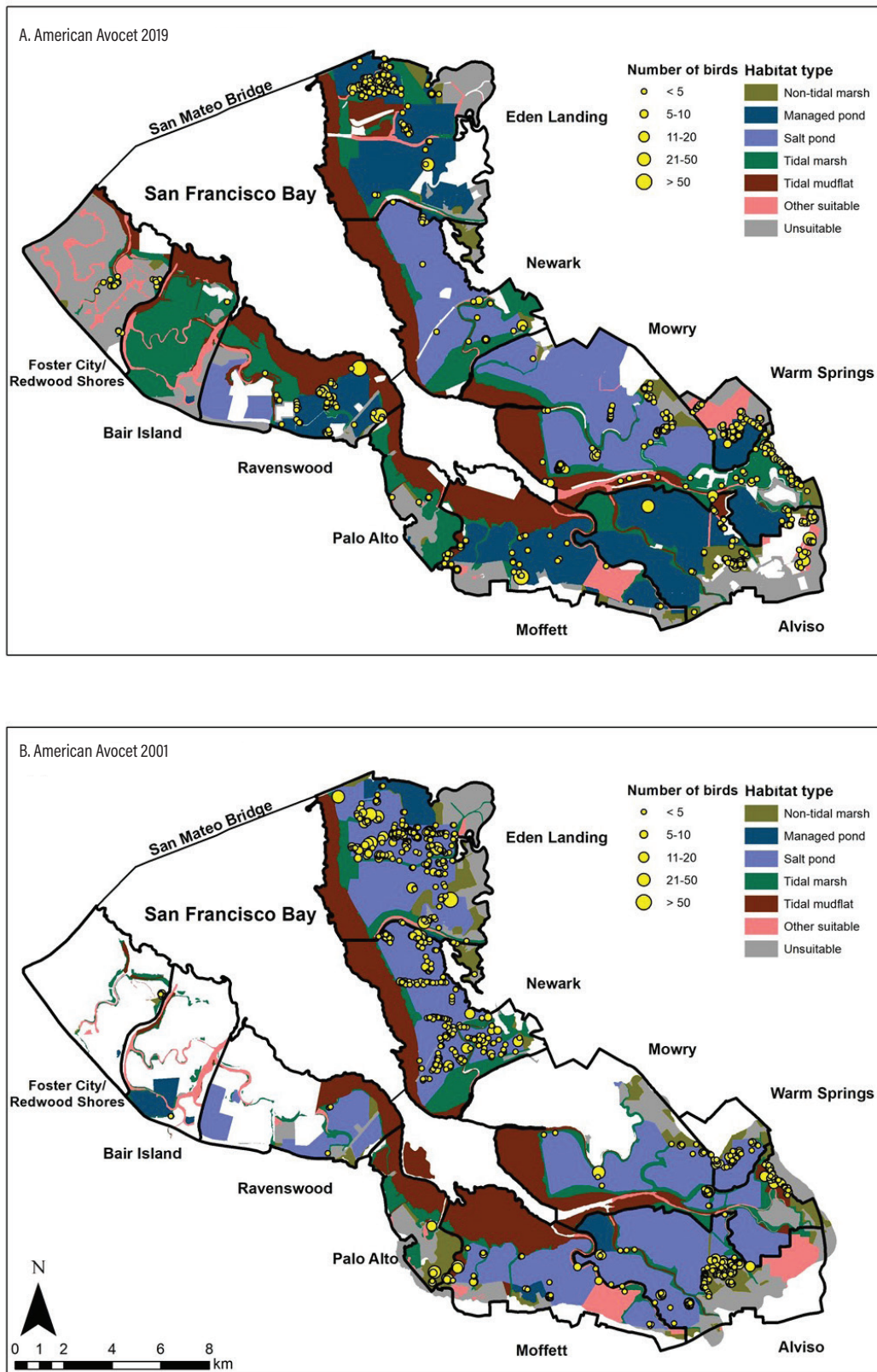
We evaluated changes in breeding waterbird populations in south San Francisco Bay from 2001 to 2019 using two approaches. First, in 2019, we repeated the 2001 waterbird survey by Rintoul et al. (2003) to reexamine the abundance, distribution, and habitat use of American Avocets and Black-necked Stilts in south San Francisco Bay. In 2019, we also surveyed for Forster's Terns, and several less abundant species including Caspian Terns (*Hydroprogne caspia*), Black Skimmers (*Rynchops niger*), Elegant Terns (*Thalasseus elegans*), and California Least Terns (*Sternula antillarum browni*). Second, we used a long-term nest monitoring data set in south San Francisco Bay (2005–2019) to evaluate changes in the abundance and distribution of nests of American Avocets, Black-necked Stilts, and Forster's Terns, both across south San Francisco Bay and at individual colony sites, over the past 15 years. Comparing the results of the waterbird population surveys in 2001 vs. 2019 throughout south San Francisco Bay—in combination with analyses of trends in annual nest abundance and distribution between 2005 and 2019—allowed us

to present a detailed assessment of changes to these breeding waterbird populations in south San Francisco Bay over the past 2 decades. Additionally, as pond habitat availability decreases with tidal marsh restoration, those ponds that remain will be critical to meeting the SBSP Restoration Project's goal of maintaining breeding populations of waterbirds. Thus, identifying pond characteristics that support higher breeding waterbird abundance and reproductive success may help with the selection of ponds for tidal marsh conversion, as well as management of remaining ponds. We therefore evaluated the relationship between the abundance of American Avocets, Black-necked Stilts, and Forster's Terns and pond characteristics, including size, shape, location, and salinity during the 2019 survey. Data supporting this manuscript is available as a USGS Data Release (Hartman and Ackerman 2021).

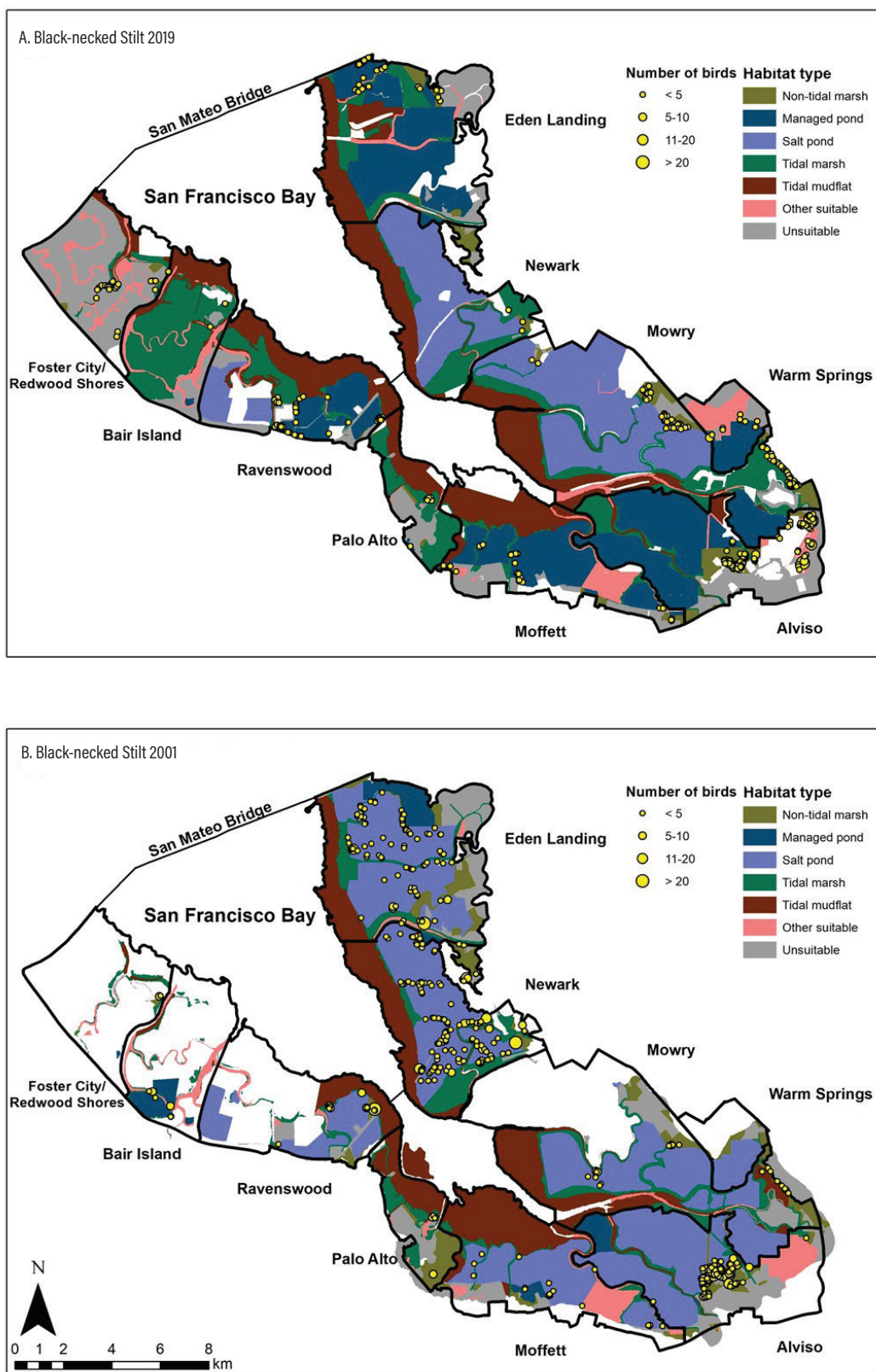
## METHODS

### Waterbird Population Survey

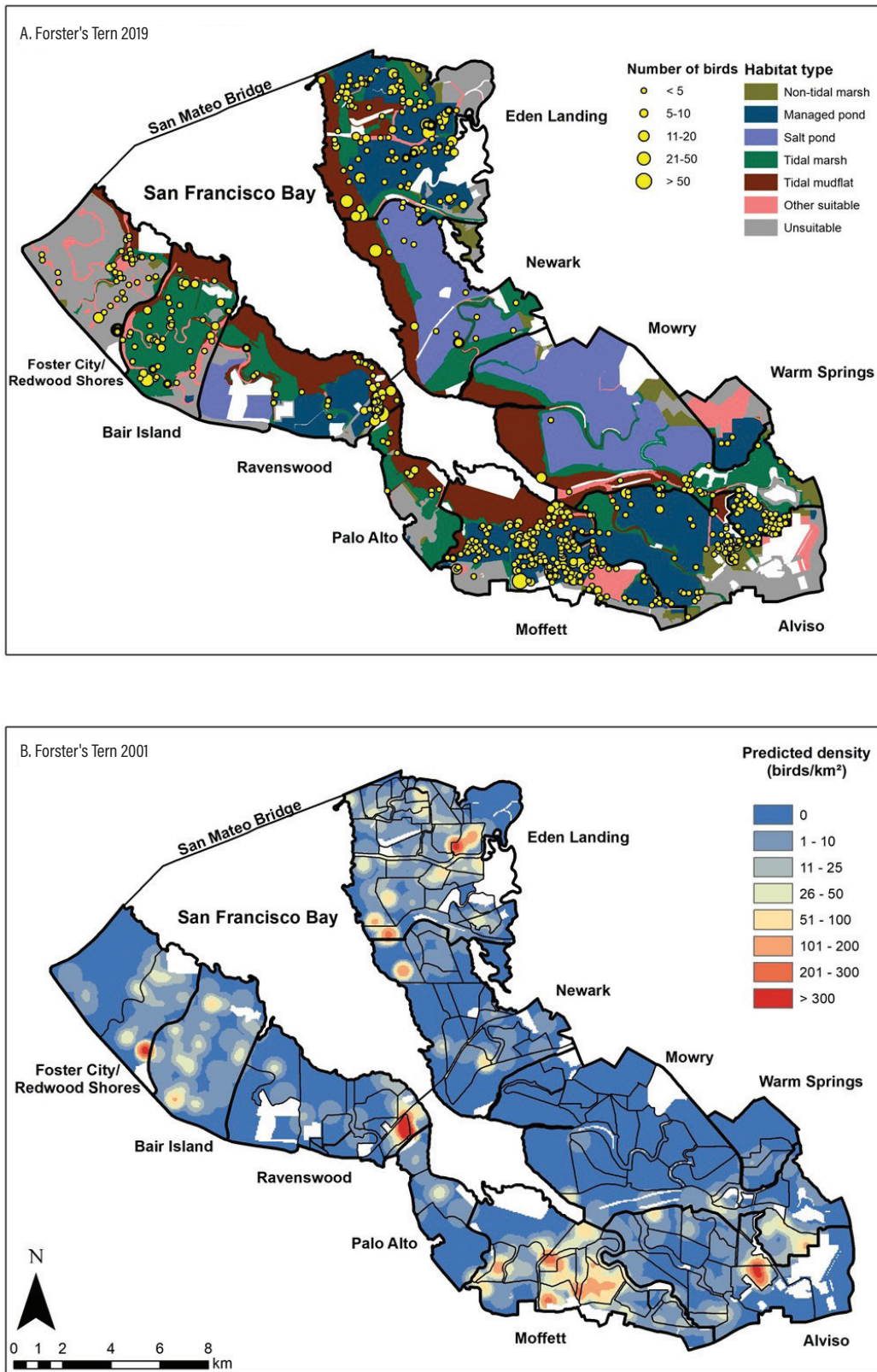
In 2019, we surveyed all accessible wetland habitat in San Francisco Bay south of the San Mateo Bridge (Figures 1–3). Importantly, the 2019 survey extent closely matched that of the original survey conducted in 2001 (Rintoul et al. 2003), allowing for direct comparison between years. We surveyed waterbirds over an 11-day period (May 14–24, 2019) equivalent to the 11-day period of the original 2001 survey (May 15–25, 2001; Rintoul et al. 2003). As with the original 2001 survey, we reduced the potential for double-counting birds by having multiple teams survey simultaneously during a short period of time. We divided the south San Francisco Bay survey area into complexes, many of which were based on existing complexes within the Don Edwards San Francisco Bay National Wildlife Refuge and Eden Landing Ecological Reserve (hereafter Eden Landing; Figures 1–3). We then further sub-divided complexes into individual survey units (Figures A1, A2), most of which could be completely surveyed in  $\leq 1$  day. Teams of 1 to 4 surveyors visited each unit, and by driving, walking, and/or boating, systematically surveyed the entire area using binoculars and 20x–60x



**Figure 1** American Avocet observations and habitat types in south San Francisco Bay during (A) 2019 and (B) 2001. Habitat classifications are based on data from the GIS layer (San Francisco Estuary Institute 1998), which we modified based on aerial imagery and habitat assessments made during the surveys. Areas in *white* were not surveyed in that year.



**Figure 2** Black-necked Stilt observations and habitat types in south San Francisco Bay during (A) 2019 and (B) 2001. Habitat classifications are based on data from the GIS layer (San Francisco Estuary Institute 1998), which we modified based on aerial imagery and habitat assessments made during the surveys. Areas in *white* were not surveyed in that year.



**Figure 3** Forster's Tern (A) observations and habitat types and (B) kernel density estimates during the 2019 population survey in south San Francisco Bay. Habitat classifications are based on data from the GIS layer (San Francisco Estuary Institute 1998), which we modified based on aerial imagery and habitat assessments made during the surveys. Areas in white were not surveyed in that year.

spotting scopes. Individual observations consisted of solitary birds or groups of birds of the same species, that were close together (individuals within ~2–3 m of each other), in the same habitat, and engaged in the same behavior. For each observation, we recorded the species, the number of individuals, location within the survey unit (plotted on a printed map of the unit), their behavior, and the main and micro-habitat types (see below). Although the main focal species of this study were American Avocets, Black-necked Stilts, and Forster's Terns, we also recorded any Caspian Terns, Black Skimmers, Elegant Terns, and California Least Terns observed. In addition, we recorded any potential predator of waterbird eggs or chicks (e.g., corvids, raptors, coyotes) and also estimated the number of gulls (the vast majority of which were California Gulls) within the survey unit.

Recorded bird behaviors included feeding, roosting, walking, swimming, flushing, or flying, and those confirming or suggesting breeding activity (nest-building, incubating, brooding chicks, alarm calling, breeding display, or predator distraction display). Individuals observed in transit flying high over a survey unit (flyovers) were recorded for population estimates but were not included in any habitat analyses. We used the total number of individuals that exhibited breeding behaviors as a measure of the minimum number of breeding birds of each species. Although there were no data for 2001, average nest initiation dates obtained from nest-monitoring efforts across south San Francisco Bay (see Nest Abundance Monitoring section below) showed no significant trend in the timing of breeding for American Avocets, Black-necked Stilts, or Forster's Terns between 2005 and 2019 (JT Ackerman, MP Herzog, CA Hartman, unreferenced; see "Notes"). Thus, using the number of individuals exhibiting breeding behaviors to estimate the minimum number of breeding birds in south San Francisco Bay likely was comparable between 2001 and 2019. The mid- to late-May survey period coincided with the peak nesting time for American Avocets and Black-necked Stilts in south San Francisco Bay but was a few weeks before the peak nesting time for Forster's Terns (Ackerman and Herzog 2012).

Thus, the minimum number of breeding Forster's Terns was underestimated.

Each individual survey unit was categorized into one of several main habitat categories: (1) managed pond, (2) active salt pond, (3) sewage/holding pond, (4) tidal marsh, (5) non-tidal marsh, (6) tidal mudflat, and (7) other wetland habitat (vernal pools, channels, and man-made waterways). In addition, we recorded the micro-habitat in the immediate vicinity of each individual observation. Habitat and micro-habitat definitions are presented in [Table 1](#). Where data were available (recorded during nest monitoring or other pond surveys), ponds were classified as having salinity levels that were relatively low (<60 ppt), medium (60 ppt to 120 ppt), or high (>120 ppt). We also noted whether tidal habitat (marshes and mudflats) occurred within sloughs, within restored ponds (former salt ponds that were opened to tidal action), or along the margins of San Francisco Bay. Observations were instantaneous (Altmann 1974), in that we recorded the behavior, habitat, micro-habitat, and location when we first saw the bird(s), even if they subsequently changed. There were two exceptions:

1. If birds changed from a non-breeding behavior to a breeding behavior, we recorded both behaviors to ensure that we captured potential evidence of breeding.
2. If birds were originally observed in flight, then landed and began another behavior, such as feeding, we recorded the second behavior because it was specific to the habitat.

During surveys, we recorded the habitat types present, which were later used to ground-truth habitat data used for mapping and analysis (see below), and we noted on unit maps any areas that we were not able to survey (because of limitations of access or visibility).

We entered all spatial data (locations of observed birds, habitat mapping, and areas not surveyed) into a geographic information system (GIS; ArcMap 10.6.1; Environmental Research Systems



**Table 1** Definitions of main habitats (primary habitat of each survey unit) and micro-habitats (immediate vicinity of the observation) used during waterbird surveys in south San Francisco Bay in 2019. The 2001 survey (Rintoul et al. 2003) used slightly different habitat categories, but we adjusted their habitat data to match the habitat definitions we used in the 2019 survey.

Habitat	Definition
<b>Main habitats</b>	
Managed pond	Pond that may or may not have been used for salt production in the past, but is currently managed for other purposes
Salt pond	Pond currently used for salt production
Sewage/holding pond	Ponds used as water treatment or retention basins
Tidal marsh	Vegetated wetland that is open to the bay and has tidal influence
Non-tidal marsh	Vegetated wetland with no or very limited tidal influence
Tidal mudflat	Non-vegetated wetland of the bay that is exposed at low tide <sup>a</sup>
Other wetland	Includes open water in the bay <sup>a</sup> , deep channels within sloughs <sup>a</sup> , artificial lakes and canals, and vernal pools <sup>b</sup>
<b>Micro-habitats</b>	
Channel	Channel or small slough
Dry pond bottom	Dry pond bottom
Island	Dry island substrate >15cm from the water's edge
Island shoreline	In the water ≤3m from an island or on dry ground on an island ≤15cm from the water's edge
Levee	Top or side of a levee or dike
Levee island	Dry levee that has been cut to form an island >15cm from the water's edge
Levee island shoreline	In the water ≤3m from a levee island or on dry ground on a levee island ≤15cm from the water's edge
Mainland shoreline	In the water ≤3m from mainland or on dry ground on mainland ≤15cm from the water's edge
Wet bare ground	Wet bare ground or shallow water <10cm deep in any of the main habitat types
Structure	Artificial structure (e.g., wooden duck blind, boardwalk, post)
Vegetated marsh	Within or ≤3m from a vegetated area
Water	Open water >10cm deep

a. Final habitat determination based on classification in the 1998 GIS habitat layer (using mean tide levels; San Francisco Estuary Institute 1998).

b. Occurred only in the Warm Springs survey complex.

Institute, Redlands, California) for mapping and spatial analysis. Mapping of available habitat was based on a published data layer (San Francisco Estuary Institute 1998), updated based on current aerial imagery and our own habitat assessments made in the field during the 2019 survey. We also revised the habitat categories in the published data layer (San Francisco Estuary Institute 1998) to match the habitats we used for our field protocol (Table 1).

### Nest Abundance Monitoring

We monitored American Avocet, Black-necked Stilt, and Forster's Tern nests in San Francisco Bay south of the San Mateo Bridge annually during 2005–2019. All three species are single brooded,

may lay a replacement clutch if the first clutch fails, and have biparental incubation of eggs and care of young chicks (Ackerman et al. 2020; McNicholl et al. 2020; Robinson et al. 2020). To standardize effort among years, we monitored the main wetland complexes that support the vast majority of nesting waterbirds including: Ravenswood, Moffett, West Alviso, Central Alviso, Newark, and Eden Landing wetland complexes (Figure A1). We accessed each colony nesting site weekly from April through August each year, marked individual nests, and followed the fate of each nest until failure or hatch (detailed methods available in Ackerman 2014c; Hartman et al. 2016b). From these visits, we estimated the number of nests of each species observed each

year at each colony site. However, because of time and logistical constraints, and the large study area, we were unable to visit all of the smaller colony sites weekly during every year of the 15-year study. Thus, we preferentially targeted the largest and historically used colony sites based on previous colony monitoring efforts (Strong et al. 2004) for weekly nest monitoring. At sites where we did not monitor weekly, and sites in which the number of nests was far greater than could be monitored during weekly visits, we instead estimated the number of nests of each species in each year from one or more nest surveys conducted during the peak of the breeding season. These surveys consisted of either a walk-through survey, where individual nests were counted, or observational surveys, where nests were counted from a surrounding levee using binoculars and spotting scopes (most nests are on islands that are sparsely vegetated; Ackerman et al. 2014c). We then summed the number of nests across sites to estimate the annual number of nests of each species across the study area.

### **Statistical Analysis: Waterbird Survey**

To examine changes in abundance and distribution of birds over time, we used the raw data from the 2001 survey reported in Rintoul et al. (2003), which we re-processed using our modified behavior and habitat definitions (therefore the final numbers for 2001 presented in this paper differ slightly from those presented in their 2003 publication). The 2001 habitat data layer used by Rintoul et al. (2003) was not available; therefore, we mapped available habitat in 2001 using the same procedure we used for the 2019 data: updating the 1998 habitat layer (San Francisco Estuary Institute 1998) based on habitat assessments recorded during the 2001 survey, and resolving any ambiguous areas using historical aerial images (Google Earth Pro 7.3.2.5776 2019) taken as close as possible to the time of the 2001 survey.

Unless otherwise noted, all maps and tables contain data based on the total area surveyed in each year (2001 or 2019). However, for the comparative analyses, we restricted data to only those areas that were surveyed in both

years (we surveyed approximately 37.8 km<sup>2</sup> more suitable habitat in 2019). For each species separately, we performed chi-square tests to compare the observed distribution of birds (1) across wetland complexes and (2) across habitat types to the expected distribution of birds if they were distributed across complexes or habitats according to their availability. For the habitat type chi-square test, we evaluated waterbird use among five habitat categories: ponds (includes managed ponds, salt production ponds, and sewage/holding ponds), non-tidal marsh, tidal marsh, tidal mudflat, and other wetland (includes open water of San Francisco Bay, man-made waterways, channels, and vernal pools). Unsuitable habitats (e.g., urban areas, grasslands, landfills) were excluded from analyses. A wetland complex or habitat type was considered important to a species if it was used in a greater proportion than would be expected from its availability alone. We also used separate chi-square tests for each species to compare American Avocet and Black-necked Stilt distributions between years (2001 vs. 2019) among wetland complexes and habitats. Chi-square tests assumed that individuals selected locations independently of the presence of other individuals, and thus p-values should be interpreted with this assumption.

We used ArcMap to create kernel density surfaces for each species in each year (raster cell size: 50 m, search radius: 500 m, each observation point weighted based on the number of birds that were counted at that point). To investigate changes in densities between the 2001 and 2019 surveys across south San Francisco Bay, we subtracted the value of each cell in the 2019 kernel density raster by the value in the corresponding cell in the 2001 kernel density raster (limited to the area surveyed in both years). We also used the kernel density surfaces to identify “hotspots,” or high bird density areas. Kernel density estimates were not adjusted by habitat type and are meant to highlight, at a large scale, areas of high and low density across south San Francisco Bay. For this analysis, we defined hotspots as 50-m cells in the kernel density raster containing the top 20% of density estimates.

Ponds (especially managed ponds and salt ponds) make up a large proportion of the habitat available to waterbirds in south San Francisco Bay. We used generalized linear models in R (R Core Team 2014) to look more specifically at landscape-level factors that might influence the distribution and abundance of American Avocets, Black-necked Stilts, and Forster's Terns in pond habitat. Specifically, we tested the effects of pond type (active salt ponds or managed ponds), pond area, pond shape, pond distance to San Francisco Bay (measured to the nearest pond edge), tide level, salinity, gull abundance, and whether the pond contained islands or not. Mean tide level (m) data were obtained from the Redwood City Station (<https://tidesandcurrents.noaa.gov/>). Tide level was included to account for the fact that as tide level increases, more tidal mudflat and tidal marsh would be unavailable, potentially increasing use of non-tidal pond habitat. For each pond, we used the mean tide level recorded at the beginning of the survey, unless it took more than 4 hours to completely survey a pond, in which case we used an average of the mean tide level at the beginning of the survey and the end of the survey. Ponds were categorized as low salinity (< 60 ppt), medium salinity (60 ppt–120 ppt), or high salinity (>120 ppt) using existing US Geological Survey and San Francisco Bay Bird Observatory salinity monitoring data. Salinity categories for some active salt ponds were provided by Cargill, Inc. We quantified pond shape using a pond shape index:

$$\text{Pond shape index} = \frac{0.2 \times \text{Pond perimeter (m)}}{\sqrt{\text{Pond area (m}^2\text{)}}}, \quad (1)$$

where a larger pond shape index indicates a pond with more shoreline relative to the pond's size (McGarigal 2014). We tested the effects of pond characteristics separately for American Avocets, Black-necked Stilts, and Forster's Terns, and included the abundance of the two other species within each pond as covariates, as the presence of heterospecifics could potentially attract or repel birds. For example, the final model structure for Forster's Terns was: *Number of Forster's terns* = *pond type* + *pond area* + *pond shape index* + *distance to San Francisco Bay* + *tide level* + *salinity* + *gull*

*abundance* + *islands* (yes or no) + *number of American Avocets* + *number of Black-necked Stilts*. We used a negative binomial distribution for over-dispersed count data (Zuur et al. 2009). We considered using a zero-inflated negative binomial model (many survey units contained zero birds), but good visibility during this survey (areas with poor visibility were excluded) and conspicuous study species meant that zeroes were likely to represent a genuine absence of birds, rather than an issue of detectability. Moreover, preliminary model comparisons showed no improvement in model fit when using zero-inflated negative binomial models vs. standard negative binomial models. We used a pseudo  $R^2$  [ $1 - (\text{residual deviance} / \text{null deviance})$ ] to assess the fit of each model compared to the null model.

#### **Statistical Analysis: Nest Abundance Monitoring**

We used separate generalized linear models (negative binomial distribution for over-dispersed count data) to analyze trends in nest abundance for American Avocets, Black-necked Stilts, and Forster's Terns in south San Francisco Bay during the 15-year study period, 2005–2019. For each species, we evaluated linear and quadratic relationships of year with nest abundance and used pseudo  $R^2$  to select the relationship with greater model fit. Additionally, we evaluated changes in the number of major colony sites (specific ponds, marshes, or other survey units) of each species during the study period. Major colony sites were defined as those sites that supported greater than or equal to the median number of nests for each species among all sites and years of the study, and corresponded to  $\geq 12$  American Avocet nests,  $\geq 6$  Black-necked Stilt nests, and  $\geq 40$  Forster's Tern nests. We used separate generalized linear models to evaluate trends in nest abundance at each site that historically supported a major colony during at least 3 years over the 15-year study period. We also evaluated trends at any colony site that was established during the last 5 years of the study (2015–2019), as long as it was a major colony site during at least 1 of those years.

## RESULTS

### Waterbird Survey: Population Status

Nineteen observers surveyed for a total of 239.9 hours in 2019 (the total survey effort was 392.6 observer hours, including simultaneous observer survey hours when teams were >1 observer), covering 221.4 km of suitable habitat within south San Francisco Bay. During this period, we counted a total of 2,391 American Avocets, 828 Black-necked Stilts, 2,675 Forster’s Terns, 440 Caspian Terns, 59 Black Skimmers, nine Elegant Terns, and two Least Terns. Among American Avocets observed, 44.4% were feeding, 37.2% were engaged in other non-breeding behaviors, (roosting, walking, flying, etc.) and 18.4% (440 birds) were engaged in breeding behaviors. Among Black-necked Stilts observed, 61.5% were feeding, 17.3% were engaged in other non-breeding behaviors, and 21.3% (176 birds) were engaged in breeding behaviors. Finally, among Forster’s Terns observed, 54.4% were feeding, 35.7% were engaged in other non-breeding behaviors, and 9.9% (266 birds) were engaged in breeding behaviors. We also observed 107 American Avocet chicks, 66 Black-necked Stilt chicks, and three Caspian Tern chicks.

Compared to the 2001 survey, we observed a 13.5% decrease in the number of American Avocets, with a 57.2% decrease in confirmed or suspected breeders, and a 30.0% decrease in the number of Black-necked Stilts, with a 52.0% decrease in confirmed or suspected breeders in 2019 (Table 2). Although we surveyed more total area in 2019 (221.4 km<sup>2</sup>) than was surveyed in 2001 (183.6 km<sup>2</sup>),

there were some areas surveyed in 2001 that we were not able to survey in 2019. In 2019, a total of 143 American Avocets and 94 Black-necked Stilts were observed in areas not surveyed in 2001, whereas in 2001, 204 American Avocets and 34 Black-necked Stilts were observed in areas not surveyed in 2019. Examining only birds observed in the area surveyed in both years (170 km<sup>2</sup> of suitable habitat), we found an 11.1% decrease in American Avocets, with a 56.2% decrease in confirmed or suspected breeders, and a 35.1% decrease in Black-necked Stilts, with a 55.9% decrease in confirmed or suspected breeders in 2019 (Table 2).

### Waterbird Survey: Waterbird Distribution

In 2019, American Avocets ( $\chi^2_9 = 1,278.6, p < 0.001$ , Figure 1A), Black-necked Stilts ( $\chi^2_9 = 896.6, p < 0.001$ , Figure 2A), and Forster’s Terns ( $\chi^2_9 = 1,884.3, p < 0.001$ , Figure 3A) were not randomly distributed among survey complexes. All three species used the Bair Island, Newark, and Palo Alto complexes less than would be expected based on availability of suitable habitat (Table 3A). American Avocet abundance was greater than expected in Alviso, Eden Landing, Mowry, Ravenswood, and Warm Springs (Table 3A), and high-density areas were observed in northern Eden Landing, Ravenswood, Warm Springs, and around Alviso’s New Chicago Marsh (Figure 4A). Black-necked Stilt abundance was greater than expected in Alviso, Foster City/Redwood Shores, and Mowry (Table 3A), and high-density areas were observed in Mowry, Warm Springs, and Alviso’s New Chicago Marsh

**Table 2** Number of American Avocets, Black Necked stilts, and Forster’s Terns counted during 2001 and 2019 surveys across South San Francisco Bay, California and the percent population change between survey years

	American Avocet			Black-necked Stilt			Forster’s Tern	
	2001	2019	% change	2001	2019	% change	2001 <sup>e</sup>	2019
Total birds in survey area for that year <sup>a</sup>	2765	2391	- 13.5%	1184	828	- 30.0%	NA	2675
Total breeding birds in survey area for that year <sup>b</sup>	1028	440	- 57.2%	367	176	- 52.0%	NA	266
Total birds in areas surveyed in both years <sup>c</sup>	2538	2256	- 11.1%	1136	737	- 35.1%	NA	2504
Total breeding birds in areas surveyed in both years <sup>d</sup>	936	410	- 56.2%	354	156	- 55.9%	NA	264

- a. Total number of birds counted across the full survey area for that year.
- b. Total number of birds counted across the full survey area for that year that were exhibiting breeding behaviors (see text for details).
- c. Total number of birds counted across the common area surveyed during both years.
- d. Total number of birds counted across the common area surveyed during both years that were exhibiting breeding behaviors (see text for details).
- e. Forster’s terns were not surveyed in 2001.

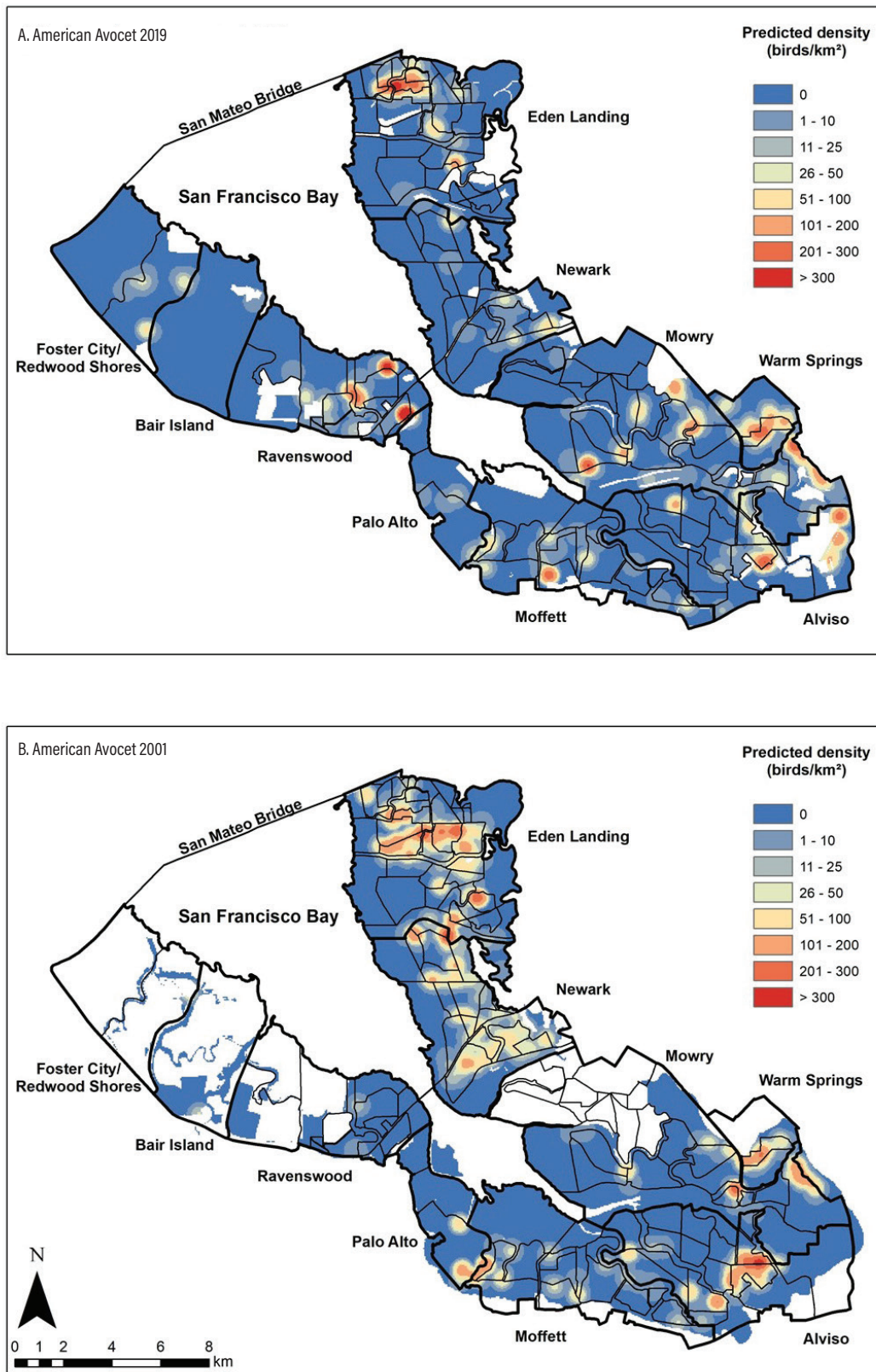
(Figure 5A). Finally, Forster's Tern abundance was greater than expected in Eden Landing, Foster City/Redwood Shores, Moffett, and Ravenswood (Table 3A), and high-density areas were observed in Eden Landing, Moffett, Ravenswood's Pond SF2, Redwood Shores, and Alviso's New Chicago Marsh (Figure 3B).

American Avocet ( $\chi^2_9 = 1,174.9$ ,  $p < 0.001$ , Figure 1) and Black-necked Stilt ( $\chi^2_9 = 496.5$ ,  $p < 0.001$ , Figure 2) distributions among complexes in south San Francisco Bay have changed significantly between 2001 and 2019. Both species showed decreased use of Eden Landing and Newark, and greater use of Foster City/Redwood Shores,

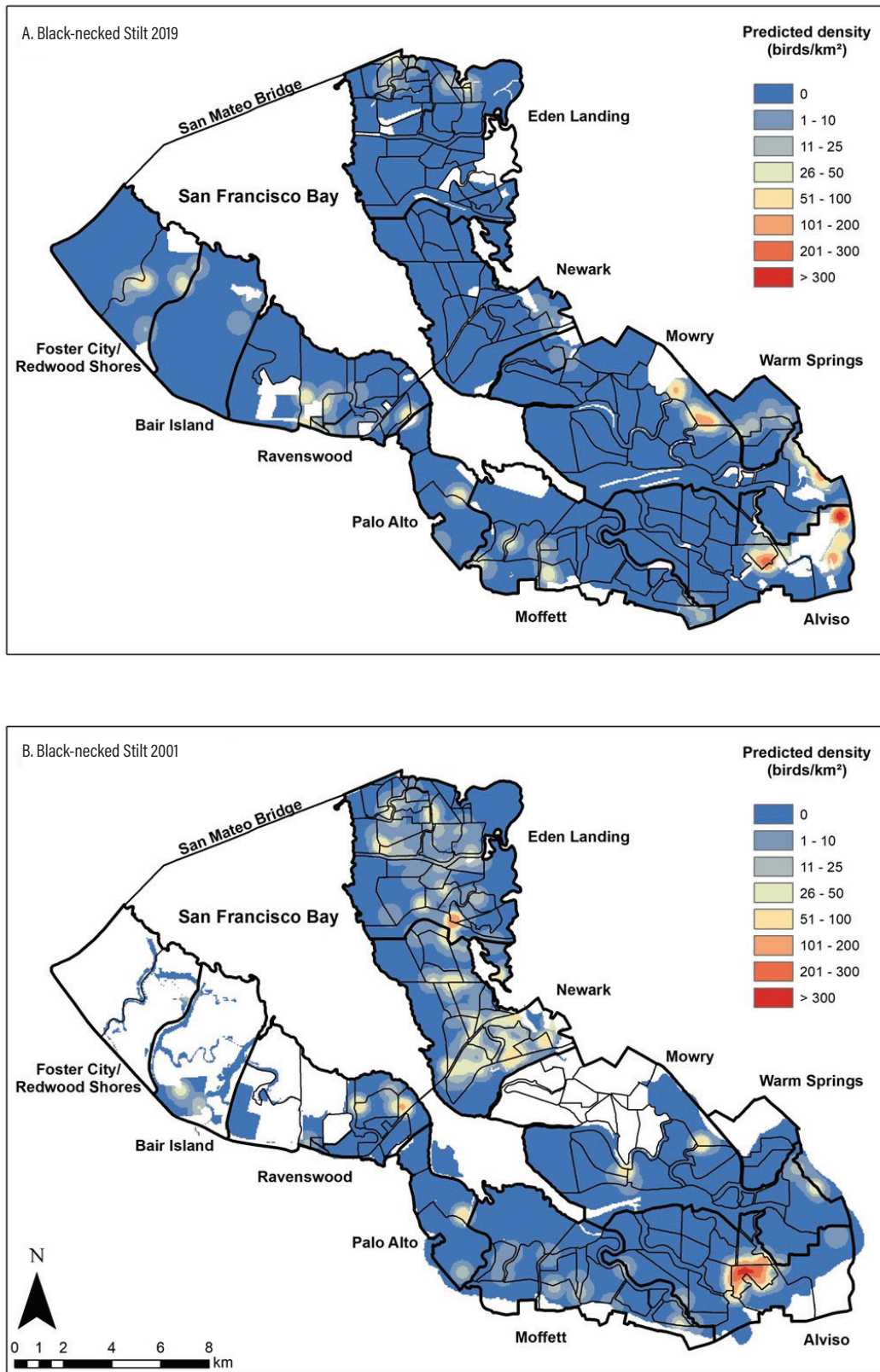
Mowry, Ravenswood, and Warm Springs in 2019 compared to 2001 (Table 3A). There also was less area of moderate to high densities (25 to  $> 300$  birds  $\text{km}^{-2}$ ) in 2019 compared to 2001, most notably in southern Eden Landing and Newark (Figures 4 and 5). American Avocet and Black-necked Stilt densities have decreased in southern Eden Landing and Newark, and increased in northern Eden Landing, and parts of Moffett, Mowry, Warm Springs, and Ravenswood (Figure 6). Densities of both species decreased sharply in Alviso Pond A16 and the northern part of New Chicago Marsh but increased in the southern part of New Chicago Marsh (Figure 6).

**Table 3** Distribution of American Avocets, Black-necked Stilts, and Forster's Terns according to (A) complex and (B) habitat type during 2019 and 2001 population surveys in south San Francisco Bay, shown as the percent of birds observed within (A) each complex and (B) habitat type compared to the percent of birds expected based on the available area surveyed within each complex or habitat type. For (A) only areas of suitable habitat were included to calculate expected values. For (B) 34 American Avocets, 9 Black-necked Stilts and 183 Forster's Terns observed as flyovers in 2019 were excluded as we could not associate them with a particular habitat type.

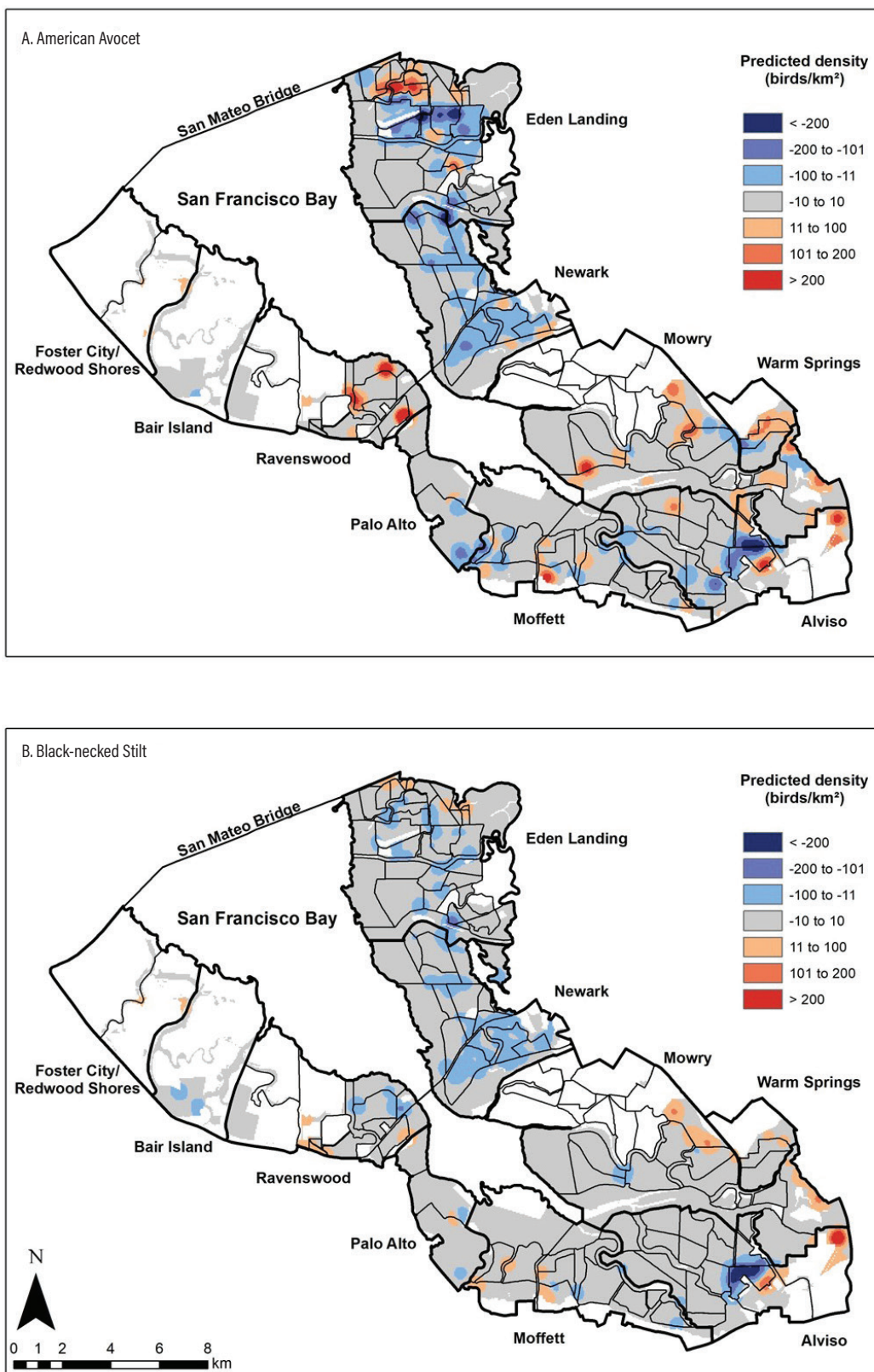
	2019 observed			2019 expected	2001 observed		2001 expected
	American Avocet (n = 2391)	Black-necked Stilt (n = 828)	Forster's Tern (n = 2675)		American Avocet (n = 2765)	Black-necked Stilt (n = 1184)	
<b>A</b>							
Alviso	16.9	39.5	10.3	10.9	17.3	33.2	13.8
Bair Island	0.1	0.4	6.2	8.4	0.3	1.9	3.0
Eden Landing	18.8	6.5	21.2	14.5	37.0	19.6	19.0
Foster City/Redwood Shores	1.8	6.4	6.6	2.6	0.5	0.6	0.9
Moffett	6.8	6.4	30.4	10.8	6.5	2.8	14.1
Mowry	24.2	25.6	6.0	22.0	9.9	5.8	19.5
Newark	2.6	0.7	3.8	13.9	20.3	29.1	16.2
Palo Alto	0.5	2.2	0.9	3.7	2.4	1.9	4.7
Ravenswood	18.2	9.5	14.4	10.5	0.2	5.2	6.8
Warm Springs	10.2	2.8	0.1	2.7	5.6	0	2.0
<b>B</b>							
Bay	0	0	< 0.1	0.2	0	0	< 0.1
Channel	1.0	0.2	4.0	3.1	0.3	0.4	2.5
Man-made waterway	0.3	0.5	1.8	0.9	0	0	0.2
Managed pond	53.9	38.6	65.6	25.8	3.1	2.2	4.2
Non-tidal marsh	11.5	36.8	6.9	3.8	13.6	38.0	7.0
Salt pond	8.1	0.6	1.7	20.6	74.8	48.0	48.5
Sewage/holding pond	4.7	12.0	0.2	1.5	0.6	0.9	2.8
Tidal marsh	8.5	9.4	5.9	21.3	2.7	10.3	13.2
Tidal mudflat	9.9	0.9	13.9	21.6	4.8	0.2	21.6
Vernal pool	2.0	1.1	0	1.2	0	0	0



**Figure 4** American Avocet kernel density estimates in south San Francisco Bay in (A) 2019 and (B) 2001. Areas in *white* were not surveyed in that year.

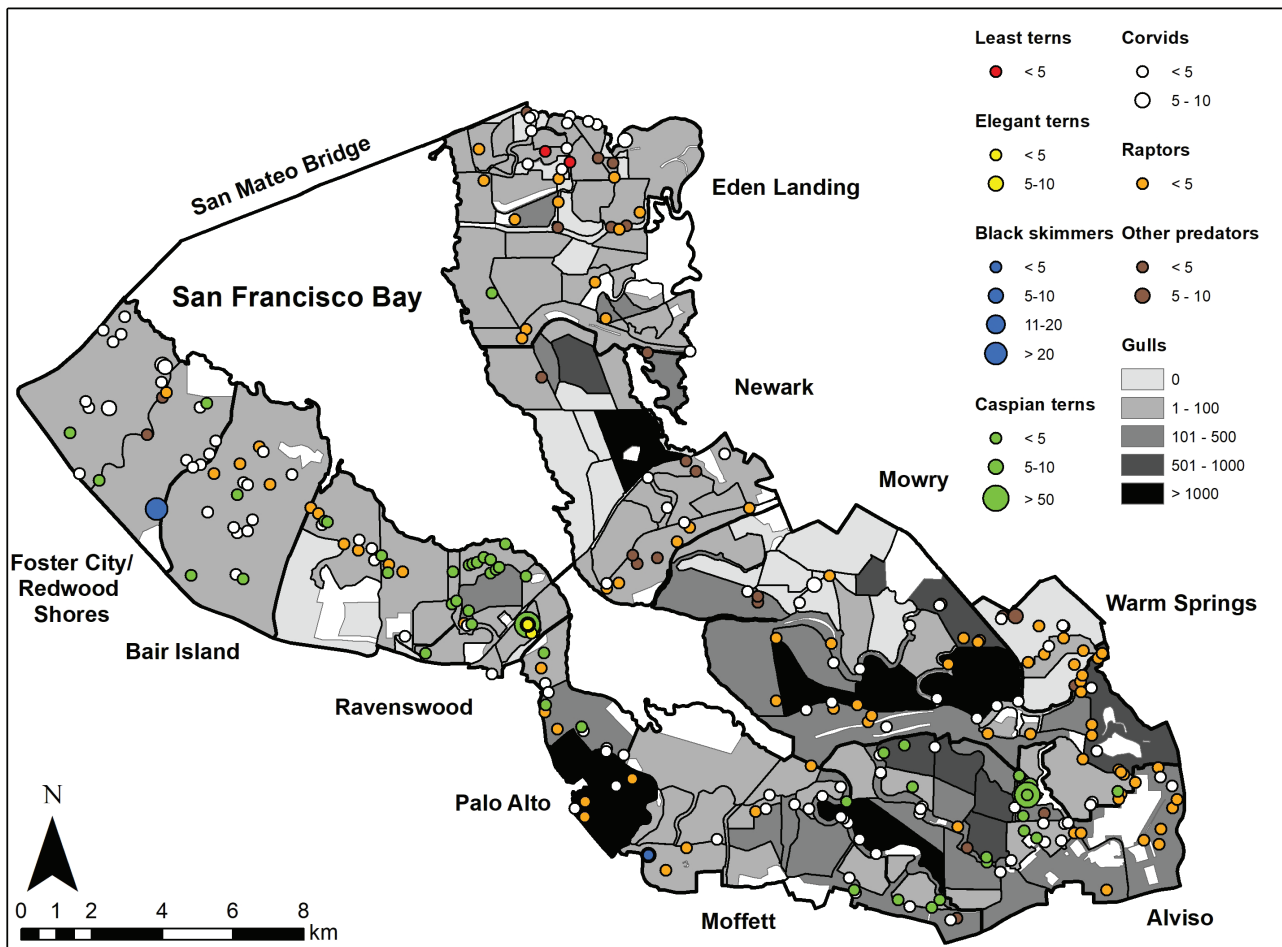


**Figure 5** Black-necked Stilt kernel density estimates in south San Francisco Bay in (A) 2019 and (B) 2001. Areas in *white* were not surveyed in that year.



**Figure 6** Changes in kernel density estimates for (A) American Avocets and (B) Black-necked Stilts in south San Francisco Bay between the 2001 and 2019 surveys. *Darker blue* colors indicate declining abundance whereas *darker red* colors indicate an increase in abundance from 2001 to 2019. Areas in *white* were not estimated because they were not surveyed in one or both years.





**Figure 7** Distribution of Least Terns, Elegant Terns, Black Skimmers, Caspian Terns, corvids, raptors, other predators (foxes, coyotes, and turkey vultures), and gulls in south San Francisco Bay in 2019. Gulls were too numerous to map individually and, instead are represented by shading each survey unit according to the total count of gulls in each survey unit (*light gray* denotes fewer gulls, *dark gray* indicates more gulls).

Two Least Terns were observed in northern Eden Landing (they later nested at Eden Landing Pond E14), Elegant Terns were observed nesting at Ravenswood Pond SF2 (nine nests), Black Skimmers were observed in Foster City/Redwood Shores and Moffett (they later nested at Redwood Shores, Alviso Pond A16, and Ravenswood Pond SF2), and Caspian Terns were observed primarily around their colony nesting sites in Alviso Pond A16 and Ravenswood Pond SF2 (Figure 7). Corvids, gulls, and raptors were observed throughout the study area, although the greatest concentrations of gulls were observed around California Gull nesting colonies in Alviso, Mowry, Newark, and Palo Alto (Figure 7).

**Waterbird Survey: Habitat Use**

In 2019, the majority of all waterbirds surveyed (American Avocets, Black-necked Stilts, Forster’s Terns, Caspian Terns, Elegant Terns, Least Terns, and Black Skimmers) were observed in managed ponds (59.6%), followed by non-tidal marsh (12.1%), tidal mudflat (9.8%), and tidal marsh (7.0%). Managed pond habitat accounted for the majority of American Avocet (53.9%) and Forster’s Tern (65.6%) observations in 2019, whereas Black-necked Stilt observations occurred primarily in both managed ponds (38.6%) and non-tidal marshes (36.8%; Table 3B). Sloughs are an integral part of the landscape in south San Francisco Bay. However, because they comprise the main habitats (tidal mudflat, tidal marsh, and open

water), we did not consider them as a separate main habitat. Nevertheless, we evaluated how breeding waterbirds were using sloughs relative to their availability (10.5% of the suitable habitat) and found that sloughs accounted for 7.3% of American Avocets, 4.6% of Black-necked Stilts, and 6.2% of Forster's Terns observed. Restored ponds, which are in transition to tidal marsh and tidal mudflat, comprised 9.4% of available habitat, and contained 2.6% of American Avocets, 2.7% of Black-necked Stilts, and 5.0% of Forster's Terns observed.

In 2019, American Avocets ( $\chi^2_4 = 881.8$ ,  $p < 0.001$ ), Black-necked Stilts ( $\chi^2_4 = 2,546.5$ ,  $p < 0.001$ ), and Forster's Terns ( $\chi^2_4 = 609.7$ ,  $p < 0.001$ ) were not randomly distributed among habitat types (Table 3B). American Avocet, Black-necked Stilt, and Forster's Tern abundances were all greater in ponds (includes managed ponds, salt ponds, and sewage/holding ponds) and non-tidal marshes, and lower in tidal marshes and tidal mudflats than would be expected based on availability (Table 3B). Black-necked Stilts showed a much stronger preference for non-tidal marshes (contributing 91% of the overall  $\chi^2$  value) than American Avocets (41% of overall  $\chi^2$  value) and Forster's Terns (10% of overall  $\chi^2$  value), and a weaker preference for ponds. When only birds engaged in breeding behaviors were considered, results were similar, but all three species exhibited similar strength in preference for non-tidal marsh, and only American Avocets and Forster's Terns showed a preference for ponds.

Using data from areas surveyed in both 2001 and 2019, American Avocet habitat use changed significantly ( $\chi^2_4 = 172.5$ ,  $p < 0.001$ ). There was a large increase in use of tidal mudflats (+74%) and tidal marshes (+155%) and decreases in use of ponds (-24%) and non-tidal marshes (-29%). This analysis does not take into account habitat availability, so some of these changes likely reflect habitat changes between surveys (e.g., ponds transformed into tidal habitat). However, the magnitude of the change in use was, with the exception of non-tidal marshes, greater than the magnitude of changes in habitat availability (tidal mudflats: +3%, tidal marshes: +43%, ponds:

-10%, non-tidal marshes: -29%). Unlike American Avocets, Black-necked Stilts did not show a significant change in habitat use between 2001 and 2019 ( $\chi^2_4 = 8.79$ ,  $p = 0.067$ ).

Micro-habitat use varied by species and main habitat type (Table A1). Within managed ponds, American Avocets and Black-necked Stilts were primarily observed on wet bare ground (40.3% and 46.8%, respectively) and along mainland shorelines (17.3% and 31.3%, respectively), while Forster's Terns were mostly observed foraging over water (47.5%) or roosting on structures (20.7%) and islands (17.6%; Table A1). Micro-habitat use within salt ponds was similar to managed ponds, but with greater American Avocet presence on islands (37.2% in salt ponds, 9.4% in managed ponds), greater Black-necked Stilt presence on island shoreline (40.0% in salt ponds, 0.9% in managed ponds), and greater Forster's Tern presence on levee islands within salt ponds than managed ponds (57.1% in salt ponds, 0.6% in managed ponds). In non-tidal marsh, American Avocets and Black-necked Stilts were primarily observed on wet bare ground (56.5% and 33.9%, respectively) and in vegetated micro-habitats (19.6% and 45.2% respectively), and Forster's Terns were mostly observed in vegetated micro-habitats (63.0%) and on structures (15.6%). In tidal marsh, American Avocets and Black-necked Stilts were mostly observed on wet bare ground (60.7% and 24.7%, respectively), along mainland shoreline (13.9% and 36.4%, respectively), and in vegetated micro-habitats (17.4% and 36.4%, respectively), while Forster's Terns were mostly observed over water (54.4%) and in channels (32.0%). Interestingly, Forster's Terns were observed in vegetated habitat much more in non-tidal marshes (63%) than in tidal marshes (1.4%). This difference is almost entirely due to high tern use of New Chicago Marsh (a non-tidal marsh that contained a breeding colony of 200 Forster's Tern nests in 2019), where 85% of the 109 Forster's Terns we observed in vegetated micro-habitat were incubating nests. Finally, within tidal mudflat habitat, American Avocets were primarily observed on wet bare ground (87%), Black-necked Stilts ( $n = 7$ ) were found exclusively on the mainland shoreline (100%), and

Forster's Terns were mostly observed over open water (60.1%) and roosting on wet bare ground (28.3%).

### Factors Affecting Waterbird Use of Pond Habitat

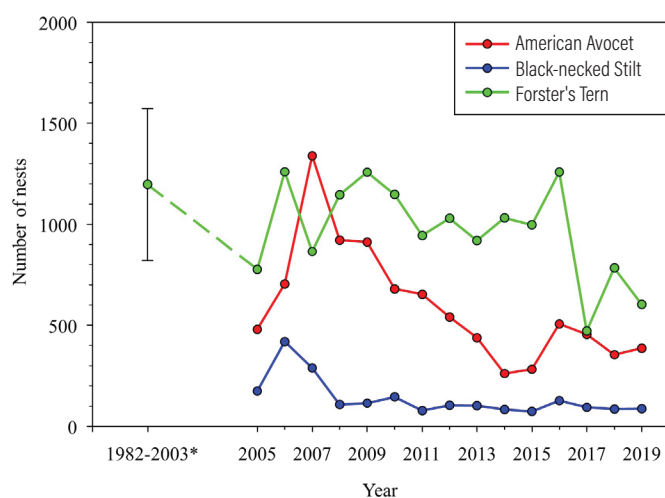
The number of American Avocets, Black-necked Stilts, and Forster's Terns observed within each individual pond unit ( $n = 89$ ) during the 2019 waterbird survey is provided in Table A2, and a map showing pond locations is provided in Figure A1. However, we lacked sufficient salinity data for nine ponds, and tide level data for an additional pond that was surveyed over multiple days, leaving 79 ponds available for this analysis. The American Avocet model (pseudo  $R^2 = 0.40$ ) showed that avocet abundance was greater in managed ponds than in salt ponds ( $z = 2.21$ ,  $p = 0.03$ ), was greater in ponds of medium salinity (60–120 ppt) than low salinity (< 60 ppt;  $z = 2.40$ ,  $p = 0.04$ ) and high salinity (> 120 ppt;  $z = 3.81$ ,  $p < 0.001$ ), was greater in ponds where islands were present ( $z = 2.91$ ,  $p < 0.01$ ), and increased with increasing abundance of Black-necked Stilts ( $z = 2.22$ ,  $p = 0.03$ ). There was no effect of pond area ( $z = 1.78$ ,  $p = 0.07$ ), pond shape ( $z = 0.71$ ,  $p = 0.48$ ), distance to San Francisco Bay ( $z = 0.46$ ,  $p = 0.65$ ), tide level ( $z = 1.12$ ,  $p = 0.26$ ), gull abundance ( $z = 1.25$ ,  $p = 0.21$ ), or Forster's Tern abundance ( $z = 0.21$ ,  $p = 0.83$ ) on American Avocet abundance in ponds.

The Forster's Tern model (pseudo  $R^2 = 0.68$ ) showed that tern abundance was higher in managed ponds than in salt ponds ( $z = 4.45$ ,  $p < 0.001$ ), increased with pond area ( $z = 3.14$ ,  $p < 0.01$ ), and decreased with gull abundance ( $z = 2.97$ ,  $p < 0.01$ ) and distance to San Francisco Bay ( $z = 2.73$ ,  $p < 0.01$ ). Forster's Tern abundance increased as salinity decreased (low salinity (< 60 ppt) > medium salinity (60–120 ppt):  $z = 2.91$ ,  $p < 0.01$ ; medium salinity > high salinity (> 120 ppt):  $z = 2.51$ ,  $p = 0.03$ ). There was no effect of pond shape ( $z = 0.45$ ,  $p = 0.65$ ), tide level ( $z = 1.38$ ,  $p = 0.17$ ), presence of islands ( $z = 1.23$ ,  $p = 0.22$ ), American Avocet abundance ( $z = 0.30$ ,  $p = 0.76$ ), or Black-necked Stilt abundance ( $z = 1.25$ ,  $p = 0.18$ ) on Forster's Tern abundance in ponds.

Because a majority of Black-necked Stilts were found in ponds of unknown salinity, we removed the salinity factor from the model and analyzed Black-necked Stilt abundance among 88 ponds. The Black-necked Stilt model (pseudo  $R^2 = 0.43$ ) showed that stilt abundance was higher in managed ponds than in salt ponds ( $z = 3.30$ ,  $p < 0.001$ ), increased with pond area ( $z = 2.62$ ,  $p < 0.01$ ) and tide level ( $z = 3.07$ ,  $p < 0.01$ ), and decreased with gull abundance ( $z = 2.53$ ,  $p = 0.01$ ). There was no effect of pond shape ( $z = 0.67$ ,  $p = 0.50$ ), distance to San Francisco Bay ( $z = 0.96$ ,  $p = 0.34$ ), presence of islands ( $z = 0.57$ ,  $p = 0.57$ ), Forster's Tern abundance ( $z = 1.28$ ,  $p = 0.20$ ) or American Avocet abundance ( $z = 0.10$ ,  $p = 0.92$ ) on Black-necked Stilt abundance in ponds.

### Nest Abundance Monitoring: Changes During 2005–2019

We recorded 8,907 American Avocet, 2,084 Black-necked Stilt, and 14,489 Forster's Tern nests at 63, 39, and 32 individual colony sites, respectively, in south San Francisco Bay during 2005–2019. All three species exhibited declines over the study period (Figure 8). American Avocet nest abundance exhibited a linear relationship with year ( $z_{\text{year}} = -4.02$ ,  $p < 0.0001$ , pseudo  $R^2 = 0.51$ ), decreasing from a high of 1,338 nests in 2007 to only 386 nests in 2019. Black-necked Stilt nest abundance exhibited a quadratic relationship with year, ( $z_{\text{year}} = -3.53$ ,  $p < 0.0001$ ,  $z_{\text{year}}^2 = 2.49$ ,  $p < 0.05$ , pseudo  $R^2 = 0.68$ ), decreasing sharply from a high of 419 nests in 2006 to 107 nests in 2008 and then remaining between 73 and 145 nests annually between 2009 and 2019. Lastly, Forster's Tern nest abundance exhibited a quadratic relationship with year ( $z_{\text{year}} = 1.86$ ,  $p = 0.06$ ,  $z_{\text{year}}^2 = -2.47$ ,  $p < 0.05$ , pseudo  $R^2 = 0.41$ ), changing little between 2005 and 2016, followed by a steep decrease from 1,258 nests in 2016 to  $\leq 784$  nests annually between 2017 and 2019. Nest abundance in 2005 was low for all three species because some nesting sites were not monitored in 2005, the first year of the study. Nevertheless, comparing average nest abundances in the final 3 years of the study (2017–2019) to the first 3 years of the study (2005–2007) showed a 53%, 71%, and 36% decline for American Avocets, Black-necked Stilts, and Forster's Terns, respectively.



**Figure 8** Nest abundance of American Avocets, Black-necked Stilts, and Forster's Terns in south San Francisco Bay from 2005 to 2019. \*Also shown is the mean  $\pm$  standard deviation annual Forster's tern nest abundance in South San Francisco Bay during 1982-2003 from Strong et al. (2004), in which annual nest abundance was estimated by dividing the number of Forster's Tern adults observed among all major nesting colonies in south San Francisco Bay by two.

The number of major colonies has similarly declined over the study period. There were (mean  $\pm$  SD)  $12.4 \pm 5.4$  major American Avocet colonies annually between 2005 and 2009,  $10.8 \pm 3.1$  between 2010 and 2014, and  $9.4 \pm 1.7$  between 2015 and 2019. For Black-necked Stilt, there were  $6.6 \pm 1.8$  major colonies annually between 2005 and 2009,  $4.0 \pm 1.0$  between 2010 and 2014, and  $3.8 \pm 1.1$  between 2015 and 2019. Finally, there were  $6.6 \pm 2.3$  major Forster's Tern colonies annually between 2005 and 2009,  $7.0 \pm 0.7$  between 2010 and 2014, and  $4.2 \pm 0.4$  between 2015 and 2019.

Nest abundance at many of the major colony sites exhibited declines between 2005 and 2019 (Table 4, Figure A3). Of 21 major American Avocet colony sites, eight exhibited significant declines, nine showed no significant change, and four exhibited significant increases (three of which were recently established between 2015 and 2019) over the 15-year study period. Of ten major Black-necked Stilt colony sites, four exhibited significant declines, four showed no significant change, and two exhibited significant increases (both of which were recently established between 2015 and 2019) over the 15-year study period. Finally, of

11 major Forster's Tern colony sites, six exhibited significant declines, two showed no significant change, and three exhibited significant increases (two of which were recently established between 2015 and 2019) over the 15-year study period. Over the past 3 years (2017–2019), there have been no nests at five American Avocet, two Black-necked stilt, and four Forster's Tern colony sites that historically supported major colonies (Table 4).

## DISCUSSION

Using two independent data sources, we found strong evidence that breeding American Avocet, Black-necked Stilt, and Forster's Tern populations in south San Francisco Bay have declined considerably over the past 2 decades. In May 2001, Rintoul et al. (2003) counted 2,765 American Avocets and 1,184 black-necked stilts in south San Francisco Bay. Using the same methods used in that 2001 survey, we counted 2,391 American Avocets and 828 Black-necked stilts in May 2019, representing declines of 13.5% and 30.0%, respectively. Considering only individuals exhibiting breeding behaviors, declines were even greater, with American Avocets decreasing 57.2% and Black-necked Stilts decreasing 52.0% in 2019.

Because breeding waterbirds spend a great deal of their daily time budget engaged in behaviors that do not indicate breeding activity (e.g., feeding; Gibson 1978; Robinson et al. 2020), the number of individuals exhibiting breeding behaviors underestimated the actual breeding population size for each species. Moreover, Forster's Tern peak nesting is a few weeks later than peak nesting of American Avocets and Black-necked Stilts (Ackerman and Herzog 2012), and therefore the timing necessary to survey for breeding avocets and stilts underestimated the Forster's Tern breeding population. Nevertheless, because the same methods were used during the 2001 and 2019 surveys, the relative change suggests that the number of breeding American Avocets and Black-necked Stilts in south San Francisco Bay has decreased markedly. Using a second data set of annual nest abundance monitoring, we confirmed that the breeding populations of American Avocets, Black-necked Stilts, and Forster's Terns

**Table 4** Changes in waterbird nest abundance among major colony sites in south San Francisco Bay during 2005-2019. Major colonies were defined as those containing greater than or equal to the median number of nests among all sites in all years for American Avocets ( $\geq 12$  nests), Black-necked Stilts ( $\geq 6$  nests), or Forster's Terns ( $\geq 40$  nests), in at least three years (or one year if new colony established between 2015-2019). The log number of nests lost or gained per year ( $\beta_{\text{year}}$ ) and  $p$ -values for individual generalized linear models ( $\log(\text{Number of nests}) = \text{year}$ ) by site and species are presented. \* Indicates sites where no nests have been observed over the past three years (2017-2019). † Indicates a new colony site established between 2015 and 2019. Colony sites in bold denote significant change in nest abundance between 2005 and 2019.

Colony site by species	Complex	Number of years as major colony	Last year as major colony	Average number of nests			Log number of nests $\pm$ SE lost or gained per year ( $\beta_{\text{year}}$ )	$p$	Pond management
				2005-2009	2010-2014	2015-2019			
<b>American Avocet</b>									
A12	Alviso	7	2017	238	10.2	36	$-0.19 \pm 0.13$	0.13	
A16	Alviso	13	2019	89.6	54.2	72.6	$-0.005 \pm 0.05$	0.93	Construction of nesting islands in 2012.
<b>A17*</b>	<b>Alviso</b>	<b>3</b>	<b>2012</b>	<b>51</b>	<b>30.2</b>	<b>0</b>	<b><math>-1.05 \pm 0.29</math></b>	<b>0.0003</b>	Converted to tidal action from managed pond in 2012, loss of island nesting habitat.
<b>A7*</b>	<b>Alviso</b>	<b>4</b>	<b>2011</b>	<b>22.5</b>	<b>10</b>	<b>0</b>	<b><math>-0.47 \pm 0.09</math></b>	<b>&lt;0.0001</b>	Converted to muted tidal action from managed pond in 2011, loss of island nesting habitat.
<b>A8*</b>	<b>Alviso</b>	<b>9</b>	<b>2013</b>	<b>216.4</b>	<b>36.2</b>	<b>0</b>	<b><math>-0.70 \pm 0.08</math></b>	<b>&lt;0.0001</b>	Converted to muted tidal action from managed pond in 2011, loss of island nesting habitat.
New Chicago Marsh	Alviso	15	2019	106.8	60.4	52.6	$-0.07 \pm 0.04$	0.08	
<b>A1*</b>	<b>Moffett</b>	<b>6</b>	<b>2011</b>	<b>29.8</b>	<b>14</b>	<b>0</b>	<b><math>-0.47 \pm 0.08</math></b>	<b>&lt;0.0001</b>	Loss of island nesting habitat due to erosion, water management.
<b>A2W*</b>	<b>Moffett</b>	<b>10</b>	<b>2016</b>	<b>42.3</b>	<b>35</b>	<b>10.6</b>	<b><math>-0.20 \pm 0.07</math></b>	<b>0.007</b>	Loss of island nesting habitat due to erosion, water management.
<b>AB1</b>	<b>Moffett</b>	<b>6</b>	<b>2015</b>	<b>25.4</b>	<b>11</b>	<b>6.4</b>	<b><math>-0.15 \pm 0.06</math></b>	<b>0.007</b>	
AB2	Moffett	7	2018	12.8	53.8	16.2	$0.07 \pm 0.07$	0.35	
E12†	Eden Landing	1	2016	0.2	0	11.7	$0.39 \pm 0.22$	0.08	Construction of nesting islands in 2015.
<b>E13†</b>	<b>Eden Landing</b>	<b>2</b>	<b>2019</b>	<b>0</b>	<b>0</b>	<b>11</b>	<b><math>1.00 \pm 0.29</math></b>	<b>0.0006</b>	Construction of nesting islands in 2015.
E14B†	Eden Landing	5	2019	1.6	0	23	$0.23 \pm 0.13$	0.09	
E2	Eden Landing	5	2019	19.5	20.2	13.8	$-0.09 \pm 0.09$	0.28	
<b>NPP1</b>	<b>Newark</b>	<b>3</b>	<b>2019</b>	<b>0</b>	<b>3.2</b>	<b>16.8</b>	<b><math>0.58 \pm 0.18</math></b>	<b>0.002</b>	
<b>N4/N5</b>	<b>Newark</b>	<b>4</b>	<b>2011</b>	<b>20</b>	<b>19.3</b>	<b>0</b>	<b><math>-0.68 \pm 0.17</math></b>	<b>&lt;0.0001</b>	
<b>N4AB</b>	<b>Newark</b>	<b>4</b>	<b>2015</b>	<b>26.3</b>	<b>6.8</b>	<b>4</b>	<b><math>-0.27 \pm 0.10</math></b>	<b>0.006</b>	
R1	Ravenswood	9	2019	68.7	34	28	$-0.09 \pm 0.07$	0.17	
<b>R3†</b>	<b>Ravenswood</b>	<b>1</b>	<b>2019</b>	<b>0</b>	<b>0</b>	<b>9</b>	<b><math>0.88 \pm 0.17</math></b>	<b>&lt;0.0001</b>	
SF2	Ravenswood	10	2018	8	61.2	56.8	$-0.02 \pm 0.09$	0.84	Construction of nesting islands in 2010.
<b>A22†</b>	<b>Warm Springs</b>	<b>3</b>	<b>2018</b>	<b>0</b>	<b>0</b>	<b>16.3</b>	<b><math>1.45 \pm 0.40</math></b>	<b>0.0003</b>	

Table 4 Continued

Colony site by species	Complex	Number of years as major colony	Last year as major colony	Average number of nests			Log number of nests $\pm$ SE lost or gained per year ( $\beta_{\text{year}}$ )	p	Pond management
				2005-2009	2010-2014	2015-2019			
<b>Black-necked Stilt</b>									
A16	Alviso	8	2019	7.8	5.4	6.8	0.02 $\pm$ 0.08	0.78	
<b>New Chicago Marsh</b>	<b>Alviso</b>	<b>15</b>	<b>2019</b>	<b>133.2</b>	<b>61.8</b>	<b>53.6</b>	<b>-0.10 <math>\pm</math> 0.03</b>	<b>0.001</b>	
A2W*	Moffett	10	2016	12.3	12.4	5.3	-0.12 $\pm$ 0.05	0.02	Loss of island nesting habitat due to erosion, water management.
AB1*	Moffett	4	2012	6.2	3.4	0	-0.34 $\pm$ 0.13	0.01	
E13†	Eden Landing	1	2016	0	0	2	0.27 $\pm$ 0.10	0.009	Construction of nesting islands in 2015.
E14B†	Eden Landing	1	2019	0.2	0	1.6	0.49 $\pm$ 0.17	0.004	
Stilt Marsh	Eden Landing	7	2017	31.5	11.6	2.4	-0.30 $\pm$ 0.07	<0.0001	
R3†	Ravenswood	1	2019	0	0	10	0.87 $\pm$ 0.12	<0.0001	
SF2	Ravenswood	6	2018	0	4.6	7	0.14 $\pm$ 0.04	0.001	Construction of nesting islands in 2010.
Redwood Shores Nob Hill Market	Redwood Shores/ Foster City	1	2018	0	0.5	2.6	0.24 $\pm$ 0.21	0.26	
<b>Forster's Tern</b>									
A16	Alviso	6	2010	214.8	33.4	7.2	-0.26 $\pm$ 0.12	0.03	Construction of nesting islands in 2012. No recolonization until 2019.
A7*	Alviso	8	2013	133.3	107.2	0	-0.73 $\pm$ 0.12	<0.0001	Converted to muted tidal action from managed pond in 2011, loss of island nesting habitat.
A8*	Alviso	8	2013	73.6	104.8	0	-0.55 $\pm$ 0.12	<0.0001	Converted to muted tidal action from managed pond in 2011, loss of island nesting habitat.
<b>New Chicago Marsh</b>	<b>Alviso</b>	<b>9</b>	<b>2019</b>	<b>22</b>	<b>57.8</b>	<b>437</b>	<b>0.25 <math>\pm</math> 0.10</b>	<b>0.01</b>	Construction of nesting islands in adjacent Pond A16 in 2012. No recolonization of Pond A16 until 2019.
A1*	Moffett	7	2012	112.8	53.4	0	-0.60 $\pm$ 0.10	<0.0001	Loss of island nesting habitat due to erosion, water management.
A2W*	Moffett	7	2015	59.8	308	33.4	-0.02 $\pm$ 0.05	<0.0001	Loss of island nesting habitat due to erosion, water management.
AB1	Moffett	9	2019	75.4	160.8	90.4	0.004 $\pm$ 0.006	0.48	
AB2	Moffett	8	2019	90	83.8	79.8	0.06 $\pm$ 0.08	0.49	
Charleston Slough	Moffett	3	2008	65	23.3	14	-0.16 $\pm$ 0.03	<0.0001	
SF2†	Ravenswood	2	2018	0	0	101.6	1.95 $\pm$ 0.41	<0.0001	Construction of nesting islands in 2010. Colonization in 2015.
Redwood Shores Nob Hill Market	Redwood Shores/ Foster City	1	2018	0	0	25.2	1.08 $\pm$ 0.28	0.0001	

have decreased substantially over the past 15 years. Moreover, these declines have occurred relatively recently; American Avocet nest abundance began to steadily decrease after 2010, whereas Forster's Tern nest abundance decreased sharply in 2017 (Figure 8). The 3-year average number of American Avocet, Black-necked Stilt, and Forster's Tern nests in south San Francisco Bay during 2017–2019 decreased 53%, 71%, and 36%, respectively, compared to 2005–2007.

To understand breeding waterbird population declines in south San Francisco Bay, it is important to examine these local declines in the context of regional trends. If declines are observed within south San Francisco Bay, but not over a larger regional area, this may indicate that factors local to south San Francisco Bay are driving observed population declines. Conversely, if declines are observed both within south San Francisco Bay and over a larger regional area, this may indicate that factors not exclusive to south San Francisco Bay may be driving observed population declines. Data from the North American Breeding Bird Survey show no significant trends in the number of American Avocets, Black-necked Stilts, or Forster's Terns across the state of California nor across the Coastal California Bird Conservation Region 32 between 2005 and 2015 (Sauer et al. 2017). Bird Conservation Region 32 includes coastal areas north of San Francisco Bay south to Baja California, as well as California's Central Valley. Shuford et al. (2016) found that Forster's Terns throughout inland California declined 74% between surveys conducted in 1997–1999 and surveys conducted in 2009–2012. However, the 2009–2012 surveys took place following a prolonged drought, whereas the 1997–1999 surveys took place after years of well-above-average precipitation. During drought years, inland California wetland habitat may be reduced (Shuford et al. 2016; Reiter et al. 2018), potentially resulting in movement of breeding terns out of the region. Thus, factors local to south San Francisco Bay likely are driving the large declines in breeding American Avocet, Black-necked Stilt, and Forster's Tern populations observed in this study. Moreover, winter populations of large-

bodied shorebirds, including American Avocets, in south San Francisco Bay declined between 2006 and 2013 (State of the Estuary Partnership 2015), suggesting that landscape changes may also be negatively influencing some winter waterbird populations.

In addition to overall population declines, the distribution of waterbirds and waterbird nests in south San Francisco Bay have changed over the past 2 decades. Compared to the 2001 survey, American Avocets and Black-necked Stilts were largely absent from Newark and the southern portion of the Eden Landing Ecological Reserve but increased in the northern portion of the Eden Landing Ecological Reserve (avocets), Ravenswood (avocets), and eastern Warm Springs (both species) during the 2019 survey (Figures 4–6). The Newark wetland complex has few suitable nesting islands, and two very large California Gull nesting colonies have been established in Newark since 2001, which totaled > 10,000 gulls in 2019 (Burns et al. 2018; Tarjan and Burns 2019). Thus, declining use of the Newark area by American Avocets and Black-necked Stilts may be the result of a lack of suitable nesting habitat and the presence of large numbers of gulls. The increase in American Avocet abundance within the northern portion of the Eden Landing Ecological Reserve during the 2019 survey occurred around ponds E12 and E13 where new nesting islands were constructed in 2015, and where nests have been documented each year since island construction. Similarly, the construction of 30 new nesting islands at Ravenswood Pond SF2 in 2010 led to an immediate increase in American Avocet nest abundance (Ackerman et al. 2014a) and the establishment of a new Forster's Tern nesting colony in 2017. Furthermore, social attraction, in which decoys and recorded calls are used to mimic active nesting colonies, was used successfully to establish large Caspian Tern nesting colonies on newly constructed islands at Ravenswood Pond SF2 and Alviso Pond A16 (Hartman et al. 2019), and, in 2019, nesting Forster's Terns returned to Alviso Pond A16 for the first time in 8 years with the help of social attraction efforts (Hartman et al. 2020). Finally, nesting islands that once supported hundreds of waterbird nests annually

(Ackerman and Herzog 2012) have been lost to erosion as a result of higher managed water levels at Ponds A1 and A2W in Moffett, inundation of breached ponds with conversion of ponds to tidal marsh at Pond A17, and management of a muted tidal system in Ponds A7 and A8 in Alviso (Table 4).

The majority (59.6%) of all waterbirds during the 2019 survey were observed in managed pond habitat (25.8% of available habitat), and American Avocets, Black-necked Stilts, and Forster's Terns all used managed pond habitats more than would be expected based on availability (Table 3B). These results are similar to those found during the 2001 survey in which salt ponds (before they were converted to managed ponds) accounted for more than 50% of Black-necked Stilt observations and approximately 75% of American Avocet observations, but only 48.5% of available habitat (Table 3B; Rintoul et al. 2003). Moreover, previous radio-telemetry studies in south San Francisco Bay have found that salt ponds and managed ponds accounted for the majority of bird locations and were used more than expected by American Avocets, Black-necked Stilts, and Forster's Terns during the breeding season (Hickey et al. 2007; Ackerman et al. 2009; Demers et al. 2010; Bluso-Demers et al. 2016). Marshes also were used more than expected during the 2019 survey, particularly by Black-necked Stilts, a result similar to what was found during the 2001 survey (Rintoul et al. 2003). However, unlike the original 2001 survey, we separated marshes into tidal and non-tidal marshes, and found that American Avocets, Black-necked Stilts, and Forster's Terns used tidal marsh less than expected but non-tidal marsh more than expected based on availability (Table 3B). Much of this effect is from high bird use of New Chicago Marsh, a large non-tidal marsh in Alviso. Availability of diked, non-tidal marsh is low in south San Francisco Bay, because most diked wetlands are sparsely vegetated managed ponds. New Chicago Marsh is one of the most important diked, non-tidal marshes and supports large nesting colonies of all three species (Table 4). Although nest success is lower in New Chicago Marsh relative to islands in managed ponds, the dense vegetation cover within marshes provides

preferred brood-rearing habitat for chicks (Ackerman et al. 2014c). Conversely, only 9.8% of all waterbird observations were in tidal mudflat, and only 7.0% were in tidal marsh, even though these two habitat types combined accounted for more than 42% of the available wetland habitat, indicating strong avoidance of these habitats by these breeding waterbird species in south San Francisco Bay. Comparisons between the 2001 and 2019 surveys show that use of tidal mudflats and tidal marshes increased as their availability increased, whereas use of total pond habitat (managed ponds, salt ponds, other ponds) and non-tidal marsh has decreased as the amount of these habitats has declined. However, we did not observe similar increases in the proportion of nests outside of pond habitat, indicating that even if birds were able to use tidal mudflats and tidal marsh for foraging and other needs, they lacked suitable habitat for nesting.

Numerous studies have demonstrated the importance of managed pond habitat in south San Francisco Bay to waterbirds during the breeding and non-breeding seasons (Warnock and Takekawa 1995; Takekawa et al. 2001; Warnock et al. 2002; Strong et al. 2004; Hickey et al. 2007; Ackerman et al. 2009; Demers et al. 2010; Bluso-Demers et al. 2016; Hartman et al. 2016a). For example, multiple telemetry studies have demonstrated preferential use of ponds and avoidance of tidal marsh by terns and shorebirds (Warnock and Takekawa 1995; Hickey et al. 2007; Ackerman et al. 2009; Demers et al. 2010; Bluso-Demers et al. 2016). Recognizing the importance of managed pond habitat to waterbirds, the SBSP Restoration Project plans to retain and enhance some managed ponds, even as 50–90% of this habitat is converted to tidal marsh. Enhancements include the construction of waterbird nesting islands; 30, 16, and six new islands have already been constructed in Ravenswood (Pond SF2), Alviso (Pond A16), and Eden Landing Ecological Reserve (Ponds E12 and E13), respectively. Because only a small fraction of pond habitat would remain after tidal marsh restoration (potentially as little as 10%), the remaining managed ponds would be critical for the support of large numbers of breeding



waterbirds. Therefore, we examined what pond characteristics supported the highest waterbird abundance during the 2019 survey. Abundance of all three species was greater in managed ponds vs. salt ponds. American Avocet abundance was greater in ponds of medium salinity (60–120 ppt) and in ponds in which islands were present. Black-necked Stilt and Forster's Tern abundance increased with pond area. Forster's Tern abundance in ponds also decreased with distance to San Francisco Bay and as salinity increased. In a previous study, we found that waterbird nest abundance and nest success in south San Francisco Bay was greater within ponds < 1 km from San Francisco Bay (nest abundance was also high among ponds > 4 km from San Francisco Bay), and that nest abundance decreased as the number of islands increased, such that ponds with < 5 islands had more waterbird nests than ponds with > 20 islands (Hartman et al. 2016a). Thus, managed ponds that are larger (> 50 ha), < 1 km from San Francisco Bay, of low to medium salinity, and with three to five islands are likely to support greater waterbird abundance and nest success. However, given the varied preferences in salinity and pond characteristics among waterbird species, reducing the total managed pond area to as little as 10% of what existed before restoration will present significant challenges in ensuring that conditions will be sufficient to maintain the diversity of breeding waterbird populations in south San Francisco Bay.

The increasing population of predatory California Gulls (Burns et al. 2018) is also likely to continue to negatively influence waterbird use of pond habitat. California Gulls account for more than 50% of American Avocet and Forster's Tern chick mortalities (Ackerman et al. 2014b, 2014c) and at least 13% of American Avocet nest failures (Herring et al. 2011). In this study, abundance of Black-necked Stilts and Forster's Terns within individual ponds decreased as the number of gulls in the pond increased. Previously, Ackerman et al. (2014b) found that Forster's Tern chick survival increased by 900% after the managed relocation of a nearby California Gull colony in the Alviso complex of south San Francisco Bay and that chick survival at waterbird nesting

colonies was negatively related to a gull predation index, which incorporated both the number and distance of gulls from waterbird colonies. Thus, breeding waterbirds appear to prefer ponds and have higher productivity in ponds where California Gull presence is reduced, suggesting that managed ponds further away from California Gull nesting colonies are likely to support more breeding waterbirds. Moreover, as more managed ponds are converted to tidal marsh, breeding waterbird colonies may become concentrated into fewer remaining ponds, potentially facilitating predation by gulls on these colonies. Thus, management of breeding California Gulls may be necessary.

## CONCLUSION

In conclusion, breeding waterbirds have decreased in abundance and have changed their distribution markedly in south San Francisco Bay over the past 2 decades. Two factors are likely causes for these declines. First, the number of California Gulls—major predator of Forster's Tern, American Avocet, and Black-necked Stilt chicks (Ackerman et al. 2014b, 2014c)—has almost tripled from 16,998 gulls in 2001 to 45,026 in 2019 (Burns et al. 2018; Tarjan and Burns 2019). Second, the conversion of managed ponds to tidal marsh has resulted in the direct loss of historical island nesting habitat. Forster's Tern, and especially American Avocet nest abundance, began to decline after 2010 (Figure 8), coinciding with the loss of highly productive island nesting habitat in Alviso (Ponds A7 and A8) as a result of the opening of these managed ponds to muted tidal action to begin the process of tidal marsh restoration. The abandonment of highly productive nesting islands in Moffett Ponds A1 and A2W in 2017 from erosion that resulted from higher managed water levels further contributed to declines in nest abundance, particularly of Forster's Terns (Figure 8). In an effort to maintain breeding waterbird populations, the SBSP Restoration Project constructed new nesting islands to enhance four managed ponds (SF2, A16, E12, and E13) that will not be converted to tidal marsh. Forster's Tern and Caspian Tern nesting colonies have been established at two of these

ponds, aided in part by social attraction efforts (Hartman et al. 2019; Hartman et al. 2020), and American Avocet have nested at all four enhanced ponds. In addition, Forster's Tern nest abundance has increased substantially at New Chicago Marsh where nest success is lower (Ackerman et al. 2014c), and new colonies have been established in Ravenswood Pond SF2 and the Redwood Shores Nob Hill Market area. However, increased nest abundance at these sites has not made up for the steep declines observed at other historically large colony sites (Table 4). As the SBSP Restoration Project continues to convert more managed ponds to tidal marsh, breeding waterbirds will lose additional nesting habitat, which may lead to further population declines. Retaining more managed ponds (particularly those that already support large numbers of nesting waterbirds), and ensuring that suitable nesting islands are provided, while reducing predation by California Gulls, may help to limit breeding waterbird population declines during future phases of the SBSP Restoration Project. Furthermore, regular monitoring of breeding waterbirds in south San Francisco Bay would help assess the effect of tidal marsh restoration, track population changes, and inform management decisions.

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## NOTES

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