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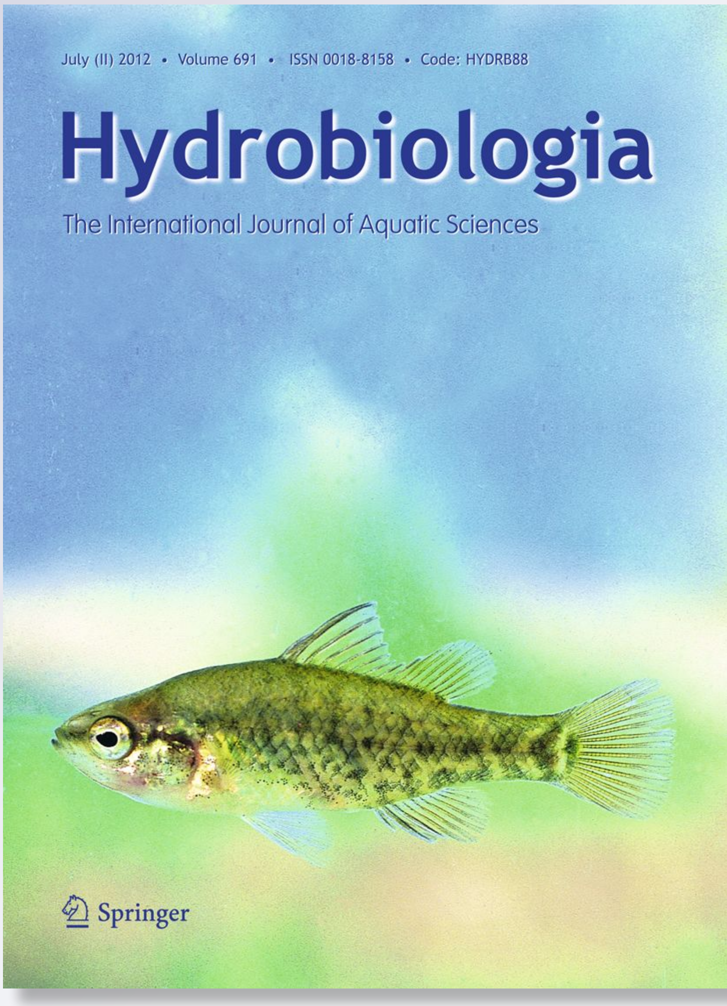
Hydrobiologia
The International Journal of Aquatic Sciences

ISSN 0018-8158

Hydrobiologia
DOI 10.1007/s10750-012-1177-y



Springer

Hydrobiologia
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LIMNOLOGY AND AQUATIC BIRDS

Variability in habitat value of commercial salt production ponds: implications for waterbird management and tidal marsh restoration planning

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Abstract Salt evaporation ponds are used in place of lost natural estuarine habitats for foraging and roosting by waterbirds around the world, but have started to be decommissioned in some areas due to low profitability. In San Francisco Bay, three former salt pond complexes (Alviso, Eden Landing, and Ravenswood) have been decommissioned, i.e., taken out of commission, and are planned for marsh restoration. We compared total and foraging abundance and densities of ducks, shorebirds, and piscivores, as well as eared grebes (*Podiceps nigricollis*) among decommissioned and commercial pond complexes. Complex use was consistent within groups and variable among groups, with most use occurring in decommissioned ponds: 73% of ducks were observed in the Alviso complex and 9% in the commercial ponds; 51% of shorebirds were in the Eden Landing complex and only 17% in commercial ponds; and 56% of piscivores were in the Alviso complex and <18% in commercial ponds. Only eared grebes were more abundant (59%) in commercial ponds. Differences among groups in within-complex and within-pond abundance were likely related to pond salinity and topography, respectively. Our results suggest that the effects of pond conversion on waterbird groups may be disproportionate to pond area depending on the characteristics of the converted ponds.

Keywords Salt ponds · Saline wetlands · Artificial habitat · Salt marsh restoration

Guest editors: F. A. Comín & S. H. Hurlbert / Limnology and Aquatic Birds: Monitoring, Modelling and Management

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Introduction

Natural supratidal wetlands around the world have been lost to urban development or agriculture (Masero, 2003; Bellio et al., 2009). Commercial salt evaporation

Published online: 31 May 2012

ponds (hereinafter referred to simply as ponds) are artificial wetlands that have replaced some natural estuarine habitats in many places, including France (Britton & Johnson, 1987), Spain (Velasquez & Hockey, 1992; Masero & Pérez-Hurtado, 2001; Paracuellos et al., 2002; Sanchez et al., 2006), Portugal (Rufino et al., 1984; Dias, 2009), Italy (Baccetti et al., 1995), Sri Lanka (Bellio et al., 2009), and the United States (Carpelan, 1957; Warnock et al., 2002; Takekawa et al., 2006). Salt ponds provide important foraging habitats for waterbirds. Shorebirds, which feed on intertidal mudflats at low tide, generally use salt ponds for feeding during high tide when the mudflats are inundated; however, salt ponds are frequently used for feeding at low tide as well (Rufino et al., 1984; Masero et al., 2000 Masero & Pérez-Hurtado, 2001; Warnock et al., 2002; Dias, 2009). Salt ponds are favored waterbird habitats for several reasons. The large expanses of water facilitate taking flight and predator avoidance, while the shallow, sheltered impoundments likely have created a favorable microclimate for roosting (Warnock & Takekawa, 1996). Although tidal mudflats are important for shorebirds, lack of nearby roosts may constrain the ability of shorebirds to exploit mudflats as foraging habitats (Dias et al., 2006). The roosting and foraging value of salt ponds during high tide may help maintain high densities of shorebirds on mudflats (Masero et al., 2000). Several species also use salt pond levees, islands, and dry flats for nesting.

Salt ponds around the world have begun to be decommissioned and abandoned because of low profitability (Paracuellos et al., 2002; Dias, 2009). Conversion of salt ponds for natural habitat restoration or for other purposes may impact local waterbird species. Salt ponds have often become an integral part of the existing landscape providing essential habitats for large numbers of waterbirds, especially during migration and winter (Anderson, 1970; Accurso, 1992; Takekawa et al., 2001; Warnock et al., 2002). Salt ponds are unique hypersaline wetland habitats. These habitats produce dense populations of high-salinity tolerant invertebrates such as brine shrimp (*Artemia* spp.) and brine flies (*Ephydra* spp.; Takekawa et al., 2006) important as food items to a wide array of migratory birds.

In San Francisco Bay (SFB) estuary, an important staging and wintering area for migratory waterfowl and shorebirds (Harvey et al., 1992; Page et al., 1999), large saline ponds were not a natural feature of the landscape. Instead, the intertidal area included salt marshes and small salt pannes that provided hypersaline habitats in the landscape (Goals Project, 1999). During the past 200 years, over 79% of historic SFB salt marshes were lost, resulting in diminished habitat for native marsh species and fragmentation of remaining marshlands (Goals Project, 1999) and were often replaced by salt ponds that were introduced to the landscape more than 150 years ago (Ver Planck, 1958; Josselyn, 1983). Extant SFB salt ponds vary both seasonally and spatially in salinity from brackish to >200 g l^{-1}, range from a few centimeters to a few meters in depth, and support relatively simple but productive assemblages of algae and invertebrates (Carpelan, 1957; Lonzarich & Smith, 1997). The unique characteristics of individual salt ponds and the collective character of salt ponds in the estuary offer a heterogeneous landscape that provides habitats to waterbird species with diverse foraging strategies and differing habitat needs.

San Francisco Bay salt ponds provide unique habitats in an otherwise urbanized estuary that support large populations of migratory waterbirds (Takekawa et al., 2001; Warnock et al., 2002; Takekawa et al., 2006). South SFB includes a diverse array of 76 salt ponds (>8,300 ha) of differing water depths and salinity concentrations. About 33–60% of south SFB salt pond area is planned for restoration to tidal wetlands under the South Bay Salt Pond Restoration Project (Fig. 1; SBSPRP; www.southbayrestoration.org). Converting salt ponds to tidal marsh will likely benefit some species at the expense of others; for example, most shorebirds prefer more open habitats rather than the vegetated tidal marsh plain habitats (Warnock & Takekawa, 1995).

Conversion of some salt ponds may impact waterbird species more than others because of the variability in salt pond salinity and water depth. Salt ponds differ in their topography and salinity, and the removal of even a small subset of ponds may result in a loss of habitat for waterbird species with specific salinity, depth, and habitat needs. Unfortunately, no alternative habitats exist to support large numbers of migratory and wintering shorebirds and waterfowl in SFB due to extensive urbanization (Warnock et al., 2002). Thus, we examined the potential impact of conversion of salt ponds on different groups of waterbirds with south SFB salt ponds as a case study.

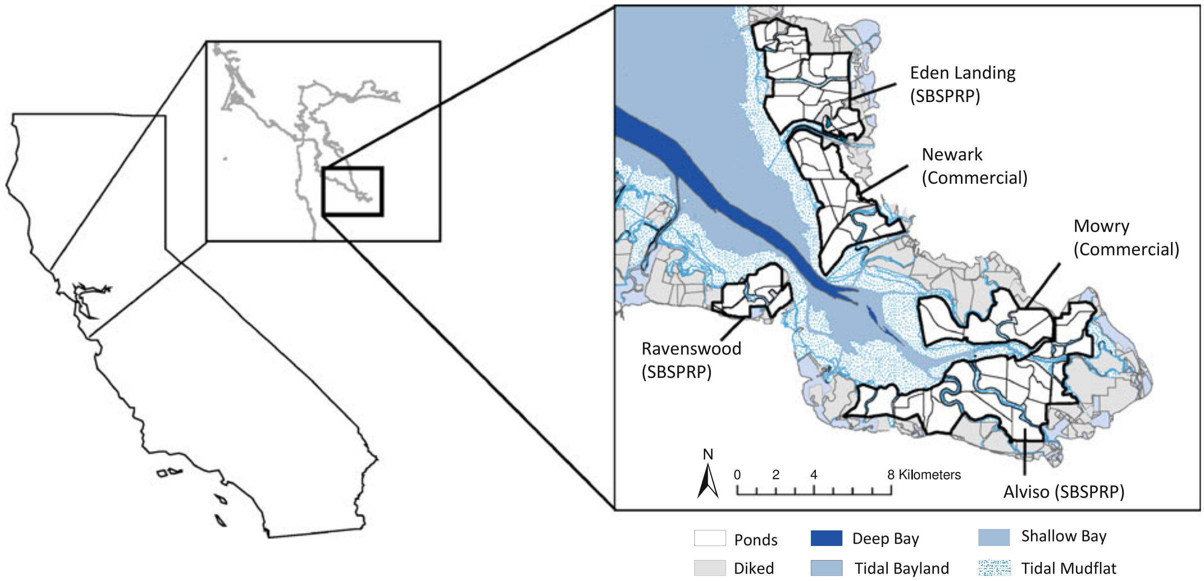

Fig. 1 Study area showing pond complex delineations, south San Francisco Bay, CA, USA

Materials and methods

Study area

We examined five saline pond complexes in the South Bay (37.42°N–37.62°N; 121.93°W–122.22°W) sub-region of the SFB estuary (Fig. 1); these 76 Ponds comprised about 8,361 ha of commercial (2,774 ha) and formerly commercial (5,587 ha) salt ponds. Newark and Mowry complexes (commercial ponds) comprised 16 (total 1,584 ha) and 6 (total 1,190 ha) ponds, respectively. The other three complexes (SBSPRP Ponds) comprised 53 formerly commercial ponds (total 5,518 ha) acquired in 2003 by the U.S. Fish and Wildlife Service (FWS) as part of the Don Edwards San Francisco Bay National Wildlife Refuge (Alviso: 25 salt ponds, 3,064 ha; Ravenswood: 7 salt ponds, 610 ha) and by the California Department of Fish and Game (DFG) as part of the Eden Landing Ecological Reserve (Eden Landing: 22 ponds, 1,844 ha). Pond E3C, a 69-ha salt pond near Eden Landing, was not transferred to DFG, but we included it in the complex due to its proximity. Individual salt ponds ranged in size from 12 to 276 ha.

Commercial ponds were managed in closed systems. Bay water entered each complex through a one-way gate at the lowest-numbered salt pond, and salinity increased due to evaporation and concentration as the water was moved through the higher numbered salt ponds until salt was harvested in the final stages of the process. SBSPRP Ponds were managed similarly prior to the summer of 2004. By the initiation of this study in late 2005, water control structures had been added to several salt ponds in the Alviso and Eden Landing complexes to allow for controlled circulation of most salt ponds in these complexes with Bay water and to prevent salt concentrations from increasing prior to tidal marsh restoration. Additionally, three Alviso ponds (A19, A20, and A21) comprising 200 ha were breached in March 2006 and subsequently experienced unrestricted Bay water tidal exchange with SFB. These changes, detailed in the Initial Stewardship Plan (ISP; Life Science, 2003), resulted in lower salinity and altered hydrology in the Alviso and Eden Landing complexes compared to commercial ponds and to SBSPRP Ponds in the Ravenswood complex, which experienced neither tidal exchange nor commercial removal of salts.

Methods

Salinity

We measured salinity in all salt ponds to examine differences within and among complexes and potentially explain some differences in bird use (Velasquez, 1992). To account for spatial variation within salt ponds, we measured salinity monthly from 1 to 4 locations per pond, depending on pond size and site accessibility. We took measurements within 1 week of bird surveys to represent water quality conditions relevant to bird use. Where pond salinity was <70 g l^{-1}, we used a Hydrolab Minisonde® (Hydrolab-Hach Company, Loveland, CO) to measure specific conductance (internally converted to salinity with the 1978 Practical Salinity Scale). We measured salinity from near-surface (10 cm below) and, where pond depths exceeded 60 cm, from near-bottom (about 10 cm above the substrate). Because pond salinities often exceeded the calibration capabilities of water quality meters, we additionally used temperature-corrected specific gravity, measured with a hydrometer (Ertco, West Paterson, New Jersey) scaled for the appropriate range, to calculate salinity in all ponds. We used a grab sampler to obtain water from about 10 cm below the surface and transferred water to a 500-ml cylinder for measurement of specific gravity and temperature in the field. Although we obtained water temperature from all ponds with a water quality meter, a separate temperature reading of the water in the cylinder was used to correctly adjust for the temperature of the water sample used to calculate salinity.

Bird surveys

We comprehensively censused birds on all 22 commercial ponds and all 54 SBSPRP Ponds between October 2005 and May 2009. We superimposed a 250 m × 250 m (6.25 ha) Universal Transverse Mercator (UTM) grid upon 1-m resolution aerial imagery (USDA National Agriculture Image Program 2005) to create maps of individual ponds; observers used existing landmarks and physical features to identify the grid cell locations of each bird (Matveev, 1995; Posey et al., 1995; Takekawa et al., 2006). Observers conducted counts of all species with binoculars and spotting scopes from vantage points on pond levees. When a group of birds spanned two or more grid cells, observers were instructed to first count the entire group and then to approximate the group's distribution among grid cells to avoid missing or double-counting birds that were close to the dividing lines between cells. We observed behavior to indicate whether birds were actively foraging (e.g., diving, dabbling, pecking, or probing); this was likely a conservative estimate, as only birds engaging in foraging behavior at the time of observation were recorded as foraging. We conducted surveys during daylight within 3 h of the highest high tide, which we assumed corresponded with the largest number of waterbirds in the ponds. We also timed high-tide counts of the three breached ponds to occur when ponds were fully inundated, to maximize comparability of bird use with unbreached ponds. The breached ponds drained completely and were more comparable to mudflats than to other ponds during low tide, whereas high-tide bird use was similar to the period before breaching (Athearn et al., unpubl. data).

We identified all waterbirds to species and separated them into ducks, shorebirds, and piscivores (pelicans, cormorants, herons, and terns) to examine differences among major groups in addition to differences among key species. We focused on these groups because of their relative abundance in ponds and because of their diverse foraging strategies. We additionally reported on several representative species typically found in high densities on ponds relative to other SFB habitats (Takekawa et al., 2001; Takekawa et al., 2006): (1) northern shoveler (NSHO; *Anas clypeata*)—a dabbling duck that feeds in the upper water column; (2) ruddy duck (RUDU; *Oxyura jamaicensis*)—a diving duck that feeds in deeper water on benthic invertebrates; (3) western sandpiper (WESA; *Calidris mauri*)—a small shorebird that forages in the top layer (<3 cm) of sediments; (4) marbled godwit (MAGO; *Limosa fedoa*)—a medium-sized shorebird that reaches deeper into the substratum than small shorebirds; (5) American white pelican (AWPE; *Pelecanus erythrorhynchos*)—a fish consumer; and (6) eared grebe (EAGR; *Podiceps nigricollis*)—a grebe that forages on water column and benthic invertebrates.

Data analysis

Salinity was examined as a potential explanation for differences in bird use among complexes. Water depth was also considered to be an important explanatory variable (see Velasquez, 1992), but depth data were not equally available for all pond complexes. We collected monthly water level readings from all commercial and SBSPRP ponds, but at this time we have collected corresponding bathymetric data (see Athearn et al., 2010; Takekawa et al., 2010) only from

SBSPRP Ponds. We thus address water depth only descriptively in this article, to generalize shallow (i.e., <6 cm), moderately shallow (6–10 cm), moderate (10–20 cm), and deep (>20 cm) water based on the foraging depth needs of small shorebirds, larger shorebirds, dabbling ducks and herons, and diving ducks (e.g., Colwell & Taft, 2000). To avoid an analysis confounded by the lack of depth data, we examined salinity separately from bird densities to form a qualitative relationship that can be expanded upon in future work. To characterize the salinity distribution of complexes, we plotted the mean salinity values of individual ponds within complexes by season and calculated the median value for each data set (Fig. 1).

The objective of our study was to compare total bird abundances in commercial and SBSPRP complexes, but waterbird abundances change annually and especially seasonally due to migration patterns and other factors that may not relate to habitat selection. Habitat use by a species during periods of relatively low abundance may be less informative than during periods where habitat is at or near capacity because resource selection may only be apparent when the resource is scarce (Johnson, 1980), otherwise many high-quality habitats may go unused simply because there are not enough birds present to show a preference. We assigned months to seasons to define periods of the annual waterbird migration cycle: winter (December–February), spring (March–May), summer (June–August), and fall (September–November). We plotted monthly bird abundance at the five complexes for 42 months (December 2005–May 2009) for each species or species group and examined these for seasonal and annual trends (Figs. 3, 4, 5).

For comparison of the five complexes, we chose a "main season" for each species group for which abundance was relatively high and consistent across years. These main seasons were: winter for ducks ($n = 12$ dates); winter and spring combined for shorebirds and eared grebes ($n = 24$ dates); and fall for piscivores ($n = 9$ dates). With these data sets, we calculated geometric mean densities (birds $\cdot$ 100 ha^{-1}) for both total birds and foraging birds for each species group for each complex. We compared geometric means of total and foraging densities among complexes for each species or species group (Fig. 6). We evaluated dissimilar trends in complex use for foraging and total birds to identify complexes used differently for foraging or roosting by some waterbird species.

To examine the spatial distribution of species groups within complexes, we calculated geometric means of total bird abundance within survey grids during the selected seasons. We added a constant value of 0.16 (a count of 1 bird divided by the maximum grid cell size of 6.25 ha) to eliminate zeros prior to computation of geometric means. We then spatially joined the data with ArcGIS feature classes to create distribution maps. We used five bins for classifying abundance data by natural breaks using the Jenks optimization method (ArcGIS 9.3.1, ESRI, Redlands, CA).

Results

We found consistent density and abundance differences among the five south SFB complexes in all waterbird groups and species that we examined. Most waterbird groups had highest density and abundance at SBSPRP complexes Alviso and Eden Landing, except eared grebes, which were more abundant at the Newark complex. Waterbird species that use SFB Ponds are diverse in their foraging strategies and habitat needs, and these differences were reflected in the relative densities of waterbird groups we examined at the different pond complexes.

Median winter salinity was lowest in the Alviso (29.3 g l^{-1}) and Eden Landing (47.2 g l^{-1}) complexes, and only slightly higher in the Newark complex (52.1 g l^{-1}). Ravenswood (126.6 g l^{-1}) and Mowry (215.7 g l^{-1}) had the highest values. This trend generally held for other seasons as well (Fig. 2). Ponds within SBSPRP complexes were more saline in summer and fall, particularly in the Ravenswood complex, where ponds mostly dried up during these seasons. In contrast, commercial complexes showed less variation in salinity among seasons. In the Ravenswood complex, where shallow ponds were not managed for salt production and were also not flushed with Bay water, seasonal salinity shifts were likely driven by precipitation and evaporation patterns. However, salinity patterns in commercial ponds were likely controlled by deliberate water transfer during the process of salt production. Some SBSPRP Ponds were at lower salinities during the spring and summer than during the winter because Alviso and Eden Landing ponds were flushed with Bay water under the ISP during these seasons.

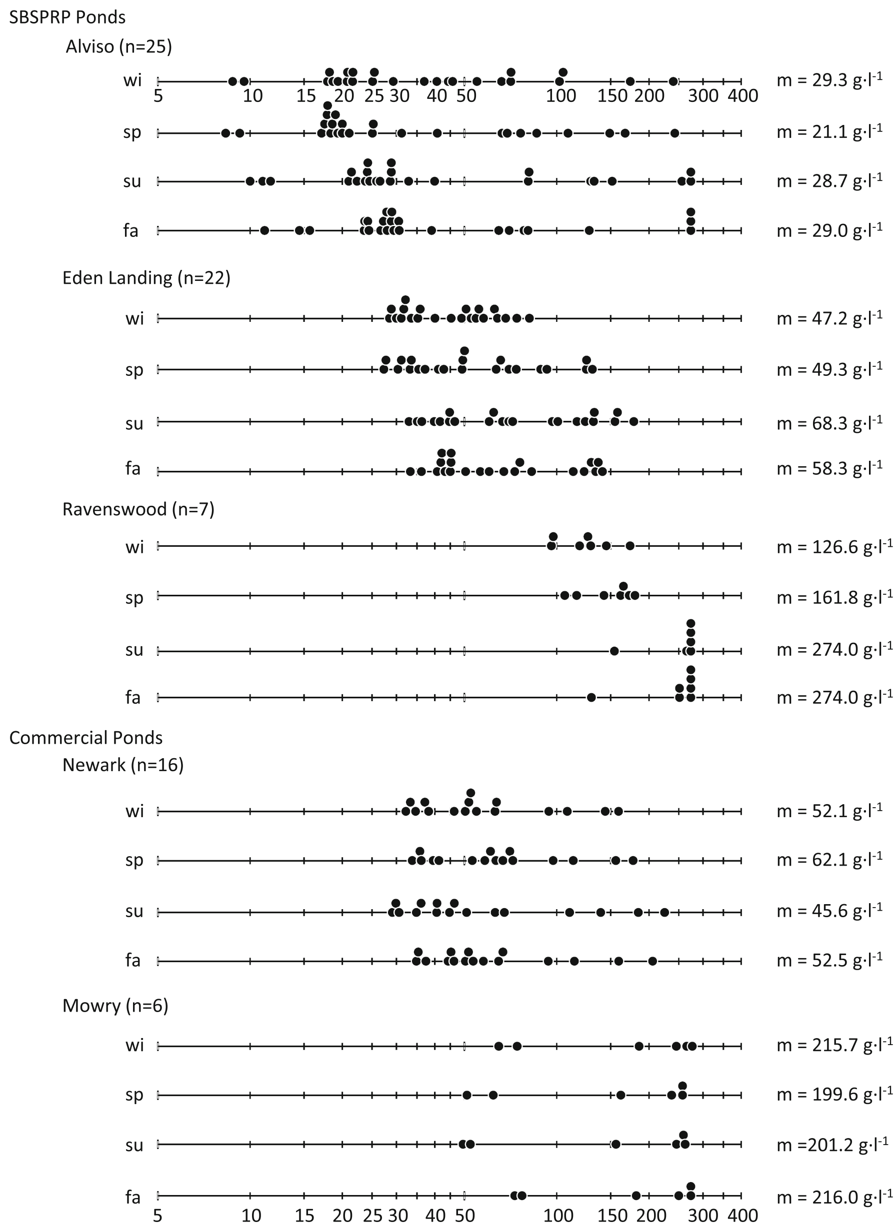

Fig. 2 Salinity (g l^{-1}) distributions for ponds within complexes, by season, Dec 2005–Feb 2009; wi = winter (Dec–Feb), sp = spring (Mar–May), su = summer (Jun–Aug), fa = fall (Sept–Nov). Median values are given to the right of each graphic. Similar values are extended perpendicularly for visibility

Monthly abundance of most groups and species examined was higher in SBSPRP than in commercial ponds; this difference was most pronounced for ducks, shorebirds, and their representative species (Figs. 3, 4, 5). However, eared grebes were most abundant in the Newark complex, particularly in 2006, but were also relatively abundant in the Alviso complex in other years (Fig. 5). Ducks as a group, including northern shovelers and ruddy ducks, exhibited a distinct seasonal pattern and were consistently more abundant during the winter months. About 73% of total ducks counted during the winter were located in the Alviso complex, 16% were in Eden Landing, and 9% were in Newark; very few ducks were counted in Ravenswood or Mowry. Shorebirds were least abundant during the summer and generally peaked in early winter and again during spring migration. Although peaks also occurred during fall migration, we used winter and spring values for comparison because abundance during these seasons was more consistent across years (Fig. 4). We observed 51% of total shorebirds in the Eden Landing complex, with 23% in Alviso, 13% in Newark, 9% in Ravenswood, and the

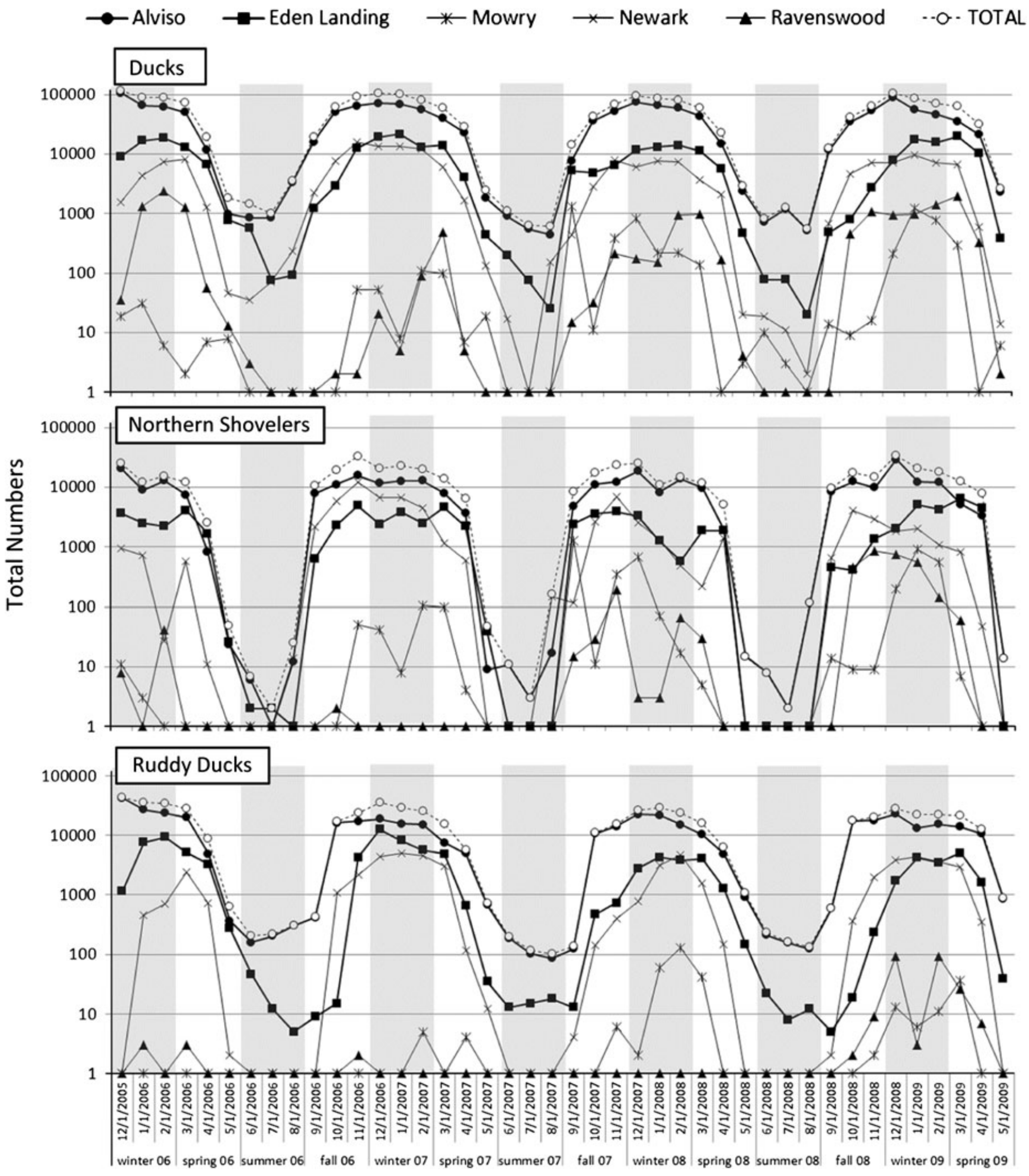

Fig. 3 Abundance of total ducks, northern shovelers, and ruddy ducks at SBSPRP (Alviso, Eden Landing, and Ravenswood) and commercial (Newark and Mowry) salt pond complexes by month and season, Dec 2005–May 2009

remainder in Mowry. Piscivores, including American white pelicans, were most abundant during fall, and about 56% of fall piscivores were counted in Alviso, followed by 26% in Eden Landing and 17% in Newark; about 1% of piscivores were distributed among Ravenswood and Mowry complexes (Fig. 5). Eared grebes were generally most abundant during winter and spring, and were most abundant in the Newark (44%) and

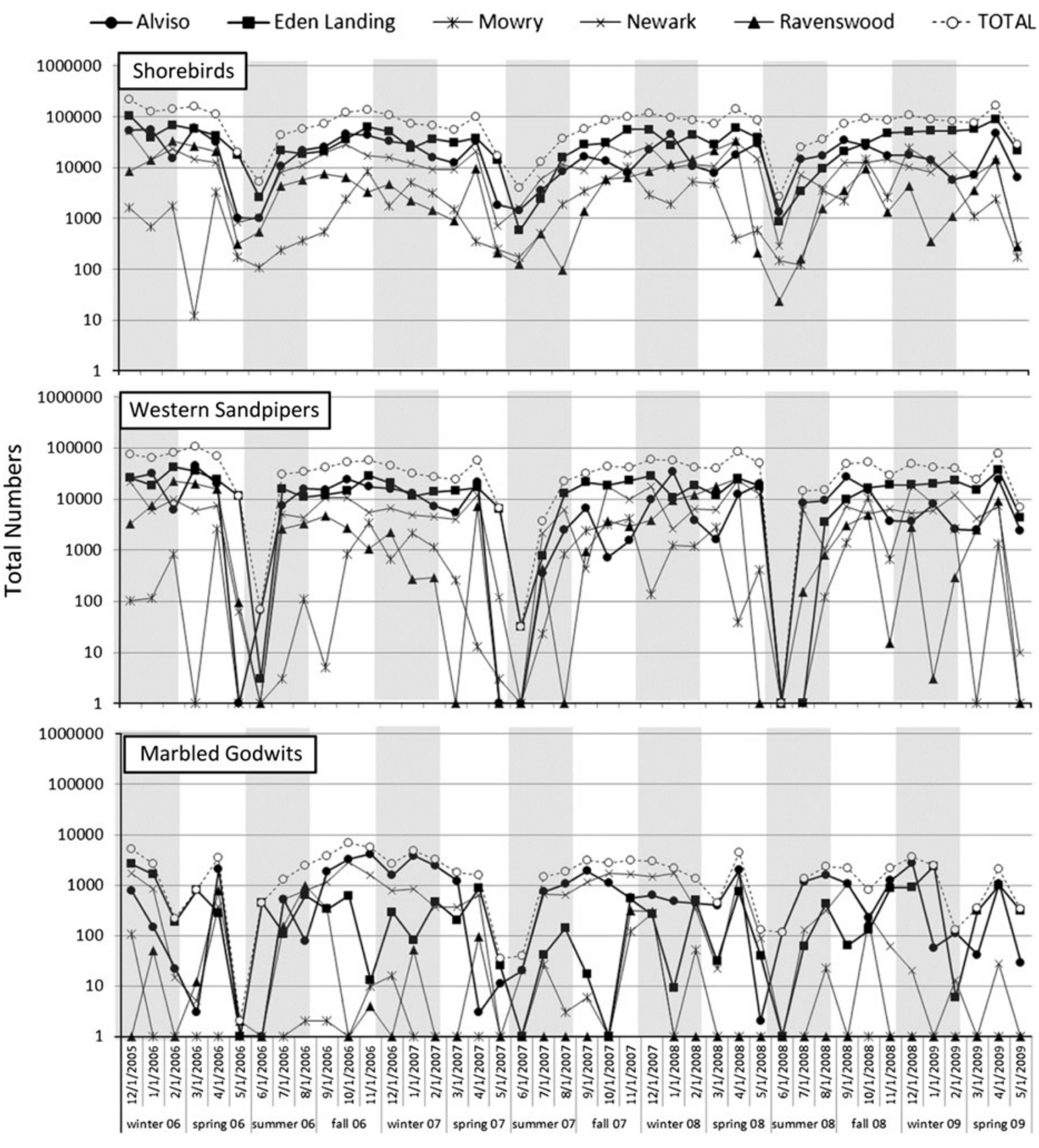

Fig. 4 Abundance of total shorebirds, western sandpipers, and marbled godwits at SBSPRP (Alviso, Eden Landing, and Ravenswood) and commercial (Newark and Mowry) salt pond complexes by month and season, Dec 2005–May 2009

Alviso (35%) complexes, with fewer birds in Mowry (14%) and Eden Landing (6%); very few birds were counted in Ravenswood (Fig. 5). Relative eared grebe density was similar for foraging and total birds regardless of complex, suggesting that this species uses ponds for feeding rather than roosting (Fig. 6).

For most species, density values (Fig. 6) showed patterns of relative complex use similar to those for total abundances (Figs. 3, 4, 5). However, total shorebird, western sandpiper, and marbled godwit densities in the Ravenswood complex were similar to those at the Newark complex, whereas absolute

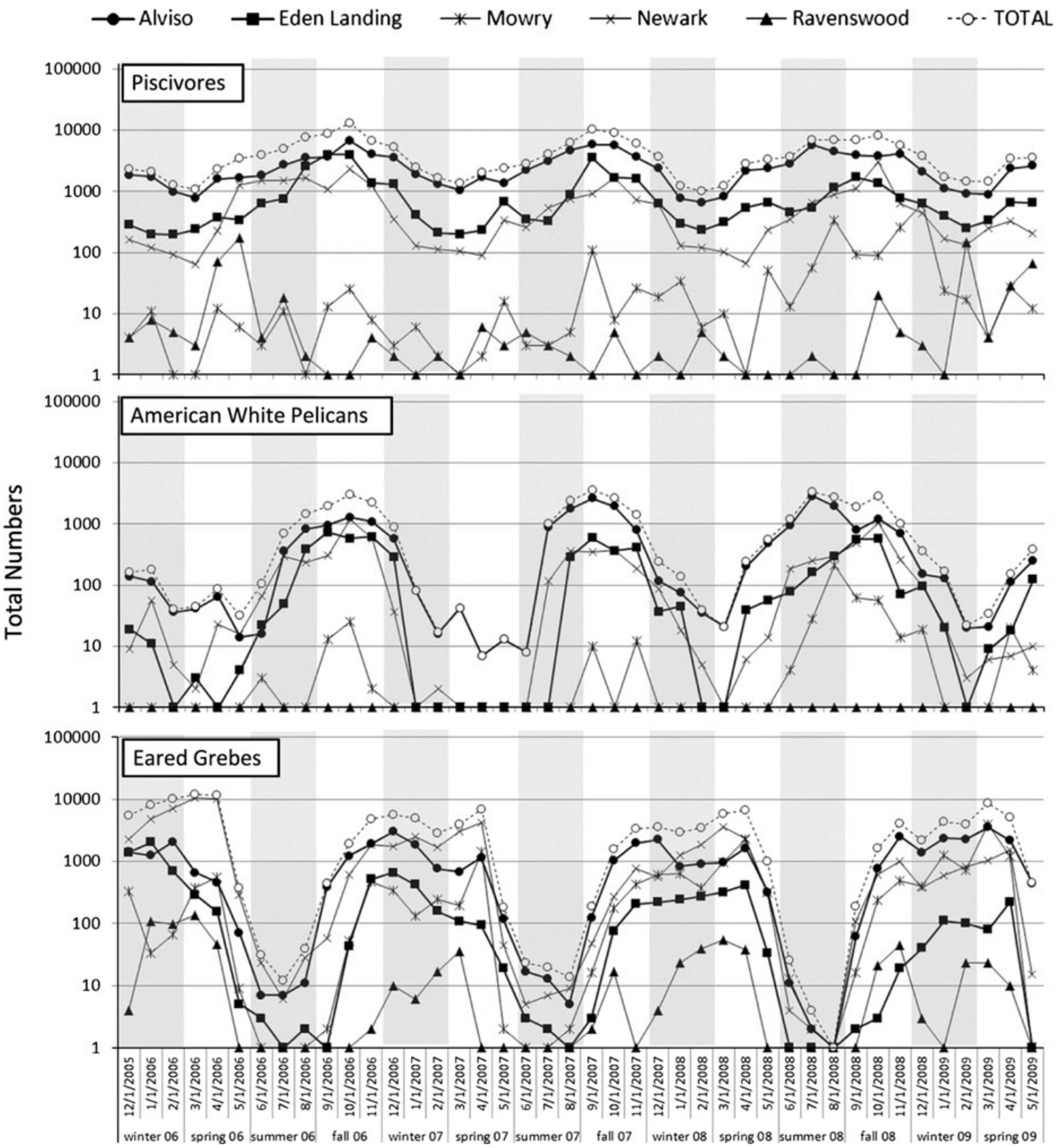

Fig. 5 Abundance of total piscivores, American white pelicans, and eared grebes at SBSPRP (Alviso, Eden Landing, and Ravenswood) and commercial (Newark and Mowry) salt pond complexes by month and season, Dec 2005–May 2009

numbers of these three categories were lower at Ravenswood than at Newark. Foraging densities were lower than total densities and showed similar patterns of relative complex use as total densities for all species except American white pelicans, for which foraging densities at Alviso and Mowry were relatively lower.

Spatial distribution of groups and species were unique and dissimilar from one another. Ducks were nearly absent from Ravenswood and Mowry ponds, which were primarily >100 g l^{-1}, during the winter. Although they were abundant in Alviso ponds, which were generally the lowest in salinity (<35 g l^{-1}), they

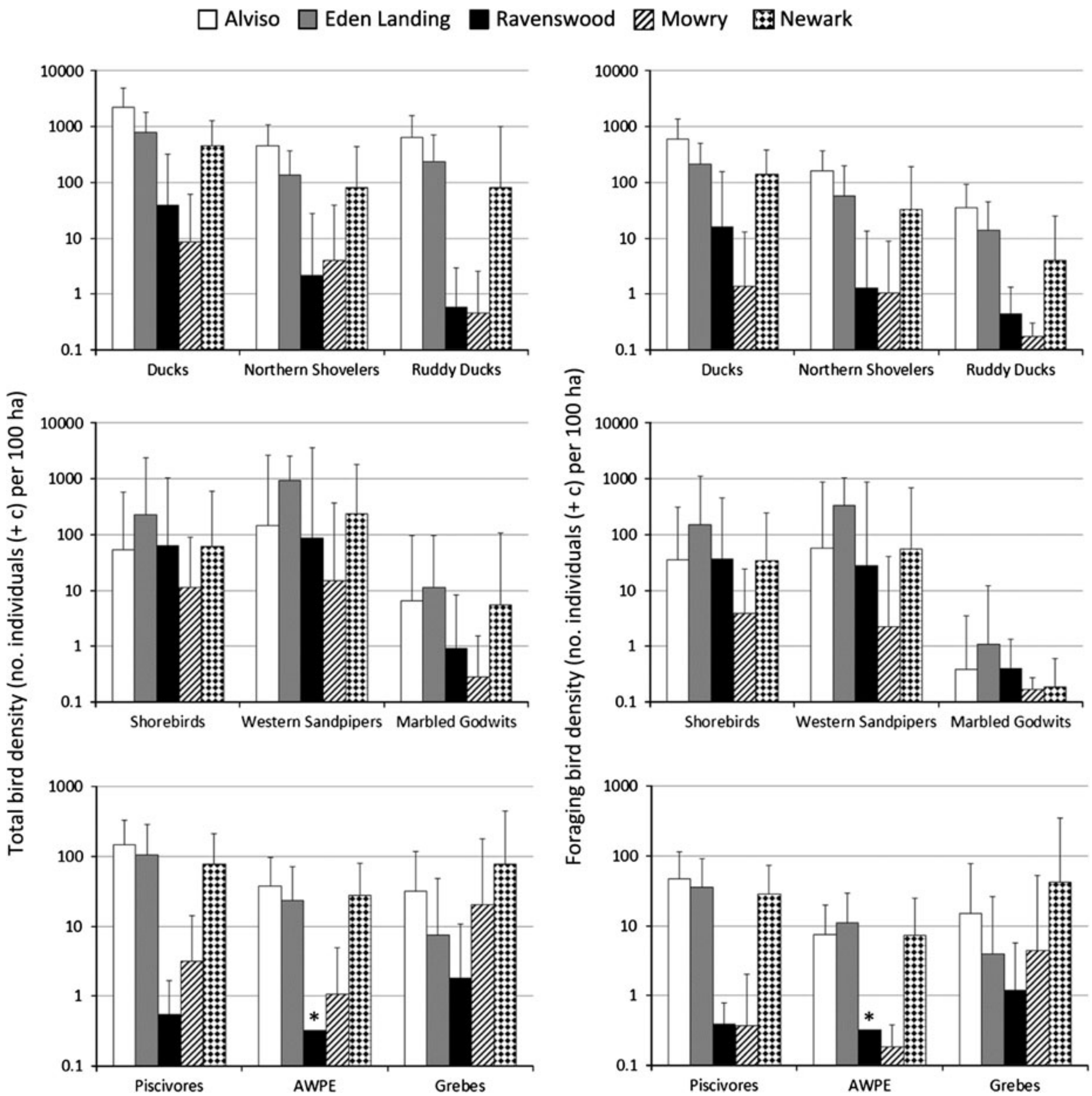

Fig. 6 Geometric mean densities (+SD) of total birds and foraging birds at the five SFB salt pond complexes, Dec 2005–May 2009. Densities calculated for the following seasons: winter only (total ducks, northern shovelers, ruddy ducks; $n = 12$ dates), winter and spring (total shorebirds, western sandpipers, marbled godwits, eared grebes; $n = 24$ dates), and fall [total piscivores, American white pelicans (AWPE); $n = 9$ dates]. The constant c varied with complex area and, for the five complexes in the legend, was 0.033, 0.054, 0.16, 0.084, and 0.063, respectively. *Asterisks* indicate where the geometric mean will equal exactly zero when fully backtransformed by subtracting c

were nearly absent from several Alviso ponds; conversely, high densities of ducks were observed in a few ponds within Eden Landing and Newark (Fig. 7), which were both dominated by moderate salinity ponds (<60 g l^{-1}). Shorebirds were abundant in a few Alviso and Newark Ponds during the winter and spring, but were most abundant in Eden Landing, where almost all birds were located in moderately saline ponds (40–80 g l^{-1}) in the northern end of the complex and often concentrated within specific grid cells (Fig. 8). Although ponds in the Newark complex were similar in salinity to Eden Landing, western

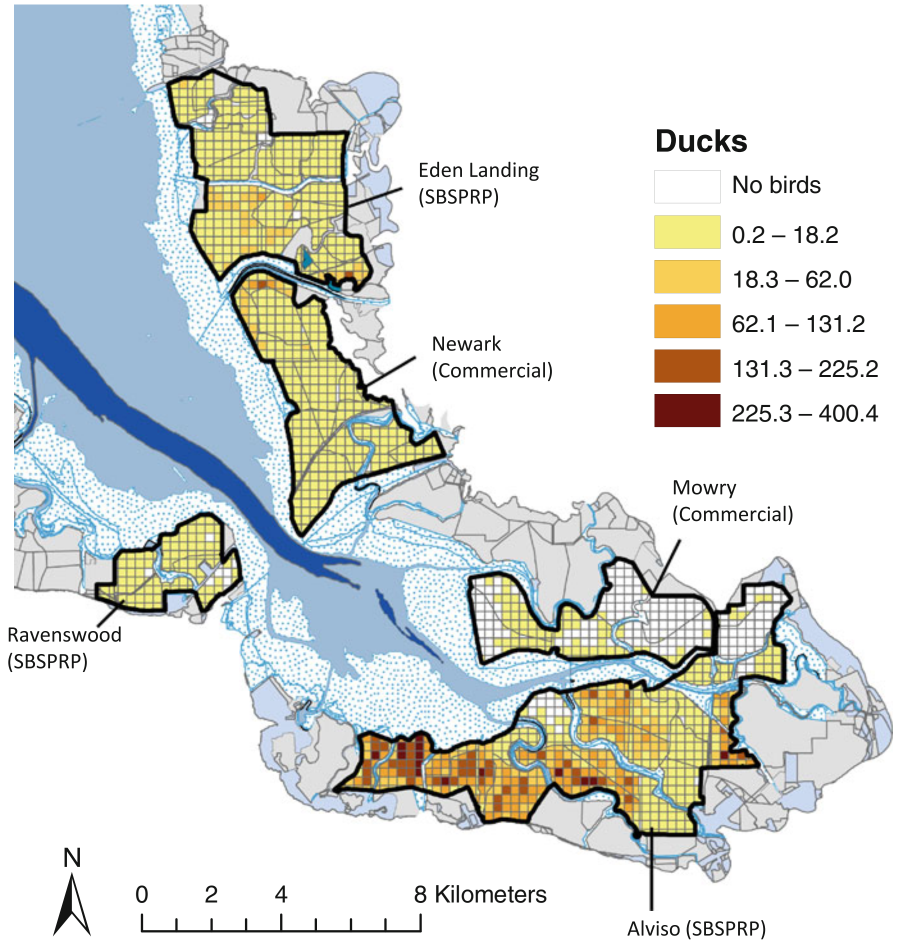

Fig. 7 Winter (Dec–Feb, $n = 12$ dates) geometric mean number of ducks per survey grid cell (6.25 ha) in South San Francisco Bay, Dec 2005–Feb 2009

sandpiper and total shorebird density in Newark was lower and restricted to a few ponds. Additionally, foraging marbled godwit density in Newark was relatively lower than expected based on total density, suggesting the use of this complex for roosting rather than foraging. Although shorebirds used some Ravenswood ponds during the winter and spring, relative use of the Ravenswood complex by all shorebirds declined in favor of Eden Landing ponds during the fall, when most of its Ponds became very saline (>250 g l^{-1}), while the majority of Eden Landing ponds remained <100 g l^{-1}. During the fall, piscivores were distributed throughout Alviso and Eden Landing and in the northern portion of Newark, but not in Ravenswood or Mowry (Fig. 9). Foraging densities were relatively lower in Newark and Mowry than expected based on total densities, whereas foraging densities were highest and pond salinity was lowest in Alviso. Eared grebe density was highest in the moderately saline southern Newark ponds during the winter and spring, and was relatively high in a few Alviso ponds (Fig. 10). Few eared grebes were observed in shallow Eden Landing Ponds, despite their similar salinity to the deeper Newark ponds where density was high.

Discussion

Estuarine wetlands around the world have been lost to development and other forms of habitat alteration, but commercial salt ponds constructed between the intertidal zone and developed uplands have somewhat mitigated that loss for several species of shorebirds, waterfowl, and other waterbirds by providing important foraging (Masero et al., 1999; Takekawa et al., 2009), roosting (Dias, 2009), and nesting (Bluso-Demers et al., 2008; Demers et al., 2008; Demers et al.,

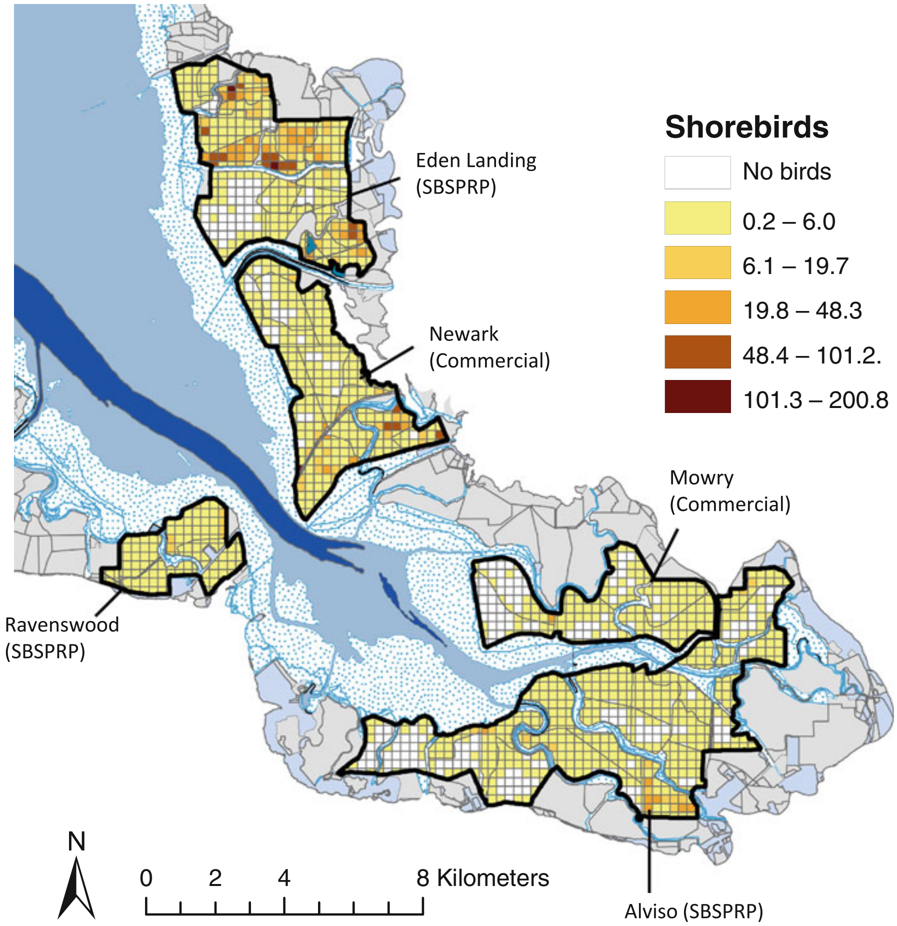

Fig. 8 Winter and spring (Dec–May, $n = 24$ dates) geometric mean number of shorebirds per survey grid cell (6.25 ha) in South San Francisco Bay, Dec 2005–Feb 2009

2010) habitats. Ponds are artificial wetlands that were created not for their wildlife value but for concentrating and evaporating salt, a process that results in the maintenance of ponds representing a wide range of salinities and water depths. Although their value for waterbirds has been well recognized, this value was not part of their intended purpose but rather incidental to it. Thus, ponds can vary widely in their value to waterbirds, which can sometimes be quite low. The potential metabolic costs of high salinity, including weight loss from dehydration and increased thermoregulatory costs from reduced waterproofing of feathers (Ma et al., 2010), may not always be offset by increased foraging opportunities, and the location and configuration of ponds may make the area susceptible to predators. For example, at the Tagus estuary in Portugal, shorebirds did not use salt ponds for feeding and preferentially selected mudflat roosts over salt pond levees, perhaps because those ponds had minimal foraging value and increased predation risk (Rosa et al., 2006). Indeed, the current case study in SFB identified several ponds within otherwise heavily used complexes that did not support many birds of any species studied during any season. In the absence of targeted management strategies, maintaining large numbers and a variety of sizes of ponds may provide the greatest opportunity to include sufficient habitat heterogeneity to meet the habitat needs of multiple species (Paracuellos & Telleria, 2004).

As salt production has become less cost-effective in urbanized estuaries, human use of ponds is declining (Dias, 2009; Paracuellos et al., 2002), and unused ponds are likely to be abandoned or converted for other land uses. Pond conversion reduces available habitat through loss of total pond area, even when ponds are converted to natural tidal habitats, because the number and composition of birds can no longer be sustained. The impact on some species can be disproportionately high if ponds selected for conversion represent habitat conditions most suited for those

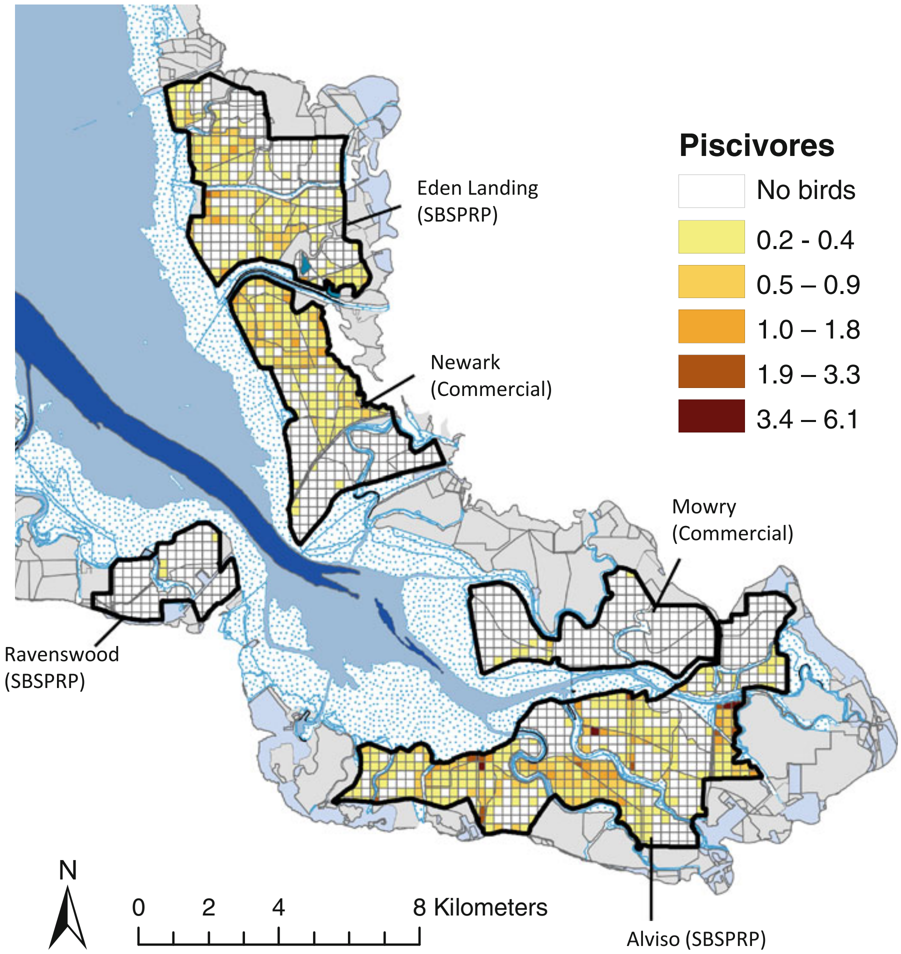

Fig. 9 Fall (Sep–Nov, $n = 9$ dates) geometric mean number of piscivores per survey grid cell (6.25 ha) in South San Francisco Bay, Dec 2005–Feb 2009

species. Although the Newark and Mowry ponds remain under production and are actively managed, these complexes have proportionately fewer of the lower salinity and shallower ponds, such as those in Alviso and Eden landing, that have recently supported large numbers of shorebirds and waterfowl in SFB. Restoration of ponds to tidal salt marsh in Alviso and Eden Landing will likely represent a loss of habitat disproportionate to the total salt pond conversion unless a strategy is implemented to select and manage ponds for long-term management as waterbird habitat.

Two important considerations for waterbird habitat conservation in specific salt ponds and pond complexes are bird distribution and total abundance, as opposed to density. Bird density assessments were affected by distribution differences between ponds; density was determined not only by the number of birds using a site, but by the amount of appropriate habitat within the site. Although we focused on complex-level differences in bird use, distribution mapping illustrated that considerable variability in bird use existed among ponds within complexes, and also within ponds; this variability can be used to inform waterbird habitat managers to select individual ponds from the SBSPRP area providing key habitats for certain species to be retained as managed ponds. Ponds generally had consistent salinity throughout, so within-pond variation in bird density was likely a reflection of bathymetry rather than of salinity. Depth variability within a pond likely favored species diversity, with wading birds using shallow areas and ducks and grebes using deeper areas. Depth variability in general allows use of ponds by a greater number of

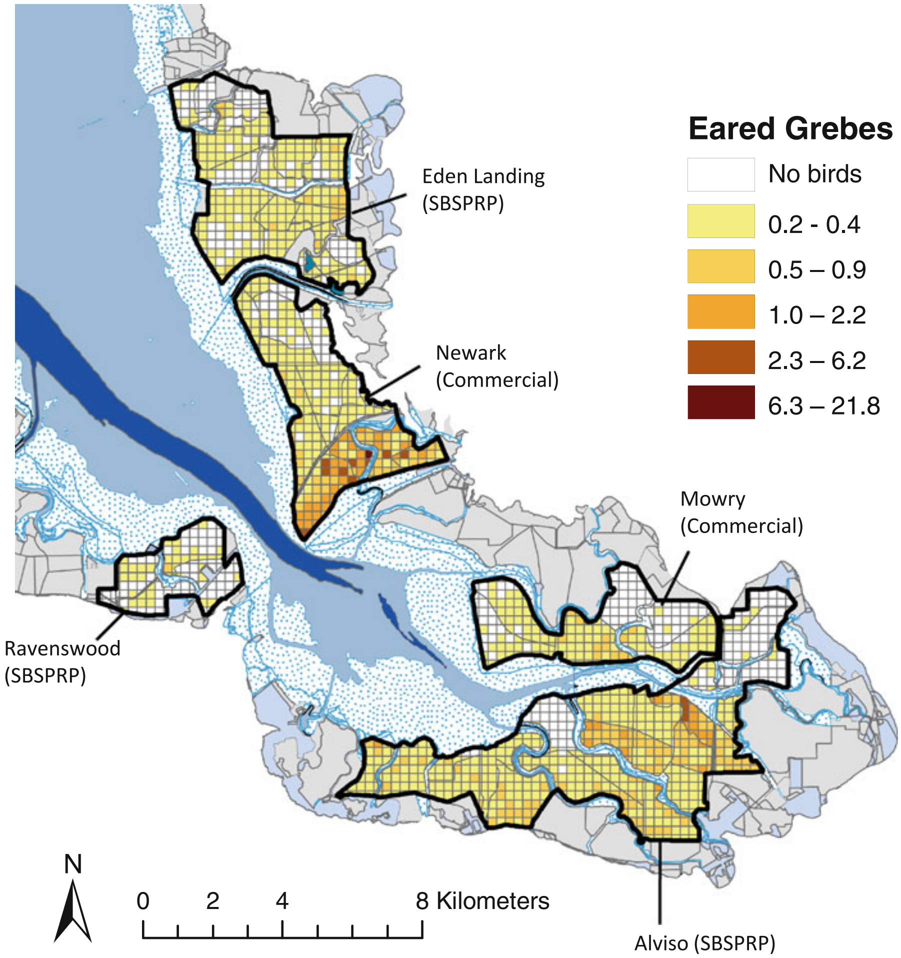

Fig. 10 Winter and spring (Dec–May, $n = 24$ dates) geometric mean number of eared grebes per survey grid cell (6.25 ha) in South San Francisco Bay, Dec 2005–Feb 2009

species and also retains the usability of ponds for single species during periods of water level fluctuations (Ma et al., 2010). Total abundance is also an important consideration for management because commercial ponds make up only about a third of total south SFB pond area, and achieving densities of some species similar to SBSPRP Ponds may still result in a loss of habitat if SBSPRP Ponds are converted. Abundance should also be a consideration because the species that are most dependent on SBSPRP habitat, ducks and shorebirds, are also the most abundant species in the south SFB ponds, and thus require more habitat to support their numbers regardless of habitat quality.

Pond salinity is an important characteristic of ponds used by waterbirds because it determines the species composition and abundance of invertebrate prey items (Velasquez, 1992). Low salinity ponds (<40 g l^{-1}) support benthic invertebrates such as those used by shorebirds in shallow water and diving ducks in deeper water, and they also provide favorable conditions for birds that consume fish, which generally cannot survive in salinities >80 g l^{-1} (Takekawa et al., 2006). However, mid-hypersaline (80–150 g l^{-1}) ponds may be particularly valuable for many shorebirds and other species, including eared grebes, because of high densities of saline-tolerant invertebrates (Masero, 2003; Takekawa et al., 2006; Takekawa et al., 2009). In mid-hypersaline SFB ponds, *Artemia* may represent an important food resource for species that exploit this prey, with biomass exceeding the combined macroinvertebrate biomass of other ponds by several orders of magnitude (Takekawa et al., 2006), and can often be consumed by birds at a high rate with little search time(Masero et al., 2000). However, *Ephydra* are likely to be preyed upon by many more species of waterbirds than are *Artemia* (Anderson, 1970; Takekawa et al., 2009). Because of the salinity tolerance ranges of different prey species, maintaining many ponds representing a range of salinities will best favor waterbird species diversity.

Long-term management of ponds no longer used for salt production is necessary because abandonment of ponds is likely to be detrimental for their waterbird value (Paracuellos et al., 2002; Masero, 2003; Athearn et al., 2009; Dias, 2009). This is in part because water levels and salinities, important drivers of bird use, are no longer maintained. In northern SFB, cessation of water manipulation after salt production ended resulted in ponds that were dry and of little use to waterbirds (Takekawa et al., 2006; Athearn et al., 2009), similar to much of the Ravenswood complex during the current study. SPSPRP managers implemented the ISP in the Alviso and Eden Landing complexes in an attempt to maintain waterbird value in the ponds prior to initiating actions to restore the ponds to tidal salt marsh, but had not yet implemented ISP actions in Ravenswood during this study. Although shorebirds used some Ravenswood ponds during the winter and spring, when natural rainfall flooded the ponds, Ravenswood ponds were generally dry and not usable in the fall. Instead, fall shorebirds were largely concentrated In Eden Landing, where water introduced from SFB under the ISP likely maintained appropriate water depths and salinities during the summer and fall. Implementation of the ISP may have reduced eared grebe habitat in Alviso, however, as salinities were generally reduced. It was primarily ponds intentionally excluded from ISP circulation, in order to maintain mid-salinity habitats, that supported high densities of eared grebes during the current study, and grebe abundance in these ponds was still lower than in previous years (Athearn, unpubl. data).

Conclusions

Our results suggest that because pond habitat value differs among ponds, selection of ponds for conversion may lead to loss of waterbird habitats. Distribution differences among the species and groups examined suggest that pond salinities and depths can be targeted to meet specific habitat requirements for key species and groups, so it may be possible to minimize habitat loss by maintaining managed ponds within targeted salinity and depth ranges, by selecting ponds for conversion that are not currently used by key species and foraging groups, or some combination of these approaches. Waterbirds should be able to quickly adapt to landscape changes as they are highly mobile and readily move between habitats in response to tidal fluctuations and changing foraging conditions (Burger et al., 1977; Athearn et al., 2009), but maintaining sufficient habitat for waterbirds that have come to depend on salt ponds will be difficult as ponds are converted for marsh restoration or other uses. Such an effort will require consideration of existing habitat value within and outside the area of pond conversion. Often, as in SFB, past development of coastal zones and inland wetlands has resulted in fewer alternative sites available for waterbirds.

Alternative wetlands may not exist outside of the area of pond conversion to compensate for loss of waterbird habitats in the ecosystem. Commercial salt ponds of waterbird habitat value similar to SFB continue to be decommissioned in Europe, other locations in the United States, and elsewhere. An important consequence of this loss of habitat is that careful planning by resource managers is needed to determine the number and characteristics of ponds and their management strategy to ensure that sufficient habitat remains available for waterbirds. It should be encouraging that past bird abundances in ponds, while often high compared to other local habitats, were maintained unintentionally through commercial salt production. In SFB, many ponds were used by certain species, but several ponds were not well-used by any species. Direct management action could emphasize emulating the depth, salinity, and bathymetric characteristics of well-used ponds in ponds not currently targeted for conversion to provide higher quality habitats within remaining ponds.

Acknowledgments U. S. Geological Survey, Western Ecological Research Center and U.S. Fish and Wildlife Service, Don Edwards San Francisco Bay National Wildlife Refuge sponsored this project with additional support from the Resources Legacy Fund, State Coastal Conservancy, San Francisco Foundation, USGS Priority Ecosystem Science Program, and membership of the San Francisco Bay Bird Observatory. Special thanks to the field staff including M. Mammoser, A. Murphy, C. Padula, S. Scott, and J. Scullen (SFBBO); and A. Anderson, M. Bauman, L. Bloch, K. Brailsford,

J. Brown, M. Carrol, W. Chan, C. Daggett, L. DeMais, E. French, E. Garfinkle, P. Gibson, B. Hattenbach, K. Henderson, K. Hirsch, C. Kranz, S. Major, D. Monié, S. Moskal, A. Murphy, S. Piotter, A. Rowan, A. Schultz, A. Shults, L. Smith, R. Unks, and B. Wensky (USGS). S. Moskal led and coordinated bird surveys for USGS, while K. Henderson led water quality monitoring for USGS and provided field and lab support for SFBBO. We appreciate support and logistical assistance provided by Don Edwards San Francisco Bay National Wildlife Refuge (J. Bradley, J. Buffa, C. Morris, E. Mruz, and M. Stewart), California Department of Fish and Game (J. Krause), and Cargill, Inc. (P. Mapelli and B. Ransom). We thank D. Barnum, S. Demers, D. Elliott-Fisk, J. Hunter, K. Phillips, and J. Yee for helpful comments on the manuscript. The use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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