CHAPTER TWELVE

Bird Communities

EFFECTS OF FRAGMENTATION, DISTURBANCE, AND SEA LEVEL RISE ON POPULATION VIABILITY

John Y. Takekawa, Isa Woo, Karen M. Thorne, Kevin J. Buffington, Nadav Nur, Michael L. Casazza, and Joshua T. Ackerman

CONTENTS

Tidal Marsh Bird Community
Habitat Fragmentation
Human Disturbance
Sea Level Rise
Population Viability
Restoration Implications
Synthesis and Future Directions

The San Francisco Bay Estuary supports a large and diverse bird community. More than 50% of most Pacific flyway diving duck populations are found in the Estuary during the winter months (Trost 2002; U.S. Fish and Wildlife Service 2002). San Francisco Bay has been designated as a site of international importance for shorebirds (Western Hemisphere Shorebird Reserve Network), supporting millions of individuals (Morrison et al. 2001; Takekawa et al. 2001; Warnock et al. 2002), including species that use tidal marsh habitats. In total, the Bay's tidal marshes support at least 113 bird species that represent 31 families (Takekawa et al., in press).

Human development and encroachment have greatly reduced the extent of tidal marshes in the San Francisco Bay Estuary and altered or fragmented its remaining areas. Native bird communities that use marshes have been adversely affected, and populations of several species or subspecies are now threatened because of their reduced abundance and limited distribution (Harvey et al. 1992; Goals Project 2000; Greenberg et al. 2006b; Shuford and Gardali 2008). Greenberg et al. (2006b) noted that birds inhabiting tidal marshes are disproportionately listed as endangered, threatened, or as species of conservation concern, compared with bird species in other habitats. Within the Bay, 17 of the 87 tidal marsh species (Harvey et al. 1992) and 14 of the 28 tidal marsh–associated birds (Table 12.1) have been designated with special conservation status from state or federal agencies.

Some species may be considered tidal marsh obligates if they are found principally in salt marsh habitats and are adapted for these saline and tidal habitats. For example, San Francisco Bay song sparrows are adapted to high salinities and can maintain their body mass in salt marshes, while riparian species such as the Marin song sparrow (*Melospiza melodia gouldii*) are less adapted for saline conditions (Basham and Mewaldt 1987). Several species of birds are regularly found in the tidal marshes of the Bay, and at least six subspecies from three families are considered primarily tidal marsh obligates

TABLE 12.1

Representative Species from Bird Communities in Tidal Salt Marshes in San Francisco Bay

Family	Common name	Scientific name	Habitat association[a]	Special status[b]
Ardeidae	Great blue heron	*Ardea herodias*	UT, MP, CH, P	CSC S4
	Great egret	*Ardea alba*	UT, MP, CH, P	CSC S4
	Snowy egret	*Egretta thula*	UT, MP, CH, P	CSC S4
Accipitridae	Northern harrier	*Circus cyaneus*	UT, MP	CSC S3, BSSC3
	Red-tailed hawk	*Buteo jamaicensis*	UT, MP	
	White-tailed kite	*Elanus leucurus*	UT, MP	CSC S3, FP
Emberizidae	Alameda song sparrow	*Melospiza melodia pusillula*	UT, MP	CSC S2, BCC, BSSC2
	Bryant's savannah sparrow	*Passerculus sandwichensis alaudinus*	UT, MP	BSSC3
	Golden-crowned sparrow	*Zonotrichia atricapilla*	UT, MP	
	San Pablo song sparrow	*Melospiza melodia samuelis*	UT, MP	CSC S2, BCC, BSSC3
	Savannah sparrow	*Passerculus sandwichensis*	UT, MP	
	Suisun song sparrow	*Melospiza melodia maxillaris*	UT, MP	CSC S2, BCC, BSSC3
	White-crowned sparrow	*Zonotrichia leucophrys*	UT, MP	
Falconidae	Peregrine falcon	*Falco peregrines*	UT, MP, P	CSC S3, FD, CE, FP, BCC
Icteridae	Red-winged blackbird	*Agelaius phoeniceus*	UT, MP	

(continued)

Parulidae	Salt marsh common yellowthroat	*Geothlypis trichas sinuosa*	UT, MP	CSC S2, BCC, BSSC3
Podicipedidae	Pied-billed grebe	*Podilymbus podiceps*	CH, P	
Rallidae	American coot	*Fulica americana*	MP, CH, P	
	Black rail	*Laterallus jamaicensis*	UT, MP	CSC S1, BCC, FP, CT
	California clapper rail	*Rallus longirostris obsoletus*	MP, CH, P	CSC S1, FE, CE, FP
	Sora	*Porzana carolina*	MP, P	
	Virginia rail	*Rallus limicola*	MP, P	
Recurvirostridae	American avocet	*Recurvirostra americana*	MP, CH, P	
	Black-necked stilt	*Himantopus mexicanus*	MP, CH, P	
Strigidae	Great horned owl	*Bubo virginianus*	UT, MP	
	Short-eared owl	*Asio flammeus*	UT, MP	CSC S3, BSSC3
Troglodytidae	Marsh wren	*Cistothorus palustris*	MP	
Tytonidae	Barn owl	*Tyto alba*	UT, MP	

[a] UT = upland transition and high marsh plain; MP = mid and low marsh plain; CH = tidal creeks and channels; P = pans and ponds.

[b] BCC = federal birds of conservation concern; BSSC = California bird species of special concern and priority ranking (1–3); CE = California endangered; CSC = California species of concern; natural heritage status subnational ranking for California (S1 = critically imperiled, S2 = imperiled, S3 = vulnerable to extirpation, S4 = apparently secure, factors exist to cause concern); CT = California threatened; FD = federal delisted; FE = federal endangered; FP = federal protected; FT = federal threatened; WL = California watch list.

(Table 12.1): three song sparrows (Alameda song sparrow, *M. m. pusillula*; Suisun song sparrow, *M. m. maxillaris*; and San Pablo song sparrow, *M. m. samuelis*), the salt marsh common yellowthroat (*Geothlypis trichas sinuosa*), and two rails (California black rail, *Laterallus jamaicensis coturniculus*; and California clapper rail, *Rallus longirostris obsoletus*). These tidal marsh birds face numerous threats (see Takekawa et al. 2006a), including habitat loss (urbanization, sea level rise), habitat deterioration (fragmentation, disturbance, contaminants), and competitive interactions (due to invasive species and predation).

Hundreds of wetland restoration projects have been initiated in the past two decades to restore areas to tidally influenced marshes and ameliorate these threats (Goals Project 1999; Steere and Schaefer 2001). Many San Francisco Bay restoration projects target the expansion of habitat for species with conservation concerns; for example, the largest tidal wetlands restoration project on the West Coast is the South Bay Salt Pond Restoration Project (Trulio et al. 2007). However, wetland restoration sites may not be functionally equivalent to natural marshes in terms of suitability for tidal marsh–dependent wildlife. For example, Pacific cordgrass (*Spartina foliosa*) plants in a created wetland in Southern California were less vigorous and failed to provide the vertical structure needed for nests of the endangered light-footed clapper rail (*Rallus longirostris levipes*) (Zedler 1993). In addition, sea level rise and extreme tide events will likely exacerbate threats already faced by tidal marsh birds by reducing the amount of tidal marsh and upland refugia available (Greenberg et al. 2006a; Takekawa et al. 2006a). In this chapter, we summarize information from the literature on San Francisco Bay tidal marsh birds (Takekawa et al. 2006b; Takekawa et al. in press) to describe the diverse tidal salt marsh bird community in the Estuary, explain some of the primary factors affecting the success of their populations, and discuss implications for restoration.

TIDAL MARSH BIRD COMMUNITY

The tidal range in San Francisco Bay from mean lower low water to mean higher high water (MHHW) varies widely across the Estuary from 0.93 m to 2.04 m (Figure 12.1). Tidal marshes are characterized by distinct vegetation zones based on the degree of local tidal inundation and the salinity tolerance of plants (Josselyn 1983; Goals Project 1999). Bird species are distributed along the gradient from the upland–high marsh transition to the estuarine edge (Figure 12.2), reflecting partitioning of their habitats as well as differences in foraging behavior. From higher to lower elevation, habitats include upland transition and marsh plain; tidal creeks and channels; and pans, ponds, and mudflats. Takekawa et al. (in press) present detailed information on the habitats and foraging guilds of San Francisco Bay tidal marshes and bird communities, which we summarize here.

The upland transition occurs above MHHW and supports taller vegetation such as coyote bush (*Baccharis pilularis*). Some terrestrial passerines are found associated with these habitats. The marsh plain occurs between mean high water and MHHW and is regularly inundated. It is dominated by common pickleweed (*Sarcocornia pacifica*) and also supports species that are less tolerant to inundation, such as salt grass (*Distichlis spicata*), fat hen (*Atriplex triangularis*), and alkali heath (*Frankenia salina*) (Goals Project 1999). Characteristic birds of the marsh plain include California black rail, northern harrier (*Circus cyaneus*), and song sparrows.

Vegetation that fringes channels and mudflats is dominated by tall emergent species such as cordgrass (*Spartina* spp.) or, in more brackish waters, bulrushes and tules (*Bolboschoenus* spp., *Schoenoplectus* spp.) that provide cover for birds. Sufficient plant height for nesting birds in these areas not only reduces the probability of nest flooding but also provides cover against predators (Zedler 1993; Greenberg et al. 2006a; Reinert 2006). Characteristic bird species include California clapper rail, willet (*Catoptrophorus semipalmatus*), and marsh wren (*Cistothorus palustris*).

Tidal creeks and channels form drainage networks through marsh plain areas. Channels serve as conduits for water, sediments, nutrients, and biota such as phytoplankton, zooplankton, and nekton (small fish and decapod crustaceans). Great blue herons (*Ardea herodias*), great egrets (*Ardea alba*), and California clapper rails are among the waterbirds that feed on the small fish and benthic invertebrates found in tidal creeks (Table 12.1). Salt pans, ponds, and mudflats are areas that lack vegetation or support submergent vegetation. Waterfowl and shorebirds may use

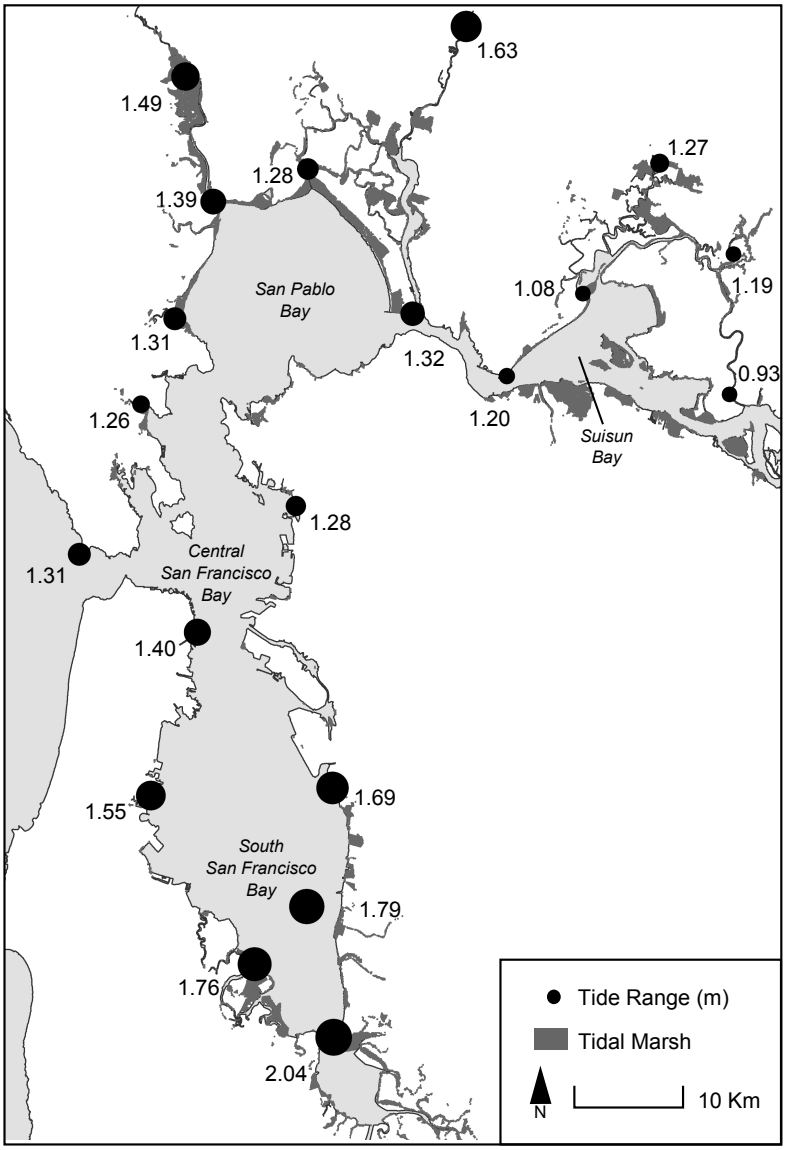

FIGURE 12.1. Variation in tidal range (mean lower low water to mean higher high water) from sites across the San Francisco Bay Estuary. Tidal data compiled from the National Oceanic and Atmospheric Administration website (http://www.tidesandcurrents.noaa.gov).

these habitats when filled with water, especially as stopover sites during migration, to consume the rich supply of invertebrates such as brine shrimp (*Artemia franciscana*) and brine flies (*Ephydra* spp.) (Takekawa et al. 2000; Takekawa et al. 2001; Warnock et al. 2002; Takekawa et al. 2005).

Many tidal marsh birds are omnivorous and take advantage of terrestrial and marine food webs (Adam 1990; Kwak and Zedler 1997; Cloern et al. 2002). Virtually all of the passerines found in tidal marshes, including swallows, song sparrows, savannah sparrows (*Passerculus sandwichensis*), marsh wrens, common yellowthroat, and red-winged blackbirds (*Agelaius phoeniceus*), are aerial foragers or gleaners that feed in the plant canopy. Raptors such as northern harriers, white-tailed kites (*Elanus leucurus*), red-tailed hawks (*Buteo jamaicensis*), and short-eared owls (*Asio flammeus*) are tertiary aerial consumers

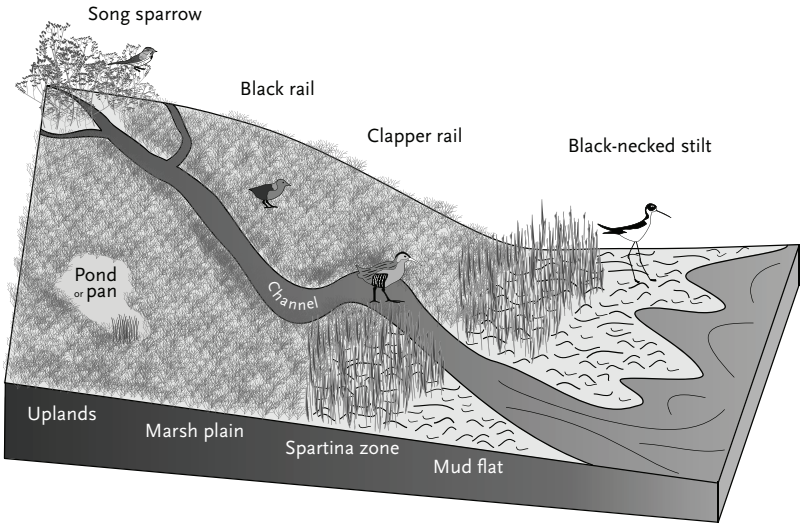

FIGURE 12.2. Representative bird species and their salt marsh habitats along the tidal gradient within a parcel.

that forage on small mammals, birds, or other insects.

Surface gleaners capture invertebrate prey such as beetles (e.g., *Cicindela* spp., *Bembidion* spp.), spiders (*Pardosa* spp., *Phidippus* spp.), amphipods (*Traskorchestia* spp.), snails (*Myosotella* spp., *Assiminea* spp.), isopods, and seeds (Takekawa et al. unpublished data). Tidal marsh song sparrows may have longer and deeper bills, compared with their nontidal marsh relatives, adapted to capturing invertebrate prey (Grenier and Greenberg 2006), while herbivorous species such as Moffitt's Canada geese (*Branta canadensis moffitti*) graze on aquatic vegetation. Benthic foragers such as black-necked stilts (*Himantopus mexicanus*), California clapper rail, herons, and egrets feed in channels, ponds, or mudflats on organisms that include crabs (*Hemigrapsus* spp.), threespine stickleback (*Gasterosteus aculeatus*), silversides (*Menidia* spp.), gobies (Gobiidae), prickly sculpin (*Cottus asper*), brine shrimp (*Artemia franciscana*), shrimp (*Palaemon* spp., *Crangon* spp.), and water boatmen (*Trichocorixa reticulate*) (Goals Project 2000). In contrast, dabbling ducks, herons, and grebes may obtain pelagic prey, including aquatic vegetation, fish, and other invertebrates. Diving ducks and waterbirds that forage by tipping are benthivorous, feeding on bottom substrates of ponds and mudflats to obtain invertebrates and submergent plant parts.

BLACK-NECKED STILT
PANS, PONDS, AND MUDFLATS

Historically uncommon residents (Grinnell et al. 1918; Grinnell and Wythe 1927). Common in the fall (>6,200), winter (>5,100), and spring (>1,000) (Stenzel et al. 2002). Breeds in marshes (590 pairs in South Bay: Rintoul et al. 2003), but uses salt ponds heavily for foraging. Radio-marked stilts used managed marshes (49%–66%) and salt ponds (20%–32%) heavily (Ackerman et al. 2007; Ackerman et al. unpublished data; Hickey et al. 2007).

Aquatic foragers that consume small fish and some seeds but also invertebrates such as brine shrimp and brine flies when foraging in ponds or pans (Hamilton 1975; Robinson et al. 1999). Nest in managed or diked marsh, with 88% of 385 nests in South Bay in marsh (Ackerman unpublished data) and 95% associated with vegetation within 1 m of nest bowl at 15.2 cm height.

HABITAT FRAGMENTATION

Tidal marsh habitat fragmentation is the process by which larger, contiguous areas are broken up into smaller, more disconnected areas. Johnson

(2001) identified three mechanisms that contribute to the deleterious impacts of habitat fragmentation: patch-size dynamics, edge effects, and isolation. These mechanisms interact with species-specific life histories and demographic parameters (home range, habitat requirements at different life stages, reproductive success, survival, and dispersal dynamics) as well as the fragmented environment (degree and extent of discontinuity, landscape scale to which specific life stages are sensitive) (Wiens 1994; Bolger et al. 1997; Haig et al. 1998; Bergin et al. 2000; Chalfoun et al. 2002; Stralberg et al. 2010).

Urban development and habitat conversions in San Francisco Bay have resulted in loss of 80% of historic tidal marshes, and the remnant parcels are often patchy, narrow areas drained by compromised channel networks and surrounded by developed areas (Goals Project 1999; Takekawa et al. 2006b). The modern Bay tidal marsh landscape is primarily limited to edges of large tidal creeks and sloughs and along the bayside margins of levees and roads (Takekawa et al. 2006b). Patch size effects are those that result from differential use or reproductive success associated with habitat patches of different sizes. In tidal marshes on the eastern coast of the United States, species richness was greater in larger salt marshes (Shriver et al. 2004), and salt marsh specialists such as the seaside sparrow (*Ammodramus maritimus*) were absent or occurred less frequently in smaller marshes (<100 ha: Benoit and Askins 2002).

Abundance of tidal marsh bird species in San Francisco Bay has been examined at both the local habitat and landscape spatial scales (Spautz et al. 2006; Stralberg et al. 2010). Relative abundance of song sparrows had a strong positive relationship to marsh size, while common yellowthroat and marsh wren demonstrated decreasing abundance with increasing perimeter-to-area ratio (Spautz et al. 2006). Presence of California black rail was suggested to be associated with marsh size (Evens and Nur 2002), although abundance is more strongly related to local habitat features such as taller vegetation surrounding channels and areas of high marsh (Spautz et al. 2006; Stralberg et al. 2010). Effects of increased "edge" habitats include effects on behavior and interspecific interactions such as avoidance, predation, and competition. Nest survival of tidal marsh song sparrows was negatively associated with proximity to upland habitat (which may harbor nest predators) and positively associated with proximity to bay edge (Chan et al. 2002). High marsh plains and upland transition zones that are used as high-tide refugia zones are often covered by nonnative plant species, limited to steep-sided levees or roads, or flanked by urban landscapes that are corridors for predators.

Invasive mammalian predators of birds often thrive in San Francisco Bay tidal marshes, because of their proximity to industrial areas and housing developments. Population estimates of the federally endangered California clapper rail were precipitously low in the 1990s because of the compounding effects of habitat loss, fragmentation, and predation (primarily on adults), and it is believed that aggressive predator control of introduced red fox (*Vulpes vulpes*) and feral cats has allowed the population to recover (Albertson and Evens 2000; Harding et al. 2001; Liu et al. 2009).

CALIFORNIA BLACK RAIL
MARSH PLAIN

San Francisco Bay tidal marshes support 90% of this state-threatened and highly secretive subspecies (Evens et al. 1991; Goals Project 2000; Conway and Sulzman 2007). In decline since the 1900s (Eddleman et al. 1994) but up 3.2% from 1996 to 2008, perhaps responding to restoration (Wood 2009).

Pickleweed habitat (Evens and Nur 2002) with tall vegetation to avoid predation (Evens and Page 1986; Goals Project 2000; Tsao et al. 2009). Breeds in mature tidal marshes (Evens et al. 1991; Spautz et al. 2006). Runs below vegetation (Eddleman et al. 1994) and selects for habitat structure (Tsao et al. 2009; Stralberg et al. 2010) with use correlated with upland, agriculture, channels <1 m wide, marsh size >8 ha, creek proximity, and predator access (Evens and Nur 2002; Spaultz et al. 2006). Small breeding home ranges (0.65 ha) and nest bowl with canopy 46–69 cm above nest (Ehrlich et al. 1988; Flores and Eddleman 1993). Consumes insects, aquatic invertebrates, and seeds (Ehrlich et al. 1988), with high-frequency items: beetles (97%), spiders (72%), amphipods (44%), and snails (28%) (Takekawa et al. unpublished data).

Clapper rail population size has also been affected by nest failures, of which 45% were attributed to egg predation, primarily by avian predators and invasive rats (Schwarzbach et al. 2006).

Habitat fragmentation also can act as an isolating mechanism resulting in higher extinction rates, lower colonization rates, lower species richness (MacArthur and Wilson 1967), higher nest-predation rates (Chalfoun et al. 2002), higher nest-parasitism rates, and alteration of ecological processes (Saunders et al. 1991). Tidal marsh song sparrows breeding in peripheral habitat close to uplands had lower nest survival than those in the centers of marsh areas (Chan et al. 2002). Fragmentation is thought to negatively affect San Pablo song sparrows (Takekawa et al. 2006b), where populations in smaller, more isolated fragments would be more susceptible to local extinction (Walton 1978; Marshall and Dedrick 1994; Nur et al. 1997). Recent estimates of nest survival for the San Pablo and Suisun song sparrows indicate levels of nest survival that are too low to sustain populations (Spautz and Nur 2008a,b). Concern is even greater for the Alameda subspecies, whose habitat is even more fragmented and whose nest survival is even lower than that of the other tidal marsh song sparrows (Nordby et al. 2009).

Tidal marsh bird responses to habitat fragmentation (with respect to occupancy, reproduction, or survival) can be variable, species specific, and context specific, as observed in a variety of habitat types (Bolger et al. 1997; Chalfoun et al. 2002). Obligate tidal marsh birds can be differentially affected by fragmentation, depending on their level of habitat specialization (Andren 1994; Benoit and Askins 2002) and the landscape scale to which they are sensitive (i.e., patch sensitivity, sensu Kotliar and Wiens 1990). Recent studies (Spautz et al. 2006; Stralberg et al. 2010) have indicated that abundance of song sparrows (San Pablo, Suisun, and Alameda subspecies) and California black rails are correlated with marsh size, configuration, isolation, and other landscape-scale factors as well as with local-scale factors such as vegetation composition and structure (Tsao et al. 2009).

HUMAN DISTURBANCE

The growing human population leads to encroachment of natural areas, relegating wild animals to suboptimal habitats (Benítez-López et al. 2010). In addition, infrastructure developments for modes of transportation (i.e., air, rail, road, water), as well as human recreational impacts, affect wildlife both directly through habitat fragmentation, disturbance, and collisions and indirectly through water, noise, and air pollution (Kuitunen et al. 1998; Spellerberg 1998; Congleton et al. 2000; Gutzwiller and Barrow 2003; Bautista et al. 2004). For example, weekend use of recreational trails fringing San Francisco Bay marshes may exceed 400 people per hour (Trulio and Sokale 2008), and birds may be particularly sensitive to humans accompanied by dogs (Lafferty 2001a,b). Adverse behavioral responses to disturbance may result in changing abundance and distribution of populations, species composition and interactions, and potentially the entire structure of communities (Knight and Cole 1995).

Reactions to disturbance vary by species, but larger birds characterized by a longer life span and that use more extensive areas are more likely to be affected (Ydenberg and Dill 1986). Waterbirds that forage in intertidal and subtidal habitats are limited by water depth, prey quality, and prey availability (Lovvorn and Gillingham 1996), and they maximize their time in energetically profitable habitats. In addition, tidal marsh birds need adequate, predator-free roosting areas to rest between foraging bouts or to wait for low tides to expose mudflat foraging areas. Birds in better condition may be able to take advantage of distant foraging sites (Beale and Monaghan 2004), while birds in poorer condition may remain in areas where human use is high, because they are unable to take advantage of alternative foraging opportunities (Gill et al. 2001).

Disturbance increases energetic demands and reduces available time for other activities such as foraging, thermoregulation, migration, and breeding. In addition, disturbances may ultimately influence the ability of birds to migrate and successfully reproduce (Bell and Austin 1985; Haramis et al. 1986; Belanger and Bedard 1990). Disturbance during the nesting period can result in catastrophic reproduction failure as a result of displacement of breeders, which may provide nest predators with easy access to nests. Repeated disturbance may result in avoidance behavior, in which birds forage in habitats with less food profitability or leave an area, or it may even

reduce survival (Davidson and Rothwell 1993). For example, disturbed shorebirds and herons in Southern California wetlands flew farther at sites that had lower levels of human use (Ikuta and Blumstein 2003). Natural buffer zones to human disturbance may be critical to shield wetland habitats from effects of disturbance (McKinney et al. 2009).

SEA LEVEL RISE

Current climate change scenarios include changes in precipitation patterns, increases in extreme climatic events, changes in seasonal phenology, increases in mean and extreme ambient temperatures, sea level rise (SLR), and changes in ocean temperature and acidity (Cayan et al. 2005; Hansen et al. 2006; Harris et al. 2006; Intergovernmental Panel on Climate Change 2007). Coastlines and estuaries have been designated as high-risk impact zones (Intergovernmental Panel on Climate Change 2007), in particular from projected SLR. In California, projected changes include decreased winter snowpack with higher snow lines, decreased freshwater input in the summer with declining late-season runoff, and increases in mean ambient temperatures and SLR (Dettinger and Cayan 1999; Cayan et al. 2001, 2006; Knowles and Cayan 2002, 2004; Dettinger et al. 2004; Knowles 2010). Changes in precipitation and snow cover could alter both the freshwater input and estuarine salinity levels, both temporally and spatially, throughout San Francisco Bay (Cayan et al. 2008), altering habitats used by tidal salt marsh birds.

The most significant effect of climate change on San Francisco Bay tidal salt marsh habitats will be SLR. Sea level has risen 1.8 mm a year between 1961 and 1993, and more recently 3.1 mm a year since 1993 (Intergovernmental Panel on Climate Change 2007). SLR projections range from 0.19 m to 0.58 m (Intergovernmental Panel on Climate Change 2007) to as high as 1.5 m (Jevrejeva et al. 2006; Jevrejeva et al. 2008) or even 1.9 m (Vermeer and Rahmstrof 2009) by 2100. Many San Francisco Bay marshes are bordered by sea walls, levees, and roads and not natural uplands, preventing upslope transgression of the vegetation. Many San Francisco Bay salt marsh birds have evolved to live within unique habitats of this tidal ecosystem (Table 12.1). In the Gulf of Mexico, Rush et al. (2010) found that use of marsh edge for foraging by clapper rails decreased relative to tidal heights—SLR will change foraging depths that species have adapted to (Sayre and Rundle 1984). This may lead to a loss of foraging area and a reduced window of foraging time for many birds. SLR that changes the duration and depth of tidal flooding could reduce the geographical extent of tidal salt marsh habitats in San Francisco Bay, greatly affecting avian demographic and community structure.

As salt marsh inundation patterns change, bird species will be at risk of increased competition and predation pressure, reduced breeding success, changed food web dynamics and foraging availability, and decreased availability of tidal habitat, resulting in displacement into unsuitable or subpar habitat. Impacts will vary between species, depending on their mobility and adaptability. For example, artificial levees and sea walls are often obstacles to dispersal for many less mobile birds, such as the clapper rail (Eddleman and Conway 1998) and challenge the more mobile species in terms of dispersal distances. The abundance and breeding success of the marsh wren has been shown to have a positive relationship to wetland size (Tozer et al. 2010); therefore, overall reduction of an area and its connectivity may impede relocation and long-term viability.

SLR may exacerbate nest inundation or increase predation risks, especially during highest high tides. During the late spring and early summer, the highest tides flood nests of song sparrows and lead to mortality of nestlings. If these extreme high tides become more frequent, song sparrows may not be able to complete the nesting cycle before the next high tide event. One scenario indicated that SLR of 20 cm may produce a 28 cm increase in extreme high tides (Malamud-Roam 2000), but the increase in extreme high tides is dependent on the bathymetry and hydrology of a particular marsh parcel. With many of the bayland wetlands adjacent to cities or behind levees, loss of wetland habitats may result. The risks of SLR in combination with the invasion of nonnative species such as perennial pepperweed (*Lepidium latifolium*), smooth cordgrass (*Spartina alterniflora*) and *S. foliosa* × *S. alterniflora* hybrids may threaten the persistence of species. Smooth cordgrass may invade future restoration projects, leading to alterations in food resources and foraging habitat for song sparrows and creating more favorable habitat for marsh wrens. Popula-

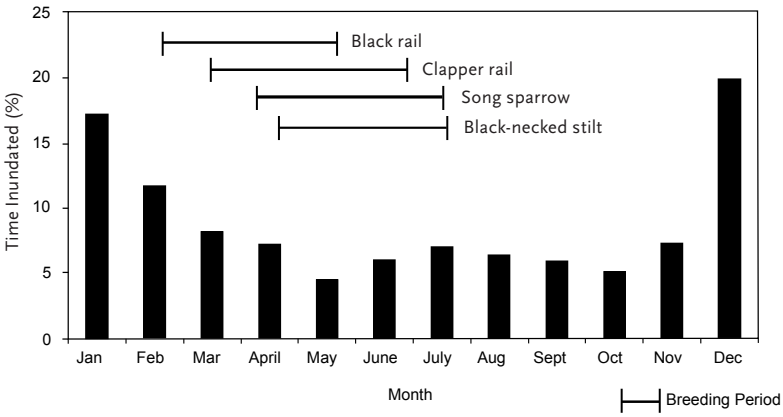

FIGURE 12.3. Monthly percent inundation of tidal marshes in the San Francisco Bay and breeding periods for representative bird species.

tion increases in marsh wrens may act to lower nesting success of song sparrows (J. C. Nordby unpublished data). Although such deleterious effects of marsh wrens on song sparrows have yet to be confirmed, increases in one species are associated with decreases in the other (PRBO unpublished data). In southern San Francisco Bay, Alameda song sparrows that nested within the invasive *Spartina* were more likely to fail during tidal flooding than those with nests built in native vegetation, because the nests in invasive *Spartina* were built at lower elevation (Nordby et al. 2009).

Plant cover and channel structure provide hiding and nesting areas for salt marsh birds (Evens and Nur 2002; Spautz et al. 2006); outside of this habitat they are vulnerable to predation. For example, the clapper rail population increased after removal of the nonnative red fox (*Vulpes vulpes regalis*) that preys on adult and young California clapper rails (Harding et al. 2001). In addition, the presence of feral cats (*Felis catus*) has had a large impact on California clapper rail populations in near-urban marshes (Foin et al. 1997). Tsao et al. (2009) found that the California black rail preferred areas of dense vegetation in the high intertidal zone for breeding and nesting sites, presumably to avoid predators during nesting. An increase in mean SLR or storm frequency or a synergism of the two will increase predation exposure of both adults and young by forcing them out of preferred areas of dense vegetation. Extreme weather events coupled with high tides may drown salt marsh vegetated habitats, resulting in heavy predation, documented for California black rails (Evens and Page 1986).

Tidal salt marsh provides nesting habitat for numerous bird species (Table 12.1). The breeding season for many tidal marsh birds coincides with lower spring tides in March–April, as opposed to higher high tides in June–July (Johnston 1956b) (Figure 12.3). To protect against flooding, nests are constructed above mean high water levels, are designed to float, or are located in taller vegetation surrounding channels and high elevation areas (Johnston 1956a; Reinert 2006; van de Pol et al. 2010), but nests that are too high may have increased visibility and predation (Greenberg et al. 2006a). Birds with small home ranges during the breeding season, like the black rail, select habitats in close proximity to high-tide refugia sites such as upland levees or tall vegetation along channels (Tsao et al. 2009). Nest site selection requires birds to balance inundation risk from tides with overstory protection from predators (e.g., song sparrows: Johnston 1956a; Greenberg et al. 2006a). While egg mortality from flooding varies among species and year (e.g., song sparrows 24%: Greenberg et al. 2006a; clapper rail 8%: Schwarzbach et al. 2006), it represents a significant cause of mortality of young that will likely increase under rapid SLR.

For many bird species, little data exist relating to feeding and foraging requirements. The rail species that penetrate the vegetation predominately feed on insects and crustaceans (Eddleman and Conway 1998). Other birds, such as the black-necked stilt (*Himantopus mexicanus*),

forage along sloughs and edges of tidal marshes (Robinson et al. 1999). In addition, the California clapper rail prefers low intertidal-zone marsh dominated by cordgrass (*Spartina* spp.) along the mudflat edge and channel networks for feeding (Foin et al. 1997).

POPULATION VIABILITY

Understanding how birds use habitat patches is a fundamental requirement to being able to identify functions and structures of landscapes critical to a bird's life cycle (Wiens 1994, 1996; Walters 1998). For birds of tidal marshes, in addition to habitat characteristics of the marsh itself (Stralberg et al. 2009), the size and shape of wetland patches may determine their value for local populations (Benoit and Askins 2002). Area-sensitive species respond to the size of habitats and may fail to find or use small habitat patches resulting from increased fragmentation.

In planning wetland restoration projects, larger patches are typically thought to be more valuable for most species (Goals Project 1999), and corridors between tidal marsh patches have often been considered valuable for maintaining populations. However, there may not be a benefit to ever-larger marshes. In urbanized areas, restoring small patches may be more cost-effective than developing movement corridors, especially for birds, which display some mobility (Beier and Noss 1998). Thus, a network of patches may promote the long-term sustainability of tidal marsh bird populations better than a few large, isolated marshes would.

Habitats in the San Francisco Bay Estuary have been reduced, modified, and fragmented by loss of 80% of the Bay's tidal marshes and 42% of its tidal flats and by construction of >13,000 ha of artificial salt evaporation ponds (Goals Project 1999). Hundreds of recent wetland restoration projects will create significant changes to the landscape, including conversion of thousands of hectares of salt ponds to tidally influenced marshes (Goals Project 1999; Steere and Schaefer 2001; Stralberg et al. 2009). Salt evaporation ponds have been part of the Estuary for decades, and they now support a rich community of migratory birds during the migration and wintering periods (Takekawa et al. 2001; Warnock et al. 2002), as well as breeding populations during the summer. Unfortunately, limited information is available to predict how the proposed changes will affect population viability of the target tidal marsh species.

Population viability analysis (PVA) models may be valuable as decision tools to assess risks in reaching proposed management goals for target species (Nur and Sydeman 1999). For example, PVAs have been used to find the best management options to reduce the chance of catastrophe and save species such as the threatened Florida scrub-jay (*Aphelocoma coerulescens*) from extinction (Root 1998). Proposed restoration of up to 8,900 ha of tidal marsh in San Pablo Bay (Goals Project 1999) will surely result in an increase in numbers of tidal marsh song sparrows, common yellowthroats, and California black rails. A recent PVA model suggests that the San Pablo song sparrow is not in imminent danger of extinction, given the current extent of tidal marsh habitats (Takekawa et al. 2006a). Restoring more tidal marsh will increase the population size of this subspecies, but it will not make its long-term persistence more likely. Other factors, including habitat quality and predator control, are much more important determinants of population persistence. For example, a PVA for the Pacific

TIDAL MARSH SONG SPARROWS
UPPER MARSH AND MARSH PLAIN

Three endemic tidal marsh subspecies (Marshall 1948; Marshall and Dedrick 1994; Chan and Arcese 2002) segregated regionally, with Samuel's in San Pablo Bay, Alameda in South Bay, and Suisun in Suisun Bay. Each subspecies phenotypically distinct but genetically similar, except for Alameda.

Historic population of Samuel's likely three times larger (Takekawa et al. 2006a). Apparent density indicated 4% increase in Central Bay (5.2 birds/ha) and 3.5% decrease in San Pablo and Suisun (14.9 birds/ha: Nur et al. 1997; Pawley and Nur 2007). Widespread but variable among marshes (Spautz et al. 2006; Stralberg et al. 2010) at higher elevation but also in low marsh. Nest heights >30 cm (Marshall 1948) along channels. Forage on channel edge and marsh plain for snails, amphipods, insects, and seeds (Grenier 2004) and associated with coyote brush and gumplant.

coast population of snowy plovers (*Charadrius alexandrinus nivosus*) concluded that increasing reproductive success would be much more effective in maximizing population persistence, compared with the provision of more habitat (Nur et al. 2007). The characteristics of channel networks in a restored marsh may be especially important for species that use linear channel habitats (Collins and Resh 1985).

Maintaining sufficiently high reproductive success may be the key to the long-term persistence of tidal marsh song sparrow species. Current levels of nest predation (Greenberg et al. 2006a; Spautz and Nur 2008a,b) are much higher than those reported by Johnston (1956a) in the 1950s (57% vs 20%). Coupled with failure due to flooding, the current observed levels of nest success appear to be insufficient to ensure long-term persistence (Spautz and Nur 2008a,b).

RESTORATION IMPLICATIONS

Future restoration projects will require careful planning to address landscape-level stressors on tidal marsh inhabitants, such as habitat fragmentation and its interaction with future climate change scenarios. Several ongoing large-scale Bay wetland restoration projects, including the Napa-Sonoma Marsh on San Pablo Bay (4,050 ha) and the South Bay Salt Pond Restoration Project (6,475 ha) (Siegel and Bachand 2002), will restore former salt ponds to a mosaic of habitats, including tidal salt marsh. Early stages of tidal marsh restorations experience rapid physical changes and multiple transition states.

The establishment of tidal marsh birds in restoration projects occurs at different rates for each species. Clapper rails are typically not found in newly restored marshes, and it can take years to decades for appropriate emergent vegetative cover and channels to develop (Foin et al. 1997). However, other tidal marsh species colonize sooner. Young, restored tidal marsh habitat is colonized quickly by song sparrows (e.g., Pond 2A in Stralberg et al. 2010), but common yellowthroats and California black rails do not colonize sites until the sites are more developed (Stralberg et al. 2010; N. Nur unpublished data). Determining whether slow colonization is a result of the development of necessary habitat elements (i.e., structural cover, channels), food availability, and food web processes or whether it is simply the failure of a species population to recognize and colonize suitable habitat is necessary in order to plan for more effective restoration and management approaches (Gilroy and Sutherland 2007).

Wetland conservation in the San Francisco Bay region has evolved from a period of preservation to an era of aggressive restoration. Marshall and Dedrick (1994) declared, "Priceless tidal marshes have become monotonous salt-evaporation ponds, pastures, cities, factories, and game refuges for fresh-water ducks." However, in this highly urbanized ecosystem, condemnation of artificial habitats or, conversely, a belief that restoring a few wetlands in a vast yet greatly degraded landscape may return function to more natural or diverse communities is an oversimplification. Numerous migratory and native species use artificial habitats such as salt evaporation ponds (Takekawa et al. 2001; Warnock et al. 2002; Ackerman et al. 2009; Athearn et al. 2009), and mosquito ditches provide channel habitat for many song sparrows in the Petaluma Marsh (Collins and Resh 1985). Conversely, many wetland restoration projects have failed to create marshes with values and functions of older marshes. For example, cordgrass plants in a created wetland of Southern California were less vigorous and did not provide the height structure needed for the endangered light-footed clapper rail (*Rallus longirostris levipes*) (Zedler 1993). In contrast, song sparrow reproductive success at the restored Pond 2A (see Stralberg et al. 2010) exceeds that observed in the ancient China Camp tidal salt marsh for the San Pablo subspecies (Nur 2008).

Multispecies management in complex ecosystems such as this highly urbanized estuary has become a difficult balancing act that requires simultaneously weighing costs and benefits of alternatives for several species (Stralberg et al. 2009). Recent restoration planning has included efforts to determine what comprises the best landscape for the most diverse community with an emphasis on tidal marsh species (Goals Report 1999). However, increasing populations of threatened tidal marsh species may require actions that benefit them at the expense of other, less threatened species (Takekawa et al. 2000). With PVA analyses, the benefits of converting habitats for threatened tidal marsh species may be quantitatively compared with predicted population losses of other species (Stralberg et al. 2009), providing for better balance in restoration decisions.

The San Francisco Bay landscape is rapidly changing with the tidal marsh restoration efforts, and avian communities vary widely in response to those changing conditions. However, many of these restoration habitats have rapid development and are transitional (Woo et al. 2007; Athearn et al. 2009), and habitat use by different foraging guilds or nesting birds may reflect the habitat succession associated. Newly inundated aquatic areas are available to diving ducks and dabblers and, with adequate sediment supply, will transition to tidal flats in a few years or decades. Tidal flats are heavily used by foraging shorebirds during low tide and also by diving benthivores (i.e., scaup, ruddy duck) when the flats are submerged by the tides.

In sediment-rich areas, continued sedimentation will favor plant colonization of the tidal flats. As low-marsh habitat develops, dominated by tall emergent cordgrass, bulrushes, or sedges, increased vegetative structure allows for greater habitat and foraging partitioning in the terrestrial environment, at the expense of the tidal flat. Vegetative marshes have greater habitat availability for nesting marsh wrens, common yellowthroats, and song sparrows (Spautz et al. 2006; PRBO unpublished data), but growth of denser vegetation then supports few shorebirds (Patten and O'Casey 2007; Stralberg et al. 2009). Small mammals found within the marsh plain can colonize and subsequently provide prey resources to raptors. In marshes with greater vegetative cover and height, black rails may colonize the marsh plain, as long as suitable high marsh and upland transition zones are nearby. Finally, establishment of channel networks in more mature marshes will result in available foraging habitat and conditions suitable for clapper rails. Often clapper rails will colonize restoring marshes where bare mud for foraging is available adjacent to channels with extensive vegetation.

With respect to the age of restored sites, it is known that song sparrows are ubiquitous within young restoration sites and older historic marshes alike. Nest survival for song sparrows varies by year and is influenced by edaphic and hydrologic conditions as well as species interactions (Chan et al. 2002). In an unseasonably wet spring in 2006, song sparrow nest success at Carl's Marsh, a relatively young marsh (breached in 1994), was over twice that at China Camp, a historic tidal marsh. At China Camp, over 50% of nest failures were due to flooding that year, compared with 21% at Carl's Marsh (Liu et al. 2007). On the other hand, nest failure due to predation was greater at Carl's Marsh (45%) compared with China Camp (30%) (Liu et al. 2007).

Conversely, California black rails are found almost exclusively in mature and older restored marshes that are dominated by pickleweed and bulrush (Evens et al. 1991; Spautz and Nur 2002). Since their breeding home ranges are relatively small (0.65 ha: Tsao et al. 2009), varied topography providing dense pickleweed canopy and an open understory for nesting, foraging, and movement (Evens and Page 1983) seem to be preferred, as well as areas with more complex habitat structure (vegetation height, stem density, and percent cover: Tsao et al. 2009).

Clapper rails inhabit mature tidal salt marshes with well-developed *Spartina* vegetative cover and

CALIFORNIA CLAPPER RAIL
TIDAL MARSH CHANNELS

Historically abundant, as thousands were harvested in one day in 1859 (Wilbur and Tomlinson 1976). Numbers declined since mid-1900s to <6,000 (55% in South Bay) in 1970s when federally listed. Numbers <600 by early 1990s (Collins et al. 1994), increased after predator management initiated in 1991 (Albertson and Evens 2000) to 1,400 in early 2000s (75% in South Bay: Wood 2009; Liu et al. 2009), but declined in the South Bay in the late 2000s coincident with invasive *Spartina* removal (PRBO unpublished data).

Forages and travels in channels, numbers positively correlated with density (Albertson and Evens 2000). Remaining habitat isolated and small, enveloped by urban areas. Small annual home range (<3 ha) and breeding area home range (average <2 ha: Albertson 1995; U.S. Geological Survey unpublished data). Nests close to tidal channels (<10 m width), under gumplant, pickleweed, or cordgrass (Foerster et al. 1990) of 57 cm mean height, with platform at 18 cm from woven cordgrass (Harvey 1988). Forages on horse mussel, crabs (*Pachygrapsus crassipes* or *Hemigrapsus* spp.), clams (*Macoma balthica*), and spiders (Lycosidae) (Williams 1929; Moffitt 1941).

creek and channel networks. Clapper rails are not usually found in new restoration sites, and it can take years or decades for the appropriate emergent vegetative cover and channels to develop (Foin et al. 1997). It may take considerable time for creek and channel networks to develop naturally (Wallace et al. 2005; Woo et al. 2007) or for constructed channels to equilibrate (Zeff 1999; Williams et al. 2002). Clapper rail recovery efforts can be difficult because it may take multiple years before colonization, and detections and densities can vary from year to year (Foin et al. 1997; Liu et al. 2009). Other factors can influence clapper rail reproductive success, including contaminants, predation, and flooding events (Schwarzbach et al. 2006).

SYNTHESIS AND FUTURE DIRECTIONS

Birds have distinct niches in San Francisco Bay tidal marshes based on their foraging guilds and habitat associations. Rather than responding to a singular, monotypic habitat type, birds respond to a composite of different resources within the tidal marsh. In addition, species show distinct responses to habitat features that vary with the evolution of a site. However, urbanization and flood protection have resulted in a much more static system in San Francisco Bay and perhaps a less resilient avian community that may not be able to respond to the combined threats of sea level rise, habitat degradation and fragmentation, invasive species and predation, and other human and environmental stressors.

Recent large-scale restoration has resulted in an increase in tidal marsh habitat and a numerical response by birds. However, the avian community in early tidal marsh restoration sites is mostly transitional, and the species abundance and diversity will likely decrease in favor of endemic tidal marsh birds as the marshes mature and become vegetated. Although the historic mosaic of tidal marshes in San Francisco Bay provided a wide range of habitats, current conditions are more restrictive because regional development now surrounds tidal marshes. SLR may eliminate tidal marshes and upland refugia zones caught between open water and urban development. This loss of habitat may be amplified with an increase in severe weather events resulting in coastal erosion and flooding of vegetation and conversion of intertidal habitats to tidal or subtidal flats. Thus, conservation of tidal marsh birds will require protection of existing marshes or expansion into new areas.

Future research should focus on identifying how birds use resources in tidal marshes during king tides and storm events, to inform restoration and management decisions. Understanding the "bottleneck" periods affecting survival, productivity, or dispersal may be a key factor in maintaining avian populations. Linking the effects of habitat alteration and fragmentation to changes in vital rates of bird populations through population viability analyses would help to identify which species are most at risk. Landscape-scale analyses may help determine the extent and location of tidal marshes needed to support endemic bird species.

ACKNOWLEDGMENTS

This review was supported by the U.S. Geological Survey, Western Ecological Research Center and National Climate Change and Wildlife Science Center, PRBO Conservation Science, and the Fish and Wildlife Service's San Francisco Bay Program (R. Morat). We thank K. J. Phillips, S. De La Cruz, A. K. Schultz, E. Flynn, S. Demers, and M. Ferner for comments on the original manuscript with writing assistance of R. Gardiner, L. Liu, and H. Spautz. We acknowledge colleagues (PRBO: Y. Chan, D. Stralberg, M. Herzog, J. Wood, P. Abbaspour, and N. Warnock) and J. L. Grenier (San Francisco Estuary Institute) who have contributed to the PRBO Tidal Marsh Bird project and supporting foundations and agencies for their financial assistance.

LITERATURE CITED

Ackerman, J. T., J. D. Bluso, and J. Y. Takekawa. 2009. Postfledging Forster's tern movements, habitat selection, and colony attendance in San Francisco Bay. *Condor* 111:100–110.

Ackerman, J. T., C. A. Eagles-Smith, J. Y. Takekawa, S. A. Demers, T. L. Adelsbach, J. D. Bluso, A. K. Miles, N. Warnock, T. H. Suchanek, and S. E. Schwarzbach. 2007. Mercury concentrations and space use of pre-breeding American avocets and black-necked stilts in San Francisco Bay. *Science of the Total Environment* 384:452–466.

Adam, P. 1990. *Saltmarsh ecology*. Cambridge University Press, Cambridge, UK.

Albertson, J. D. 1995. Ecology of the California clapper rail in South San Francisco Bay. MA thesis, San Francisco State University, San Francisco.

Albertson, J. D., and J. G. Evens. 2000. California clapper rail. In *Baylands ecosystem species and community profiles: Life histories and environmental requirements of key plants, fish and wildlife,* edited by P. R. Olofson, 332–341. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. San Francisco Bay Regional Quality Control Board, Oakland, California.

Andren, H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: A review. *Oikos* 71:355–366.

Athearn, N. D., J. Y. Takekawa, and J. M. Shinn. 2009. Avian response to early tidal salt marsh restoration at former commercial salt evaporation ponds in San Francisco Bay, California, USA. *Natural Resources and Environmental Issues* 15(14). http://digitalcommons.usu.edu/nrei/vol15/iss1/14.

Basham, M. P., and L. R. Mewaldt. 1987. Salt water tolerance and the distribution of South San Francisco Bay song sparrows. *Condor* 89:697–709.

Bautista, L. M., J. T. García, R. G. Calmaestra, C. Palacín, C. A. Martín, M. B. Morales, R. Bonal, and J. Viñuela. 2004. Effect of weekend road traffic on the use of space by raptors. *Conservation Biology* 18:726–732.

Beale, C. M., and P. Mongahan. 2004. Behavioral responses to human disturbance: A matter of choice? *Animal Behavior* 68:1065–1069.

Beier, P., and R. F. Noss. 1998. Do habitat corridors really provide connectivity? *Conservation Biology* 12:1241–1252.

Bélanger, L., and J. Bédard. 1990. Energetic cost of man-induced disturbance to staging snow geese. *Journal of Wildlife Management* 54:36–41.

Bell, D. V., and L. W. Austin. 1985. The game-fishing season and its effects on overwintering wildfowl. *Biological Conservation* 33:65–80.

Benítez-López, A., R. Alkemade, and P. A. Verweij. 2010. The impacts of roads and other infrastructure on mammal and bird populations: A meta-analysis. *Biological Conservation* 143:1307–1316.

Benoit, L. K., and R. A. Askins. 2002. Relationship between habitat area and the distribution of tidal marsh birds. *Wilson Bulletin* 114:314–323.

Bergin, T. M., L. B. Best, K. E. Freemark, and K. J. Keohler. 2000. Effects of landscape structure on nest predation in roadsides of a Midwestern agroecosystem: A multiscale analysis. *Landscape Ecology* 15:131–143.

Bolger, D. T., T. A. Scott, and J. T. Rotenberry. 1997. Breeding bird abundance in an urbanizing landscape in coastal Southern California. *Conservation Biology* 11:406–421.

Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2005. *Projecting future sea level*. California Climate Change Center Report, December 2005. CEC-500-2005 202-SD. http://www.energy.ca.gov/2005publications/2005_pubs_alpha_order.html.

Cayan, D. E., M. Maurer, M. Dettinger, K. Tyree, C. Hayhoe, P. Bonfils, P. Duffy, and B. Santer. 2006. *Climate scenarios for California*. California Energy Commission and the California Environmental Protection Agency, California Climate Change Center. http://www.climatechange.ca.gov/climate_action_team/reports/index.html.

Cayan, D. R., S. A. Kamerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson. 2001. Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society* 82:399–415.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. 2008. Climate change scenarios for the California region. *Climate Change* 87, suppl 1:S21–S42.

Chalfoun, A. D., F. R. Thompson II, and M. J. Ratnaswamy. 2002. Nest predators and fragmentation: A review and meta-analysis. *Conservation Biology* 16:306–318.

Chan, Y., and P. Arcese. 2002. Subspecific differentiation and conservation of song sparrows (*Melospiza melodia*) in the San Francisco Bay region inferred by microsatellite loci analysis. *Auk* 119:641–657.

Chan, Y., N. Nur, D. Stralberg, H. Spautz, and J. Wood. 2002. Spatial and temporal heterogeneity in reproductive success of tidal marsh song sparrows (*Melospiza melodia*): The importance of "edge effects" and habitat configuration. In *Proceedings of State of the Estuary Conference, 2001*, 2–3. San Francisco Estuary Project, Oakland, California.

Cloern, J. E., E. A. Canuel, and D. Harris. 2002. Stable carbon and nitrogen isotope composition of aquatic and terrestrial plants of the San Francisco Bay estuarine system. *Limnology and Oceanography* 47(3):713–729.

Collins, J., J. Evens, and B. Grewell. 1994. *A synoptic survey of the distribution and abundance of the California clapper rail* Rallus longirostris obsoletus *in the northern reaches of the San Francisco Estuary during the 1992 and 1993 breeding seasons*. Report to the California Department of Fish and Game, Stockton.

Collins, J. N., and V. H. Resh. 1985. Factors that limit the role of immature damselflies as natural mosquito control agents at Coyote Hills Marsh. *Proceedings of the California Mosquito Vector Control Association* 53:87–92.

Congleton, J. L., W. J. LaVoie, C. B. Schreck, and L. E. Davis. 2000. Stress indices in migrating juvenile

chinook salmon and steelhead of wild and hatchery origin before and after barge transportation. *Transactions of the American Fisheries Society* 129:946–961.

Conway, C. J., and C. Sulzman. 2007. Status and habitat use of the California black rail in the southwestern USA. *Wetlands* 27:987–998.

Davidson, N., and Rothwell P. I. 1993. Human disturbance to waterfowl on estuaries: Conservation and coastal management implications of current knowledge. *Water Study Group Bulletin* 68:97–105.

Dettinger, M. D., and D. R. Cayan. 1999. Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *Journal of Climate* 8(3):606–623.

Dettinger, M. D., D. R. Cayan, M. K. Meyer, and A. E. Jeton. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900–2099. *Climatic Change* 62:283–317.

Eddleman, W. R., and C. J. Conway. 1998. Clapper rail (*Rallus longirostris*). In *The birds of North America*, edited by A. Poole and F. Gill. no. 340. Birds of North America, Inc., Philadelphia, Pennsylvania.

Eddleman, W. R., R. E. Flores, and M. L. Legare. 1994. Black rail (*Laterallus jamaicensis*). In *The birds of North America*, edited by A. Poole and F. Gill, no. 123. Birds of North America, Inc., Philadelphia, Pennsylvania.

Ehrlich, P. R., D. S. Dobkin, and D. Wheye. 1988. *The birder's handbook*. Simon and Schuster, New York.

Evens, J. G., and N. Nur. 2002. California black rails in the San Francisco Bay region: Spatial and temporal variation in distribution and abundance. *Bird Populations* 6:1–12.

Evens, J. G., and G. W. Page. 1983. The ecology of rail populations at Corte Madera Ecological Reserve. Final report to Marin Audubon Society by Point Reyes Bird Observatory.

Evens, J. G., and G. W. Page. 1986. Predation on black rails during high tides in salt marshes. *Condor* 88:107–109.

Evens, J. G., G. W. Page, S. A. Laymon, and R. W. Stallcup. 1991. Distribution, relative abundance and status of the California black rail in western North America. *Condor* 93:952–966.

Flores, R. E., and W. R. Eddleman. 1993. Nesting biology of the California black rail in southwestern Arizona. *Western Birds* 24:81–88.

Foerster, K. S., J. E. Takekawa, and J. D. Albertson. 1990. *Breeding density, nesting habitat, and predators of the California clapper rail*. U.S. Fish and Wildlife Service, Newark, California.

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

Gill, J. A., K. Norris, and W. J. Sutherland. 2001. Why behavioral responses may not reflect the population consequences of human disturbance. *Biological Conservation* 97:265–268.

Gilroy, J. J., and W. J. Sutherland. 2007. Beyond ecological traps: Perceptual errors and undervalued resources. *Trends in Ecology and Evolution* 22(7):351–356.

Goals Project. 1999. *Baylands ecosystem habitat goals: A report of habitat recommendations*. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. U.S. Environmental Protection Agency, San Francisco, and San Francisco Bay Regional Water Quality Control Board, Oakland, California.

Goals Project. 2000. *Baylands ecosystem species and community profiles: Life histories and environmental requirements of key plants, fish, and wildlife*. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project, P. R. Olofson, editor. San Francisco Bay Regional Water Quality Control Board, Oakland, California.

Greenberg, R., C. Elphick, J. Cully Norby, C. Gjerdrum, H. Spautz, G. Shriver, B. Schmeling, B. Olsen, P. Marra, N. Nur, and M. Winter. 2006a. Flooding and predation: Trade-offs in the nesting ecology of tidal-marsh sparrows. *Studies in Avian Biology* 32:96–109.

Greenberg, R., J. Maldonado, S. Droege, and M. V. McDonald. 2006b. Tidal marshes: A global perspective on the evolution and conservation of their terrestrial vertebrates. *BioScience* 56(8):675–685.

Grenier, J. L. 2004. Ecology, behavior, and trophic adaptations of the salt marsh song sparrow *Melospiza melodia samuelis*: The importance of the tidal influence gradient. PhD dissertation, University of California–Berkeley.

Grenier, J. L., and R. Greenberg. 2006. Trophic adaptations in sparrows and other vertebrates of tidal marshes. *Studies in Avian Biology* 32:130–139.

Grinnell, J., H. C. Bryant, and T. I. Storer. 1918. *The game birds of California*. University of California Press, Berkeley.

Grinnell, J., and M. W. Wythe. 1927. *Directory to the bird-life of the San Francisco Bay region*. Pacific Coast Avifauna 18. Cooper Ornithological Society. http://elibrary.unm.edu/sora/Condor/cooper/pca_018.php.

Gutzwiller, K. J., and W. C. Barrow. 2003. Influences of roads and development on bird communities in protected Chihuahuan Desert landscapes. *Biological Conservation* 113:225–237.

Haig, S. M., D. W. Mehlman, and L. W. Oring. 1998. Avian movements and wetland connectivity in landscape conservation. *Conservation Biology* 12:749–758.

Hamilton, R. B. 1975. Comparative behavior of the American avocet and the black-necked stilt (Recurvirostridae). *Ornithological Monographs* 17.

Hansen, J., M. Sato, R. Ruedy, K. L., D. W. Lea, and M. Medina-Elizade. 2006. Global temperature change. *Proceedings of the National Academy of Science USA* 103(39):14288–14293.

Haramis, G. M., J. D. Nichols, K. H. Pollock, and J. E. Hines. 1986. The relationship between body mass and survival of wintering canvasback. *Auk* 103:506–514.

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

Harris, J. A., R. J. Hobbs, E. Higgs, and J. Aronson. 2006. Ecological restoration and global climate change. *Restoration Ecology* 14(2):170–176.

Harvey, T.E. 1988 Breeding biology of the California Clapper Rail in south San Francisco Bay. Transactions of the Western Section Wildlife Society 24:98–104.

Harvey, T. E., K. J. Miller, R. L. Hothem, M. J. Rauzon, G. W. Page, and R. A. Keck. 1992. *Status and trends report on wildlife of the San Francisco Estuary*. Prepared by the U.S. Fish and Wildlife Service for the San Francisco Estuary Project. U.S. Environmental Protection Agency, San Francisco.

Hickey, C., N. Warnock, J. Y. Takekawa, and N. D. Athearn. 2007. Space use by black-necked stilts in the San Francisco Bay Estuary. *Ardea* 95:275–288.

Ikuta, L. A., and D. T. Blumstein. 2003. Do fences protect birds from human disturbance? *Biological Conservation* 112:447–452.

Intergovernmental Panel on Climate Change (IPCC). 2007. Summary for policymakers. In *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Jevrejeva, S., A. Grinsted, J. C. Moore, and S. Holgate. 2006. Nonlinear trends and multiyear cycle in sea level records. *Journal of Geophysical Research* 111:JC003229.

Jevrejeva, S., J. C. Moore, A. Grinsted, and P. L. Woodworth. 2008. Recent global sea level acceleration started over 200 years ago? *Geophysical Research Letters* 35:L08715.

Johnson, D. 2001. Habitat fragmentation effects on birds in grasslands and wetlands: A critique of our knowledge. *Great Plains Research* 11:211–231.

Johnston, R. F. 1956a. Population structure in the salt marsh song sparrows. I. Environment and annual cycle. *Condor* 58(1):24–44.

Johnston, R. F. 1956b. Population structure in the salt marsh song sparrows. II. Density, age structure, and maintenance. *Condor* 58(4):254–272.

Josselyn, M. 1983. *The ecology of San Francisco Bay tidal marshes: A community profile*. U.S. Fish and Wildlife Service. FWS/OBS-83/23.

Knight, R. L., and D. N. Cole, eds. 1995. *Wildlife responses to recreationists*. Island Press, Washington, DC.

Knowles, N. 2010. Potential inundation due to rising sea levels in the San Francisco Bay Region. *San Francisco Estuary and Watershed Science* 8:1.

Knowles, N., and D. Cayan. 2004. Elevational dependence of projected hydrologic changes in the San Francisco Estuary and watershed. *Climatic Change* 62:319–336.

Knowles, N., and D. R. Cayan. 2002. Potential effects of global warming on the Sacramento / San Joaquin watershed and the San Francisco Estuary. *Geophysical Research Letters* 29:1–5.

Kotliar, N. B., and J. A. Wiens. 1990. Multiple scales of patchiness and patch structure: A hierarchical framework for the study of heterogeneity. *Oikos* 59:253–260.

Kuitunen, M., E. Rossi, and A. Stenroos. 1998. Do highways influence density of land birds? *Environmental Management* 22:297–302.

Kwak, T. J., and J. B. Zedler. 1997. Food web analysis of Southern California coastal wetlands using multiple stable isotopes. *Oecologica* 110:262–277.

Lafferty, K. D. 2001a. Birds at a Southern California beach: Seasonality, habitat use and disturbance by human activity. *Biodiversiy and Conservation* 10:1–14.

Lafferty, K. D. 2001b. Disturbance to wintering western snowy plovers. *Biological Conservation* 101:315–325.

Liu, L., P. Abbaspour, M. Herzog, N. Nur, and N. Warnock. 2007. *San Francisco Bay Tidal Marsh Project annual report 2006: Distribution, abundance, and reproductive success of tidal marsh birds*. PRBO Conservation Science, Petaluma, California.

Liu, L., J. Wood, N. Nur, D. Stralberg, and M. Herzog. 2009. California Clapper Rail (*Rallus longirostris obsoletus*) population monitoring: 2005–2008. Report to California Department of Fish and Game from PRBO Conservation Science. PRBO Conservation Science, Petaluma, California.

Lovvorn, J. R., and M. P. Gillingham. 1996. Food dispersion and foraging energetics: A mechanistic synthesis for field studies of avian benthivores. *Ecology* 77:435–451.

MacArthur, R. H., and E. O. Wilson. 1967. *The theory of island biogeography*. Monographs in Population Biology. Princeton University Press, Princeton, New Jersey.

Malamud-Roam, K. 2000. Tidal regimes and tidal marsh hydroperiod in the San Francisco Estuary: Theory and implications for ecological restoration. PhD dissertation, University of California–Berkeley.

Marshall, J. T., Jr. 1948. Ecologic races of song sparrows in the San Francisco Bay region. I. Habitat and abundance. *Condor* 50:193–215.

Marshall, J. T., Jr., and K. G. Dedrick. 1994. Endemic song sparrows and yellowthroats of San Francisco Bay. *Studies in Avian Biology* 15:316–327.

McKinney, R. A., M. A. Charpentier, and C. Wigand. 2009. Assessing the wildlife habitat value of New England salt marshes. II. Model testing and validation. Environmental Monitoring and Assessment 154:361–371.

Moffitt, J. 1941. Notes on the food of the California clapper rail. *Condor* 43:270–273.

Morrison, R. I. G., R. E. Gill Jr., B. A. Harrington, S. Skagen, G. W. Page, C. L. Gratto-Trevor, and S. M. Haig. 2001. *Estimates of shorebird populations in North America*. Occasional Paper 104. Canadian Wildlife Service, Ottawa, Ontario.

Nordby, J. C., A. N. Cohen, and S. R. Beissinger. 2009. Effects of a habitat-altering invader on nesting sparrows: An ecological trap? *Biological Invasions* 11:565–575.

Nur, N. 2008. Salt marsh song sparrows. In *A greener shade of blue? State of the San Francisco Bay-Delta Estuary 2008*, 33. San Francisco Estuary Project and CALFED. http://www.calwater.ca.gov/science/library/library_index.html.

Nur, N., G. W. Page, and L. E. Stenzel. 2007. Population viability analysis for Pacific coast western snowy plovers. In *Western snowy plover (*Charadrius alexandrinus nivosus*) Pacific coast population recovery plan*, Volume 2, D1–D40. U.S. Fish and Wildlife Service, Washington, DC.

Nur, N., L. Salas, S. Veloz, J. Wood, L. Liu, and G. Ballard. 2012. Assessing vulnerability of tidal marsh birds to climate change through the analysis of population dynamics and viability. Technical Report. Version 1.0. Report to the California Landscape Conservation Cooperative. PRBO Conservation Science, Petaluma, California.

Nur, N., and W. J. Sydeman. 1999. Demographic processes and population dynamic models of seabirds: Implications for conservation and restoration. *Current Ornithology* 15:149–188.

Nur, N., S. Zack, J. Evens, and T. Gardali. 1997. *Tidal marsh birds of the San Francisco Bay region: Status, distribution, and conservation of five category 2 taxa*. Final draft report to National Biological Survey (now U.S. Geological Survey). PRBO Conservation Science, Petaluma, California.

Patten, K., and C. O'Casey. 2007. Use of Willapa Bay, Washington, by shorebirds and waterfowl after *Spartina* control efforts. *Journal of Field Ornithology* 78:395–400.

Pawley, A., and N. Nur. 2007. 2007 San Francisco Bay bird indicators: An evaluation of indicators and indices to evaluate the health of San Francisco Bay's bird community in four sub-regions of the Estuary. Report to San Francisco Estuary Project, Oakland, California.

Reinert, S. E. 2006. Avian nesting response to tidal-marsh flooding: Literature review and a case for adaptation in the red-winged blackbird. *Studies in Avian Biology* 32:77–95.

Rintoul, C., N. Warnock, G. W. Page, and J. T. Hanson. 2003. Breeding status and habitat use of black-necked stilts and American avocets in South San Francisco Bay. *Western Birds* 34:2–14.

Robinson, J. A., J. M. Reed, J. P. Skorupa, and L. W. Oring. 1999. Black-necked stilt (*Himantopus mexicanus*). In *The birds of North America*, edited by A. Poole and F. Gill, no. 449. Academy of Natural Sciences, Philadelphia, and American Ornithologists' Union, Washington, DC.

Root, K. V. 1998. Evaluating the effects of habitat quality, connectivity, and catastrophes on a threatened species. *Ecological Applications* 8:854–865.

Rush, S. A., R. Mordecai, M. S. Woodrey, and R. J. Cooper. 2010. Prey and habitat influences the movement of clapper rails in northern Gulf Coast estuaries. *Waterbirds* 33(3):389–396.

Saunders, D. A., R. J. Hobbs, and C. R. Marguless. 1991. Biological consequences of ecosystem fragmentation: A review. *Conservation Biology* 5:8–32.

Sayre, M. W., and W. D. Rundle. 1984. Comparison of habitat use by migrant soras and Virginia rails. *Journal of Wildlife Management* 48:599–605.

Schwarzbach, S. E., J. D. Albertson, and C. M. Thomas. 2006. Effects of predation, flooding, and contamination on the reproductive success of California clapper rails (*Rallus longirostris obsoletus*) in San Francisco Bay. *Auk* 123:45–60.

Shriver, W. G., T. P. Hodgman, J. P. Gibbs, and P. D. Vickery. 2004. Landscape context influences salt-marsh bird diversity and area requirements in New England. *Biological Conservation* 119:545–553.

Siegel, S. W., and P. A. M. Bachand. 2002. *Feasibility analysis of South Bay salt pond restoration, San Francisco Estuary, California*. Wetlands and Water Resources, San Rafael, California.

Shuford, W. D., and T. Gardali, eds. 2008. *California*

bird species of special concern: A ranked assessment of species, subspecies, and distinct populations of birds of immediate conservation concern in California. Studies of Western Birds 1. Western Field Ornithologists, Camarillo, California, and California Department of Fish and Game, Sacramento.

Spautz, H., and N. Nur. 2002. *Distribution and abundance in relation to habitat and landscape features and nest site characteristics of California black rail (*Laterallus jamaicensis coturniculus*) in the San Francisco Bay Estuary*. Final Report to the U.S. Fish and Wildlife Service. PRBO Conservation Science, Petaluma, California.

Spautz, H., and N. Nur. 2008a. San Pablo song sparrow, *Melospiza melodia samuelis*. In *California bird species of special concern: A ranked assessment of species, subspecies, and distinct populations of immediate conservation concern in California*, edited by W. D. Shuford and T. Gardali, 412–418. Studies of Western Birds 1. Western Field Ornithologists, Camarillo, California, and Department of Fish and Game, Sacramento.

Spautz, H., and N. Nur. 2008b. Suisun song sparrow, *Melospiza melodia maxillaris*. In *California bird species of special concern: A ranked assessment of species, subspecies, and distinct populations of immediate conservation concern in California*, edited by W. D. Shuford and T. Gardali, 405–411. Studies of Western Birds 1. Western Field Ornithologists, Camarillo, California, and Department of Fish and Game, Sacramento.

Spautz, H., N. Nur, D. Stralberg, and Y. Chan. 2006. Multiple-scale habitat relationships of tidal-marsh breeding birds in the San Francisco Bay Estuary. *Studies in Avian Biology* 32:247–269.

Spellerberg, I. 1998. Ecological effects of roads and traffic: A literature review. *Global Ecology and Biogeography* 7:317–333.

Steere, J. T., and N. Schaefer. 2001. *Restoring the estuary: An implementation strategy for the San Francisco Bay Joint Venture*. San Francisco Bay Joint Venture, Oakland, California.

Stenzel, L. E., C. M. Hickey, J. E. Kjelmyr, and G. W. Page. 2002. Abundance and distribution of shorebirds in the San Francisco Bay area. *Western Birds* 33:69–98.

Stralberg, D., D. L. Applegate, S. J. Phillips, M. P. Herzog, N. Nur, and N. Warnock. 2009. Optimizing wetland restoration and management for avian communities using a mixed integer programming approach. *Biological Conservation* 142:94–109.

Stralberg, D., M. P. Herzog, N. Nur, K. A. Tuxen, and M. Kelly. 2010. Predicting avian abundance within and across tidal marshes using fine-scale vegetation and geomorphic metrics. *Wetlands* 30(3):475–487.

Takekawa, J. Y., C. T. Lu, and R. T. Pratt. 2001. Avian communities in baylands and artificial salt evaporation ponds of the San Francisco Bay Estuary. *Hydrobiologia* 466:317–328.

Takekawa, J. Y., A. K. Miles, D. H. Schoellhamer, B. Jaffe, N. D. Athearn, S. E. Spring, G. G. Shellenbarger, M. K. Saiki, F. Mejia, and M. A. Lionberger. 2005. South Bay salt ponds restoration project short-term data needs, 2003–2005. Unpublished final report. U.S. Geological Survey, Vallejo, California.

Takekawa, J. Y., G. W. Page, J. M. Alexander, and D. R. Becker. 2000. Waterfowl and shorebirds of the San Francisco Bay Estuary. In *Baylands ecosystem species and community profiles: Life histories and environmental requirements of key plants, fish and wildlife*, edited by P. R. Olofson, 309–316. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. San Francisco Bay Regional Water Quality Control Board, Oakland, California.

Takekawa, J. Y., B. Sacks, I. Woo, M. B. Johnson, and G. D. Wylie. 2006a. Effects of tidal marsh fragmentation on survival of San Pablo song sparrows in the San Francisco Bay Estuary. *Studies in Avian Biology* 32:238–246.

Takekawa, J. Y., I. Woo, R. Gardiner, M. Casazza, J. T. Ackerman, N. Nur, L. Liu, and H. Spautz. In press. Bird communities in tidal salt marshes of San Francisco Bay. *San Francisco Estuary and Watershed Science*.

Takekawa, J. Y., I. Woo, H. Spautz, N. Nur, J. L. Grenier, K. Malamud-Roam, J. C. Nordby, A. N. Cohen, F. Malamud-Roam, and S. E. Wainwright-De La Cruz. 2006b. Environmental threats to tidal marsh vertebrates in the San Francisco Bay Estuary. *Studies in Avian Biology* 32:176–197.

Tozer, D. C., E. Nol, and K. F. Abraham. 2010. Effects of local and landscape scale habitat variables on abundance and reproductive success of wetland birds. *Wetlands Ecology* 18:679–693.

Trost, R. E. 2002. *Pacific flyway 2001–2002 fall and winter waterfowl survey report*. U.S. Fish and Wildlife Service, Portland, Oregon.

Trulio, L. A., D. Clark, S. Ritchie, A. Hutzel, and the Science Team. 2007. *Adaptive management plan*. Appendix D in Science team report for the South Bay Salt Pond Restoration Project. http://www.southbayrestoration.org/science/#docs.

Trulio, L. A., and J. Sokale. 2008. Foraging shorebird response to trail use around San Francisco Bay. *Journal of Wildlife Management* 72:1775–1780.

Tsao, D. C., J. Y. Takekawa, I. Woo, J. L. Yee, and J. G. Evens. 2009. Home range, habitat selection, and movements of California black rails at tidal marshes at San Francisco Bay, California. *Condor* 111(4):599–610.

U.S. Fish and Wildlife Service. 2002. *Waterfowl population status, 2002*. U.S. Department of the Interior, Washington, DC.

van de Pol, M., B. J. Ens, D. Heg, L. Brouwer, J. Krol, M. Maier, E. Klaus-Michael, K. Oosterbeek, T. Lok, C. M. Eising, and K. Koffijberg. 2010. Do changes in the frequency, magnitude and timing of extreme climatic events threaten the population viability of coastal birds? *Journal of Applied Ecology* 47:720–730.

Vermeer, M., and S. Rahmstrof. 2009. Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences USA* 106(51):21527–21532.

Wallace, K., J. C. Callaway, and J. B. Zedler. 2005. Evolution of tidal creek networks in a high sedimentation environment: A 5-year experiment at Tijuana Estuary, California. *Estuaries* 28(6):795–811.

Walters, J. R. 1998. The ecological basis of avian sensitivity to habitat fragmentation. In *Avian conservation*, edited by J. M. Marzaluff and R. Sallabanks, 181–192. Island Press, Washington, DC.

Walton, B. J. 1978. The status of the salt marsh song sparrows of the San Francisco Bay system, 1974–1976. MS thesis, San Jose State University, San Jose, California.

Warnock, N., G. W. Page, T. D. Ruhlen, N. Nur, J. Y. Takekawa, and J. T. Hanson. 2002. Management and conservation of San Francisco Bay salt ponds: Effects of pond salinity, area, tide, and season on Pacific flyway waterbirds. *Waterbirds* 25 Special Publication 2:79–92.

Wiens, J. A. 1994. Habitat fragmentation: Island landscape perspectives on bird conservation. *Ibis* 137:S97–S104.

Wiens, J. A. 1996. Wildlife in patchy environments: Metapopulations, mosaics, and management. *In Metapopulations and wildlife conservation*, edited by D. R. McCullough. Island Press, Washington, DC.

Wilbur, S., and R. Tomlinson. 1976. *The literature of western clapper rails*. Special scientific report—Wildlife 194. U.S. Fish and Wildlife Service, Washington, DC.

Williams, L. 1929. Notes on the feeding habits and behavior of the California clapper rail. *Condor* 31:52–56.

Williams, P. B., M. K. Orr, and N. J. Garrity. 2002. Hydraulic geometry: A geomorphic design tool for tidal marsh channel evolution in wetland restoration projects. *Restoration Ecology* 10(3):577–590.

Woo, I., J. Y. Takekawa, A. Rowan, R. Gardiner, O. Bernstein, and G. T. Block. 2007. The Tubbs Setback Restoration Project: Final report. Unpubished. U.S. Geological Survey, Vallejo, California.

Wood, J. 2009. Population status and recent trends of California clapper rail and other marsh birds of concern. State of the San Francisco Estuary Conference, Oakland, California, Oakland Marriott at City Center, p. 23.

Ydenberg, R. C., and L. M. Dill. 1986. The economics of fleeing from predators. *Advances in the Study of Behavior* 16:229–249.

Zedler, J. B. 1993. Canopy architecture of natural and planted cordgrass marshes: Selecting habitat evaluation criteria. *Ecological Applications* 3(1):123–138.

Zeff, M. L. 1999. Salt marsh tidal channel morphometry: Applications for wetland creation and restoration. *Restoration Ecology* 7(2):205–211.