

TIDAL SALTMARSH FRAGMENTATION AND PERSISTENCE OF SAN PABLO SONG SPARROWS (*MELOSPIZA MELODIA SAMUELIS*): ASSESSING BENEFITS OF WETLAND RESTORATION IN SAN FRANCISCO BAY

JOHN Y. TAKEKAWA, BENJAMIN N. SACKS, ISA WOO, MICHAEL L. JOHNSON, AND GLENN D. WYLIE

Abstract. The San Pablo Song Sparrow (*Melospiza melodia samuelis*) is one of three morphologically distinct Song Sparrow subspecies in tidal marshes of the San Francisco Bay estuary. These subspecies are rare, because as the human population has grown, diking and development have resulted in loss of 79% of the historic tidal marshes. Hundreds of projects have been proposed in the past decade to restore tidal marshes and benefit endemic populations. To evaluate the value of these restoration projects for Song Sparrows, we developed a population viability analysis (PVA) model to examine persistence of *samuelis* subspecies in relation to parcel size, connectivity, and catastrophe in San Pablo Bay. A total of 101 wetland parcels were identified from coverages of modern and historic tidal marshes. Parcels were grouped into eight fragments in the historical landscape and 10 in the present landscape. Fragments were defined as a group of parcels separated by >1 km, a distance that precluded regular interchange. Simulations indicated that the historic (circa 1850) *samuelis* population was three times larger than the modern population. However, only very high levels (>70% mortality) of catastrophe would threaten their persistence. Persistence of populations was sensitive to parcel size at a carrying capacity of <10 pairs, but connectivity of parcels was found to have little importance because habitats were dominated by a few large parcels. Our analysis indicates little risk of extinction of the *samuelis* subspecies with the current extent of tidal marshes, but the vulnerability of the smallest parcels suggests that restoration should create larger continuous tracts. Thus, PVA models may be useful tools for balancing the costs and benefits of restoring habitats for threatened tidal-marsh populations in wetland restoration planning.

Key Words: fragmentation, *Melospiza melodia samuelis*, population viability analysis, salt ponds, San Francisco Bay, San Pablo Song Sparrow, wetlands.

EVALUANDO LOS BENEFICIOS DE LA RESTAURACIÓN DE HUMEDALES EN LA BAHÍA DE SAN FRANCISCO

Resumen. El Gorrion Cantor de San Pablo (*Melospiza melodia samuelis*) es una de las tres subespecies de Gorriones Cantores morfológicamente distintas en marismas de marea del estuario de la Bahía de San Francisco. Estas subespecies son raras, ya que la población humana ha crecido. El dragar y el desarrollo han resultado en una pérdida del 79% de las marismas de marea históricas. Cientos de proyectos han sido propuestos en la década pasada con el fin de restaurar las marismas de marea, así como para beneficiar poblaciones endémicas. Para poder evaluar el valor de estos proyectos de restauración para los Gorriones Cantores, desarrollamos un modelo de análisis de viabilidad de población (AVP) para examinar la persistencia de subespecies samuelis en relación al tamaño de la parcela, conectividad y a la catástrofe en la Bahía de San Pablo. Un total de 101 parcelas de humedal fueron identificadas de coberturas de marismas de marea modernas e históricas. Las parcelas fueron agrupadas en ocho fragmentos en el paisaje histórico y 10 en el paisaje actual. Los fragmentos fueron definidos como un grupo de parcelas separadas por >1 km, una distancia que impedía intercambio regular. Las simulaciones indicaron que la población histórica (circa 1850) *samuelis* era tres veces mas grande que la población moderna. Sin embargo, solamente altos niveles de catástrofe (>70% mortandad) pondrían en peligro su persistencia. La persistencia de las poblaciones fue sensitiva al tamaño de la parcela con una capacidad de carga de <10 pares, pero la conectividad de las parcelas se encontró que tenía poca importancia porque los habitats estaban dominados por unas pocas parcelas. Nuestro análisis indica que hay poco peligro de extinción de la subespecie *samuelis* con el actual alcance de las marismas de marea, pero la vulnerabilidad de las parcelas más pequeñas sugieren que la restauración debería de crear tramos contiguos más largos. Es por ello que modelos AVP quizás sean herramientas útiles para balancear los costos y beneficios de habitats en restauración par alas poblaciones en peligro de marisma de marea en las plantaciones para la restauración de humedales.

Predicting how birds use habitat patches is a fundamental requirement in 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, the size, shape, and orientation 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 decline or fail to find or use small habitat patches with increased fragmentation. In planning wetland restoration projects, larger patches are typically thought to be more valuable for most species (Dramstad et al. 1996, Goals Project 1999), and corridors between tidal-marsh patches have often been considered valuable for maintaining populations. However, in urbanized areas, restoring small patches may be more cost effective than developing movement corridors (Beier and Noss 1998).

Habitats in the San Francisco Bay estuary have been reduced, modified, and fragmented by loss of 79% of its tidal marshes, 42% of its tidal flats, and 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). Salt evaporation ponds have been part of the estuary for decades (Ver Plank 1958), and they now support a rich community of migratory birds during the migration and wintering periods (Takekawa et al. 2001), 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.

The San Pablo Song Sparrow (*Melospiza melodia samuelis*), hereafter referred to as *samuelis*, is one of three subspecies of Song Sparrows found in the San Francisco Bay estuary (Fig. 1). These include the Suisun Song Sparrow (*M. m. maxillaris*) in the eastern reach of the estuary, and the Alameda Song Sparrow (*M. m. pusillula*) in the southern reach. These three subspecies are listed as species of concern by California (Laundenslayer et al. 1991). The viability of *samuelis* is threatened because of increased fragmentation and reduction of tidal-marsh habitat around San Pablo Bay (Walton 1978, Marshall and Dedrick 1994, Nur et al. 1997). Of concern are the persistence of *samuelis* in tidal marshes of San Pablo Bay, and genetic integrity of the subspecies.

Our objective was to examine the relationship between extinction and tidal-marsh wetland parcel size. We used existing information on vital rates (Marshall 1948a, b; Johnston 1956a, b; Walton 1978, Collins and Resh 1985, Marshall and Dedrick 1994, Nur et al. 1997) to develop a population viability analysis (PVA) for *samuelis*. We used the model to estimate current and historical population size from modern and historic availability of habitats and determined

the risk of extinction for the population given the current fragmented habitats. Finally, we evaluated PVA modeling as a tool in wetland restoration planning to establish the benefits of restoring bay lands to tidal marshes.

METHODS

POPULATION RANGE

The *samuelis* subspecies is found in the remaining tidal marshes surrounding the San Pablo Bay sub-region (Fig. 1). From Richmond to the southeast, the range of *samuelis* extends around the northern edge of San Pablo Bay to Tiburon in the southwest. The highest densities are found in Petaluma Marsh (Nur et al. 1997) and along the Petaluma River, the largest continuous tract of *samuelis* habitat (Marshall and Dedrick 1994). This area is connected to the maze of sloughs, levees, and ditches that comprise the baylands at the northern end of San Pablo Bay. To the east, isolated patches of tidal marsh south of the Carquinez Strait contained small numbers of breeding *samuelis* in the mid 1970s (Walton 1978) that were still present in the late 1990s (B. N. Sacks, unpubl. data). Southwest of the Petaluma River, *samuelis* is currently found in patches of tidal marsh including a large area north of San Rafael and smaller areas to the south (Nur et al. 1997).

MODEL DEVELOPMENT

The PVA was based on a modified Leslie matrix model where elements contained functions instead of constants. Simulations were carried out for 50 time steps (t), each corresponding to a single generation (year). Parameters N, n, p, m, and K were defined respectively as total female population in the spring just prior to breeding, number of females in age class x, age-specific survivorship, age-specific fecundity expressed as the average number of female fledglings produced by each female (sex-ratios were assumed to be 50:50) and carrying capacity (see POPULATION PARAMETERS below for details). N was calculated as:

$$N_{t+1} = \sum_{x=1 \text{ to } 7} n_{x(t+1)} \quad (\text{A1})$$

Sizes of age groups were calculated for age class x = 1,

$$n_{x(t+1)} = \sum_{x=1 \text{ to } 7} n_{x(t)} m_{x(t)} P_{0(t)} \quad (\text{A2})$$

and for age classes x = 2-7,

$$n_{x(t+1)} = n_{x-1(t)} P_{x-1(t)} + n_{x-1(t)} SD_1 RV_1 \quad (\text{A3})$$

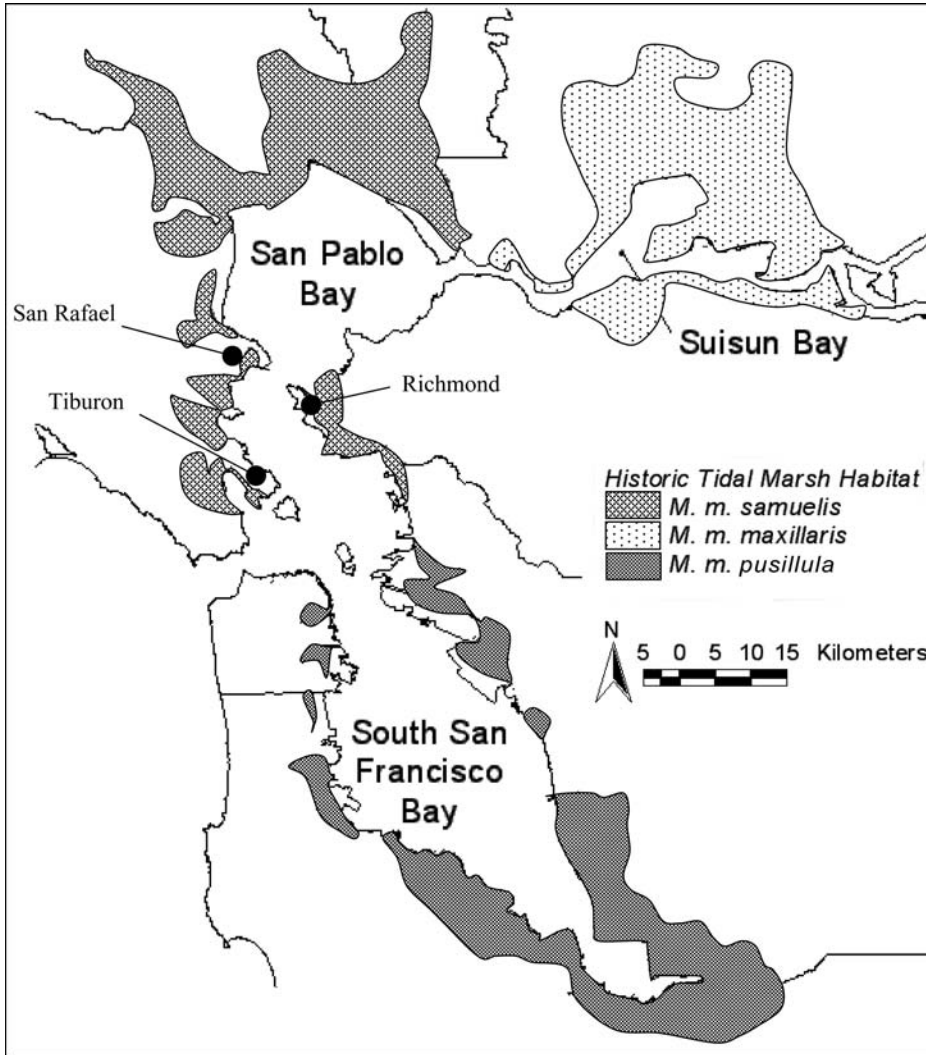


FIGURE 1. Ranges of three Song Sparrow subspecies in the San Francisco Bay estuary of California (adapted from Walton 1978).

where,

$$P_{0(t)} = 1 - [(0.304N_{(t)}/K + 0.4176) + SD_2RV_{2(\text{adult} = \text{juvenile } px)}] \quad (A4)$$

for age classes $x = 2-7$,

$$p_{x(t)} = [\text{mean estimated } p_x] + SD_3RV_{3(\text{adult} = \text{juvenile } px)} \quad (A5)$$

and,

$$m_{x(t)} = [\text{mean estimated } m_x] + SD_4RV_3 \quad (A6)$$

We incorporated demographic stochasticity into (A3) by calculating the binomial SD (Burgman et al. 1993) as

$$SD_1 = \sqrt{[(1 - p_{x(t)})p_{x(t)}/n_{x(t)}]} \quad (A7)$$

and multiplying by an approximately normally distributed and standardized random variable (RV_1), where

$$\text{pre-standardized } RV_1 = \text{arcsine } \sqrt{X},$$

and X was the average of two randomly selected numbers between 0 and 1. Values were then

standardized such that average $RV_1 = 0$ and $SD = 1$. A different RV_1 was chosen for each age class to reflect independence.

Environmental stochasticity was also incorporated into the models (A4, A5, A6). RV_2 was sampled from the negative of an approximately lognormal and standardized distribution (Burgman et al. 1993), to minimize effects of constraints (see below), and RV_3 was sampled from an approximately standard normal distribution as follows:

$$\text{pre-standardized } RV_2 = - (e^{RV_3}),$$

where RV_3 was the standardized arcsine of the square root of the average of two randomly selected numbers between 0 and 1. Separate random variables were selected for m_x (A6) and p_x (A4, A5), because Arcese et al. (1992) reported no correlation between residuals from these two vital rates when regressed on density. Carrying capacity, defined as the number of pairs in a parcel, was not determined explicitly from empirical data, but was used as a variable to examine the population response across a range of values for K . Projections were based on 100 stochastic simulations.

POPULATION PARAMETERS

We used data from previous studies (Johnston 1956a, b; Arcese et al. 1992) to estimate population parameters for the modeling. Three constraints were imposed on population numbers and vital rates. First, only whole numbers were used in modeling, such that when equations produced fractions of individuals, numbers were rounded to the nearest integer. Second, survival was constrained to fall between 0 and 1 (adults) or 0 and 0.4 (juveniles); juvenile survival was constrained to a maximum of 0.4 to be consistent with empirical data (Johnston 1956a, b), and to minimize the chance of juvenile survival exceeding adult survival. Third, annual fecundity rate was constrained between 0.5 and 3 daughters per female to be consistent with empirical data (Johnston 1956a, b).

A density-dependent function for p_0 (A4) was derived from regressions on data from Song Sparrows (*M. melodia morphna* and upland subspecies) on Mandarte Island, British Columbia (Arcese et al. 1992), but the intercept term was modified to be consistent with the larger clutch sizes for *samuelis* at Point San Pablo (Johnston 1956a, b) by adding 1.1 (based on the density-specific difference in expectations). Parameters are shown in equation (A4). Adult p_x ($\bar{x} = 0.43$) in (A5) and m_x ($\bar{x} = 2.2$ daughters) in (A6) were from Johnston's (1956a, b) data. Estimates of

SD were based on standard deviations for density-independent parameters (A5), and root-mean-square errors for density-dependent (A4) parameters; specifically, SD for juvenile (0.08; A4) and adult (0.09; A5) p_x were calculated from Mandarte Island data (Arcese et al. 1992). SD for m_x (0.70; A6) was taken directly from Point San Pablo data (Johnston 1956a, b).

HABITAT PARCELS AND FRAGMENTS

We treat habitat units hierarchically, where a parcel is defined as a contiguous tract of tidal marsh, and a fragment is defined as a group of parcels separated from other fragments by >1 km. We determined the modern extent of the tidal-marsh habitat available for *samuelis* by intersecting the modern ecoatlas coverage (San Francisco Estuary Institute 2000) with the reported range for the subspecies (Fig. 1). We identified wetland parcels and fragments in the San Pablo Bay sub-region (Figs. 2a, b) from detailed geographic information system (GIS) coverages of habitats in the estuary known as the San Francisco Bay Area Ecoatlas (San Francisco Estuary Institute 2000). The ecoatlas coverages included modern (1997) habitats in the estuary (Fig. 2a) and historic (1770–1867; Fig. 2b) wetland parcels delineated from an extensive collection of eighteenth- and nineteenth-century maps and other sources. We define parcels as contiguous tracts of tidal marsh from wetland polygons in the ecoatlas with a buffer distance of >50 m, a separation distance reported to be rarely crossed by Song Sparrows (Marshall 1948a, Collins and Resh 1985, Scollon 1993).

Little is known about dispersal rates among subpopulations of the Song Sparrow. Adults generally do not disperse and first-year birds disperse only an average of approximately 180 m (Johnston 1956a, b). Fragments separated by >1 km seemed poorly connected by dispersal on the basis of findings by Nur et al. (1997). This is also consistent with observations of Smith et al. (1996) in British Columbia where subpopulations on several small islands separated by distances >1 km were primarily driven by within-population dynamics. Most of the smaller eastern and western fragments of tidal marsh on San Pablo Bay are separated by 1–5 km, suggesting that dispersal among these patches is rare.

PARCEL CONNECTIVITY

Although habitat loss has likely reduced the historic *samuelis* population by decreasing carrying capacity (Marshall and Dedrick 1994),

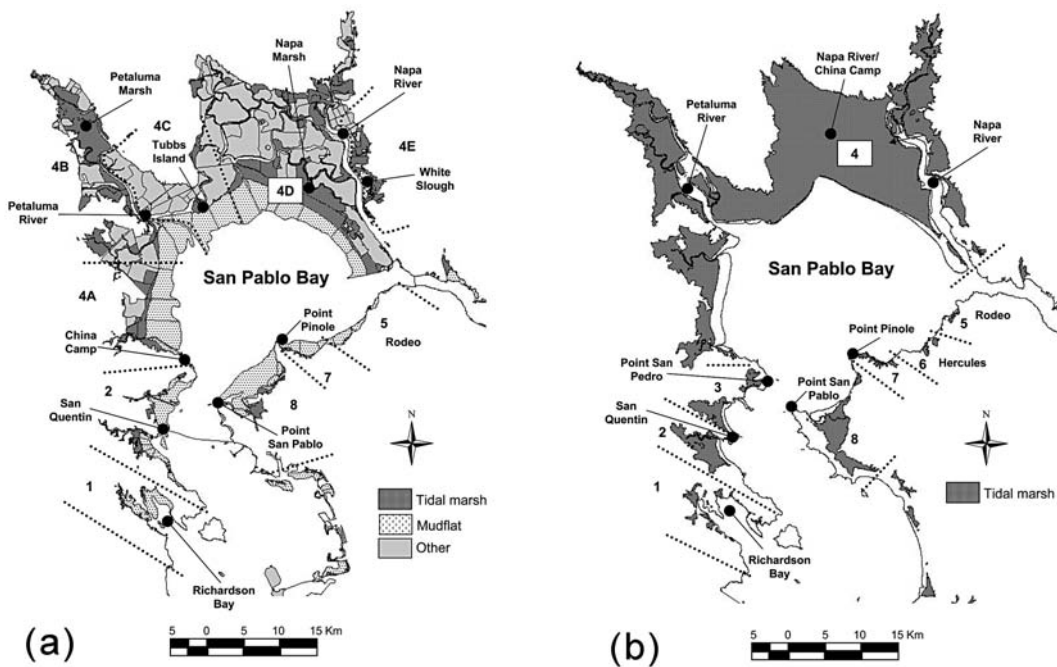


FIGURE 2. Modern (1997; a) and historical distribution (circa 1850; b) of tidal-saltmarsh parcels in the northern Central Bay and San Pablo Bay sub-regions. Figure modified from the San Francisco Bay Area Ecoatlas (San Francisco Estuary Institute 2000). Dashed lines indicate large habitat fragments separated by >1 km of terrestrial or aquatic barriers and numbers correspond to definitions in Table 1.

we wished to evaluate the added importance of loss of connectivity among wetland parcels. Rather than try to model the complex and poorly understood process of dispersal and re-colonization, we examined the most extreme assumptions, 0% and 100% connectivity among parcels within fragments, bracketing the range of possibilities. Specifically, we used equations estimating the probability of extinction as a function of parcel size under two sets of assumptions: (1) 100% connectivity of all parcels made by summing K across parcels within fragments and then calculating the expected number of sparrows in this combined area, and (2) 0% connectivity of parcels made by calculating the expected number of sparrows for each parcel and then summing these numbers across parcels to arrive at a projection for the fragment. In both cases, the expected number of sparrows (in parcel or fragment, respectively) was the product of $K+1$ (where K was assumed to be 2.75 pairs/ha; Johnston 1956b) minus the probability of extinction—a function of K determined from the simulation model described above. Assuming that the probability of extinction is a concave function of K , the expected number of sparrows in a fragment with 100% connectivity among parcels will always be

greater than the expected number of sparrows in a fragment with 0% connectivity among its fragments (Jensen's inequality). This modeling was done for the habitat configuration during historical and modern times. Extinction either occurs or does not occur and is thus a binomial variable with respect to each isolated parcel. We assumed that parcels were filled to capacity when not extinct, such that projected estimates for the fragment subpopulation were calculated as the sum over all parcels of the probability of extinction multiplied by the carrying capacity.

CATASTROPHIC EVENTS

We did not have any a priori expectation about catastrophic events because of the paucity of data on the frequency and extent of catastrophes on the *samuelis* population. Therefore, we ran a sensitivity analysis on these parameters at carrying capacities varying from 20–3,000. We ran simulations for three different extents of catastrophes (50, 70, and 90% mortality in each parcel over winter) that occurred in 10% of years, and 90% mortality at 5% frequency. At $K < 50$, the outcome was extremely sensitive to the extent of catastrophe, but at $K > 100$, the outcome was highly sensitive when extent was >50%, but

relatively insensitive when catastrophic extent was 0–50%. Frequency made little difference relative to extent at 90% mortality. The analysis assumed 0% connectivity of parcels and was then used to calculate expected population numbers (2.75 females/ha; Johnston 1956b) for both historical and modern habitat maps.

RESULTS

PARCELS AND FRAGMENTS

The area of tidal marsh included large fragments (>500 ha) in the Petaluma and Napa marshes at the center of the range, surrounded by medium-sized fragments (>350 ha) at China Camp, Tubbs Island, and White Slough, and the smallest fragments at the southwestern and southeastern extent of the range (Fig. 2a). The modern tidal-marsh area was estimated to be 8,076 ha, composed of ten fragments (1–33 parcels each, mean parcel size = 80 ha). Cogswell (2000) reported a similar number of fragments, but he defined different areas. The mean fragment size ranged from 12–3,887 ha (Table 1).

Tidal-marsh area differed greatly from the historic to the modern landscape. In the past, fragments ranging from 30–23,225 ha represented 3.2 times more tidal marsh than in the present (Table 2). Nearly 90% of the historic tidal wetlands were encompassed within a single large fragment that extended from China Camp in the southwest to Napa River in the northeast (Fig. 2b). Two other fragments to the southwest exceeded 500 ha, and the area of Point San Pablo was >1,000 ha. Each fragment was composed of 3–39 tidal-marsh parcels with a mean size of 259 ha.

POPULATION SIZE ESTIMATES

The number of pairs estimated to occupy the 10 fragments ranged from 29 pairs in a 12 ha fragment to 10,648 pairs in a 3,887 ha fragment (Table 1). We estimated the current population of *samuelis* as 22,079 pairs. This population estimate is higher than earlier figures by Walton (4,600 pairs in 1978) and Marshall and Dedrick (15,000 pairs in 1994); however, our model results compared well with a more recent

TABLE 1. HABITAT FRAGMENTS, PARCELS, AREAS, AND POPULATION PROJECTIONS BY LEVEL OF CONNECTIVITY (0%, 100%) FOR PAIRS OF SAN PABLO SONG SPARROWS IN THE MODERN BAYLANDS DETERMINED FROM THE ECOATLAS (SAN FRANCISCO ESTUARY INSTITUTE 2000).

Fragment	Name	Number of parcels	Area (ha)	Connectivity	
				0%	100%
1	Richardson Bay	14	107	269	294
2	San Quentin	15	187	488	514
4A	China Camp	4	475	1,304	1,305
4B	Petaluma Marsh	11	2,210	6,072	6,079
4C	Tubbs Island	5	477	1,306	1,313
4D	Napa Marsh	33	3,887	10,648	10,688
4E	White Slough	1	384	1,057	1,057
5	Rodeo	3	12	29	32
7	Point Pinole	9	69	176	190
8	Point San Pablo	6	268	730	738
Total		101	8,076	22,079	22,210

TABLE 2. HABITAT FRAGMENTS, PARCELS, AREAS, AND POPULATION PROJECTIONS BY LEVEL OF CONNECTIVITY (0%, 100%) FOR PAIRS OF SAN PABLO SONG SPARROWS IN THE HISTORIC BAYLANDS CIRCA 1850 DETERMINED FROM THE ECOATLAS (SAN FRANCISCO ESTUARY INSTITUTE 2000).

Fragment	Name	Number of parcels	Area (ha)	Connectivity	
				0%	100%
1	Richardson Bay	22	276	731	759
2	San Quentin	4	726	1,992	1,996
3	San Pedro	5	586	1,602	1,612
4	Napa River–China Camp	39	23,225	63,841	63,870
5	Rodeo	6	30	72	81
6	Hercules	5	58	155	160
7	Point Pinole	3	83	227	228
8	Point San Pablo	16	1,008	2,762	2,772
Total		100	25,992	71,382	71,478

estimate (25,000 pairs) based on extensive surveys in the sub-region (Nur et al. 1997).

In the historic landscape, tidal-marsh habitats surrounding San Pablo Bay were more than three times larger and the model estimated a population of 71,400 pairs, a number very similar to the 71,000 pairs calculated by Marshall and Dedrick (1994). We estimated abundance ranging from 72–63,841 pairs in the eight fragments, with most pairs (89%) found in the fragment spanning Napa River to China Camp (Table 2; Fig. 2b).

CONNECTIVITY AND CATASTROPHE

Modern population estimates of *samuelis* (22,210) differed <1% compared to the number predicted (22,079) if connectivity of populations within parcels was 100% or 0% (Table 1). Similarly in the historic landscape, we found little difference (<1%) in estimated *samuelis* numbers with 0% and 100% connectivity of parcels (Table 2). For parcels in which $K < 10$ pairs, populations were likely to go extinct at any catastrophe level (Figs. 3a, b). Low catastrophe levels (0–50%) were related to high frequency of extinction only in the parcels where $K \leq 10$ pairs. The predicted frequency of extinction was only affected in the smallest parcels with carrying capacities of ≤ 10 pairs by catastrophic rates of 0–50% in 50 yr (Fig. 3a).

DISCUSSION

PVA models may be valuable as decision tools to assess risks in reaching proposed management goals for target species (Reed et al. 2002). 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) may result in an increase in *samuelis* numbers. However, our PVA model suggests that *samuelis* is not in imminent danger of extinction with the current extent of tidal-marsh habitats. 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, may become much more important determinants of population size.

Most salt-marsh parcels surrounding San Pablo Bay were relatively small ($\bar{x} = 16$ ha), and the largest 15% of the parcels comprised the majority (89%) of the total area. Even when no inter-parcel dispersal occurred (0%

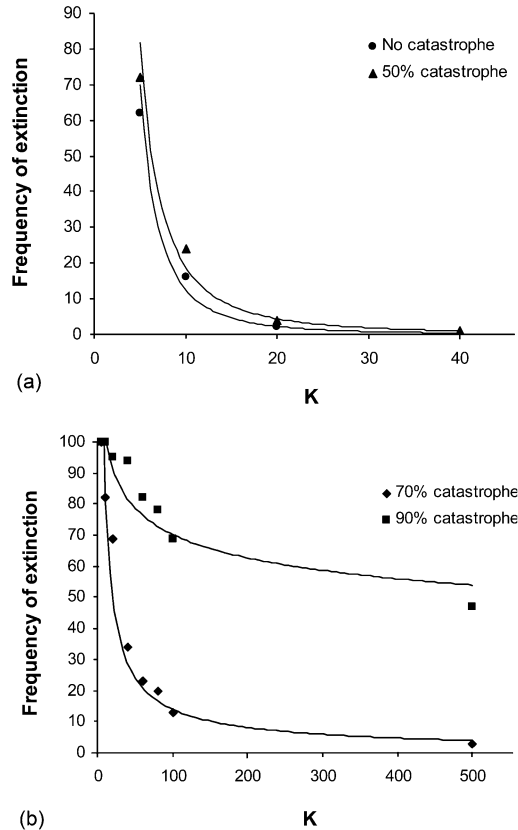


FIGURE 3. Frequency of extinction predicted as a function of carrying capacity (number of pairs per parcel) at (a) low (0, 50%) and (b) high (70, 90%) catastrophe rates within a 50-yr period as a function of K.

connectivity), population projections for *samuelis* were very similar to results assuming 100% connectivity, except when catastrophic extent was >70% mortality. Thus, although we concluded that connectivity among parcels was not a critical issue in the current landscape, our finding that small parcels had greater extinction probabilities indicates that it will be important to prevent increased fragmentation in the future. In addition, we did not examine patch shape, a factor that may affect habitat value for tidal-marsh species (Benoit and Askins 2002). Parcel shape may be an important consideration in restoring parcels for species like *samuelis* that typically use linear channel habitats (Collins and Resh 1985).

We did not incorporate habitat quality in our model, but it is known to affect population persistence in birds (Root 1998). Nur et al. (1997) found that densities of sparrows varied as a function of patch size, and smaller patches may be sinks where populations are not maintaining

themselves. Densities were much lower in the southeast part of their range compared with the northwest (Nur et al. 1997), suggesting that habitat quality in the sub-region did vary. *Samuelis* densities are greater within tall native vegetation such as gumplant (*Grindelia stricta*) and coyote bush (*Baccharis pilularis*) that are used for nesting and cover (Collins and Resh 1985). Song Sparrows seem to have greater reproductive success (Johnston 1956a, b; Nur et al. 1997) in habitats dominated by pickleweed (*Salicornia virginica*), as opposed to those dominated by native California cordgrass (*Spartina foliosa*), probably because pickleweed is associated with higher elevation marsh zones with taller vegetation and less potential for nest flooding.

CATASTROPHIC EVENTS

Although Johnston (1956a, b) found unusually high tides to be an important cause of nest failure from flooding, recent studies (Nur et al. 1997) were unable to corroborate high tides as an important source of nestling mortality (N. Nur, PRBO Conservation Science, pers. comm.). Compared with Mandarte Island, British Columbia, where cold, rainy winter conditions decimated the population in two of 17 yr (Arcese et al. 1992, Smith et al. 1996), winter storms are likely not major catastrophic events for Song Sparrows in the warmer climate of the San Francisco Bay area. In >18 yr of mist netting an upland subspecies of Song Sparrow (*M. m. gouldii*) at nearby Point Reyes National Seashore, no evidence showed any catastrophic decline (N. Nur, PRBO Conservation Science, pers. comm.). However, oscillations in Sierra Nevada stream flows may lead to periodic flood and drought events and salinity changes in the estuary (Dettinger and Cayan 2003), conditions that may alter tidal-marsh plant composition and habitat structure (Zedler et al. 1986). Effects of this type of catastrophe, delayed by time lags of more than a year, may be difficult to identify (Knopf and Sedgwick 1987).

Risks of sea-level rise may exacerbate nest inundation, especially during highest high tides. Although sea-level rise of 30–90 cm is predicted to occur in the next 100 yr, extreme high tides may increase at a higher rate. For example, one scenario indicated that sea-level rise of 20 cm may produce a 28 cm increase in extreme high tides (Malamud-Roam 2000). With many of the bayland wetlands adjacent to cities or behind levees, loss of wetland habitats may result in catastrophic losses of tidal-marsh populations. Though actual effects of higher high tides are marsh specific (due to differences in elevation and geomorphology), preliminary

analysis shows that Song Sparrow nests in exotic cordgrass are much more likely to flood than nests placed in native vegetation (J. C. Nordby and A. Cohen, unpubl. data). The risks of sea-level rise in combination with the invasion of smooth cordgrass (*Spartina alterniflora*) and *S. foliosa* × *S. alterniflora* hybrids may create catastrophes at the level where persistence of the subspecies may be threatened (Takekawa et al., chapter 11, *this volume*). Smooth cordgrass may invade future restoration projects, leading to reduced food resources and foraging habitat for Song Sparrows and creating more favorable habitat for Marsh Wrens (*Cistothorus palustris*) that may displace Song Sparrows (J. C. Nordby, unpubl. data).

PVAs IN RESTORATION PLANNING

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, blanket 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), and mosquito ditches that provide channel habitat for as many as 2,000 *samuelis* 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 may be less vigorous, and did not provide the height structure needed for the endangered Light-footed Clapper Rail (*Rallus longirostris levipes*; Zedler 1993). Similarly, Song Sparrows in restored terrestrial habitats with less structure were less productive and prone to predation because of lack of cover (Larison et al. 2001).

Multi-species 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. 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 compared with predicted population losses of other species (Stralberg et al. 2005; N. Warnock, PRBO Conservation Science, unpubl. data), providing for better balance in restoration decisions.

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