Some Key Findings of the California LCC Project, *Vulnerability Analysis and Monitoring Program for Detecting Changes in San Francisco Bay Tidal Marsh Bird Populations Resulting from Climate Change*

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**Background:**

This project assesses the vulnerability of tidal marsh-dependent bird species to anticipated climate change by considering impacts of environmental change on demographic processes, especially rates of survival and reproductive success. We have assessed the population viability and have projected population trends over time, under different environmental conditions, for each of four key species: Black Rail, Clapper Rail, Common Yellowthroat, and Song Sparrow. Each species or subspecies considered is of conservation concern, either Threatened, Endangered, or a California Species of Special Concern.

Tidal marsh populations face multiple threats, not just sea-level rise, but also high tides and storms which inundate the marsh resulting in nest-failure or mortality of juveniles and adults (Takekawa et al. in press). Such events may become more likely in the future (Cayan et al. 2008). To maximize the long-term persistence of threatened populations in the face of such impacts, information on demographic processes is required. This project focuses on two key stages of the life cycleof tidal marsh wildlife, **breeding** and **over-winter survival**. Populations are imperiled, or will not be able to recover, if either stage is compromised. A single, severe storm/flooding event during the breeding season can cripple that year’s reproduction. Similarly, during the winter, an especially high tide will lead to flooding of key roosting or foraging habitat of tidal marsh species, making them vulnerable to predators (e.g., herons and egrets) unless high-tide refugia are available. In addition, weather variables, including precipitation and temperature, can have direct effects on reproductive success in addition to indirect effects acting through vegetational change. Climate scientists anticipate changes in patterns of precipitation and temperature (Ramirez and Jarvis 2010).

A recently completed LCC project, conducted by PRBO and its colleagues (see [www.prbo.org/sfbayslr](http://www.prbo.org/sfbayslr)) developed scenarios of future marsh distribution and extent in relation to anticipated sea-level rise and marsh accretion, and then projected future marsh vegetation composition and bird populations in relation to a set of physical variables. That work focused on the anticipated availability and suitability of habitat for marsh bird populations. Habitat is a necessary requisite for the continued persistence of tidal marsh-dependent wildlife, but habitat by itself does not ensure long-term viability of robust wildlife populations. Thus the current project provides additional, essential information to guide managers, agencies, and other groups, in developing and implementing climate adaptation strategies and other responses that will maximize the long-term persistence of threatened populations.

**Approach:**

We have developed population dynamic models for each of the four tidal marsh-dependent species. The species modeled with the greatest detail is the Song Sparrow, whose tidal marsh populations have been intensively studied by PRBO scientists since 1996 (Spautz et al. 2006, Spautz and Nur 2008a, Spautz and Nur 2008b, Liu et al. 2007). In particular, reproductive success has been studied in color-marked populations at seven marsh sites over a 12-year period (Greenberg et al. 2006, Liu et al. 2007).

Statistical analyses conducted as part of this project reveal the influence of five key environmental variables on reproductive success:

* precipitation during the fall, winter, and spring preceding or including the breeding season (“bioyear” precipitation),
* precipitation during the breeding season only,
* minimum temperature during the breeding season,
* maximum temperature during the breeding season, and
* the height of the maximum tide observed during the breeding season.

We found that **the probability an individual nesting attempt is successful** increased with maximum temperature, decreased as bioyear precipitation increased, and decreased with increasing maximum tide. The effect of tide on nest success undoubtedly acts through the flooding of nests. In fact, the probability of nest failure due to flooding varied among years from 3% to 55%. Most other nest failure was due to predation. Hence, the weather effects detected more likely involve variation in predation rates on nests, such that nest survival probability is greater during years that are warmer and with less total seasonal rainfall. **The number of nesting attempts per season** decreased as minimum temperature increased, but the number of attempts increased with breeding season precipitation. More nesting attempts reflect a more extended breeding season that in turn reflects wetter conditions during the spring. The number of eggs laid or young fledged per successful nest was not related to the weather or tide variables. The Report for this project will depict the statistical results that were used in the modeling, which is described below.

**Demographic modeling:**

Information on six key demographic parameters is needed to model the dynamics of a single population, one in which there is no net flux of emigrants or immigrants (that is, if there is emigration, it is balanced by immigration; Nur and Sydeman 1999). The parameters are:

1. Adult survival
2. Survival of individuals from fledging to adulthood
3. Probability that an adult attempts to breed
4. Number of nesting attempts per year for breeders
5. Probability that an individual attempt is successful, and
6. Number of young fledged per successful nesting attempt

We assumed females are the limiting sex, since field observations indicate that there are unmated males, but no unmated females among adults. Thus, we assumed that all females aged 1 and older attempt to breed. Adult and juvenile survival values were obtained from studies on Song Sparrow populations at Palomarin (Nur et al. 2000) and the Mandarte Island population (Arcese et al. 1992). We incorporated year to year variation in adult and juvenile survival based on studies at Palomarin. The three components of reproductive success (#4, #5, and #6, above) were obtained from our statistical analyses of the long-term studies by PRBO of tidal marsh populations. The model incorporated year to year variation in the three components of reproductive success that, in turn, reflected variation due to environmental variability (due to temperature, precipitation, and maximum tide) as well as additional variation not explained by the five predictor variables.

We further broke annual survival into two components: breeding season survival for adults, and over-winter survival for juveniles and adults. “Over-winter” survival refers to survival from the end of the breeding season (July) to the beginning of the next breeding season (beginning of March).

The population dynamic models track the number of adults (both first-year adults and older individuals) as well as juveniles in each year beginning in 2010 (year 0 of the simulation) and through 2060 (year 50). The parameter values, both mean values and the variance around the mean values, were adjusted in order to replicate the behavior of the tidal marsh Song Sparrow population dynamics we have observed, as described in the Report in greater detail. More specifically, parameter values were adjusted to produce a population that declines on average ~2.1% per year, which is the best estimate for population change for tidal marsh Song Sparrows in San Pablo and Suisun Bays during the recent period, 2000 to 2009. We refer to this rate of change as a finite population growth rate of 0.979, symbolized λ (lambda). Thus, model parameters were verified using recently observed population values.

Song Sparrow population dynamics over a 50-year period were simulated under multiple scenarios. Here we highlight results from four informative scenarios. One scenario consisted of current environmental conditions continuing into the future. The other three scenarios incorporated projections of future climate (precipitation and temperature) as well as future sea levels as described below.

**Future Tides and Projected Sea-Level Rise and Future Climate Projections**

We obtained a simulation of hourly local sea-level from Cayan et al. (2009) for the San Francisco tidal gauge at Fort Point. The simulations are based on predicted tides, projected winds, barometric pressure and El Niño Southern Oscillation (ENSO) state from the National Center for Atmospheric Research Community Climate system Model (NCAR CCSM3.0) general circulation model (GCM), and sea-level rise based on projections from Vermeer and Rahmstorf (2009). The projected **change** in sea-level in these models is due to the increase in mean sea-level and not due to changes in predicted tides or weather (Cayan et al. 2008, 2009).

 We summarized the sea-level rise projections by calculating the maximum “winter” (November, December, January, February) and breeding season (March, April, May, June, July) sea-level for each year. These projections included effects of global sea level rise, tide, and weather. In addition, we extracted the change in sea level in winter and summer for each year due to tides and weather but without effects of global sea level rise. Finally, we considered a scenario which excluded effects of global sea level rise but which included periodic extreme tides that occurred on average every five years. An extreme tide was 2.5 m, which was about 0.18 m higher than highest tides observed in recent years.

 Future climate projections for the seven nest monitoring sites were extracted from statistically downscaled version of the CCSM3.0 GCM (<http://gisweb.ciat.cgiar.org/GCMPage>). The climate data were downscaled to a 2.5 minute grid (~4 x 4 km) using methods described in Ramirez and Jarvis (2010). We extracted data from the model using the A1b emission. The A1b emissions scenario is considered a moderate scenario, but projects relatively high CO2 emissions during the first half of the 21st century and then stabilizes to a mid level of CO2 emissions during the second half of the century relative to other IPCC emission scenarios. The downscaled climate models included projections for each month for precipitation, maximum temperature, and minimum temperature for each decade, using a 30-year average for each decade (i.e., 2015-2045 for the year 2030). We then interpolated temperature and precipitation values for each year for 2010 to 2060 based on the decadal values. We calculated the maximum and minimum temperatures for the breeding season and the precipitation for the breeding season only and for precipitation during the fall, winter, and breeding season, just as we did for the recent historical period.

The four Scenarios summarized here:

1. Environmental conditions continue in the future consistent with the recent past (1970-2010 for weather variables and 1996-2010 for maximum tide). Year to year variation in environmental conditions reflects a constant mean value (the recent historic value) plus the observed variation around that value.
2. Future temperature and precipitation conditions were modeled as described above, obtained from downscaled GCM. Future tides were based on maximum sea levels (calculated hourly) reflecting: global sea level rise, astronomical tides, and weather (see details above).
3. Future temperature and precipitation conditions were modeled as described above, obtained from downscaled GCM. Future tides were based on maximum sea levels (calculated hourly) reflecting astronomical tides and weather, but excluding global sea level rise (see details above).
4. Future temperature and precipitation conditions were modeled as described above, obtained from downscaled GCM. Future tides were calculated as for scenario 3, but with the addition of extreme tides of 2.5 m, occurring on average once every 5 years. Such a tide is about 18 cm greater than what has recently been recorded for tide gauges used in our analysis.

Thus, under scenario 2 it is assumed that **Song Sparrows** **are not able to compensate** for global sea level rise. Global sea level rise results in loss of habitat, reduction in habitat quality, and increased nest failure. The birds may be mobile, but their habitat is not able to adequately migrate.

Under scenario 3, **Song Sparrows are assumed to be able to fully and completely compensate** for global sea level rise. It is assumed that adequate nesting habitat will be available even as sea level increases at ever faster rates. There is no loss of habitat, no reduction in habitat quality, and no increase in nest failure due to global sea level rise.

Scenarios 2 and 3 represent extremes. Scenario 4 is a hypothetical scenario that is intermediate between the two and one which may shed light on effects of extreme events, i.e., especially high tides that may result from storm surges or other weather phenomena.

A key feature of our approach is that population change in the future reflects future environmental variation (such variation may be predictable or unpredictable or a combination of the two), as well as additional variability not accounted for by the key environmental variables. This additional variability may be due to environmental factors that we have not modeled, or maybe due to factors that do not reflect environmental variability in the usual sense, e.g., suppression or enhancement of predator species by humans. The resultant variability in demographic parameters due to predictable and unpredictable sources yields stochasticity in the population dynamics.

**Results**

Population dynamic results are shown in four panels per scenario (labeled A, B, C, and D).

* Panel A depicts mean trajectory in total number of adults at the start of the breeding season (March 1st) over the 50 years and plus or minus 1 Standard Deviation of the total number of adults in each year, reflecting results of the 100 simulations. The starting population size was set to 10,000 adults in 2010 (considered year 0).
* Panel B depicts an example of a single simulation (“run”).
* Panel C summarizes the lambda values obtained decade by decade for the 100 simulations. For each decade, the median lambda values, the lower quartile lambda, the upper quartile lambda, and the 5th and 95th percentile lambda values are shown.
* Panel D summarizes the probability of specified cumulative decline over 10 years, 20 years, 30 years, 40 years, and 50 years since the start of the simulation. Depicted are the probabilities of 50% decline over 50 years if the observed trend continues and probability of 80% decline over 50 years if the observed trend continues. For example, a population that has declined by 12.94% over ten years is declining at an average rate of 1.38% per year. If this trend continues over 50 years, the population will have declined by a cumulative 50% after 50 years. Similarly, a population that has declined by 27.52% over ten years is declining at an average rate of 3.17% per year. If this trend continues over 50 years, the population will have declined by a cumulative 80% after 50 years. We consider a projected 50% decline over 50 years to be of **moderately strong concern** and a projected 80% decline over 50 years to be of **high concern**.

**Key Results Highlighted**

**Scenario 1:**  If present conditions continue, Song Sparrows can be expected to continue to exhibit population declines. On average, the population is expected to shrink from 10,000 to fewer than 4,000 by 2060 (Figure 1A, 1B). However, a sizable proportion of simulations result in extinction as early as 2050. Decade by decade, lambda can be expected to be below 1 during the 50-year period; however about 25% of simulations exhibited a lambda of above 1 in each decade (Figure 1C). The probability of 50% decline was 80% after 50 years while the probability of 80% decline was almost 40% (Figure 1D). In only 20% of simulations was the decline less than 50%.

Figure 1. Summarization of population outcome from 2010 to 2060 for Scenario 1 (Present environmental conditions continue). A) Mean number of adults and +/- 1 S.D. in each year for 100 simulations shown. B) Example of a single simulation. C) Summarization of lambda values by decade. Shown are the median (thick center line), lower and upper quartiles (shaded region), and 5th and 95th percentile values. D) Probability of cumulative decline (after 10 years, 20 years, etc.) equivalent to 50% decline over 50 years and 80% decline over 50 years, as described above.

A)

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B)

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C)

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D)

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**Scenario 2:** With temperature and precipitation as predicted for the future (using downscaled GCMs) and projected sea levels increase due to global climate change, coupled with projected astronomical tides and weather influences, the population will quickly head towards extinction. By 2060, on average there will only be several hundred individuals compared to 10,000 in 2010 (Figure 2A), with many runs going to zero or near zero (Figure 2B).

Our results may overstate the case for extinction since we did not incorporate recolonization from elsewhere. Nevertheless expected population decline is severe and accelerates over the 50 years due to accelerating sea level rise. In the first decade the population declines at about 3% per year on average, but by the fifth decade (2050-2060), expected population decline is 12.5% per year (Figure 2C).

The probability of cumulative decline also accelerates over time. After 10 years, only 52% of the populations are on track to decline by 80% or more over a 50-year period, but by 2060, nearly 100% of the population have declined by 80% or more (Figure 2D).

Figure 2. Summarization of population outcome from 2010 to 2060 for Scenario 2 (Temperature and precipitation as predicted for future; sea level predictions incorporate global sea level rise and other effects on tides). A) – D) as described for Figure 1.

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B)

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C)

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D)

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**Scenario 3:** With temperature and precipitation as predicted for the future (using downscaled GCMs) and projected sea levels increase due to projected astronomical tides and weather influences only, the population will grow, first slowly and then quickly, due to improvement in precipitation and temperature resulting in higher reproductive success. Thus the population behavior under this scenario contrasts sharply with Scenario 2, highlighting the importance of the ability of Song Sparrows to respond to global sea level rise. The increase is gradual at first, but then accelerates after about 2025 (Figure 3A). Population growth rates stay above 1 throughout the period. It is not realistic for Song Sparrows to increase to 100,000 or more (if the starting population is 10,000) but the important point is that populations can be expected to increase by 5% or more per year (Figure 3C), if we do not factor in global sea level rise. Furthermore the probability of cumulative decline on track for a 50% decline over 50 years drops from 23% in the first decade (2010 – 2020) to 0% by the third decade. In other words, if the availability and suitability of marsh habitat is fully maintained in the future, Song Sparrows can thrive.

Figure 3. Summarization of population outcome from 2010 to 2060 for Scenario 3 (Temperature and precipitation as predicted for future; sea level predictions exclude global sea level rise but include other effects on tides). A) – D) as described for Figure 1.

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B)

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C)

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D)

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**Scenario 4:** In this scenario, temperature and precipitation are as predicted for the future (using downscaled GCMs). Projected sea levels do not include global sea level rise, but only changes in sea level as predicted due to projected astronomical tides and weather influences, except that we have added extreme tides of 2.5 m occurring on average every 5 years. The population is expected to increase over the 50 years, but not at the extreme rates seen in Scenario 3. Instead of increasing to 90,000 by 2050, the population is expected to increase from 10,000 in 2010 to about 26,000 on average in 2050 and then to 50,000 by 2060 (Figure 4A, 4B). Moreover, in the first 20 years, there is no net increase in number, and lambda values are generally at 1 or below (Figure 4C). In fact, after 10 years, 59% of the populations are decreasing at a rate that will yield a 50% decline after 50 years (Figure 4D). But by 2060, only 2% in fact declined by this much. Similarly, 42% of the populations were on track for an 80% decline after 10 years, but by 2060 the trajectories had changed so much that none of the populations exhibited such a decline.

Thus, the results of this Scenario demonstrate the potent effect of infrequent (once every 5 years in this case) extreme tides on population viability. More generally, this Scenario provides insight into future viability of tidal marsh birds if they are not able to fully compensate for increased sea levels in the future.

Figure 4. Summarization of population outcome from 2010 to 2060 for Scenario 4 (Temperature and precipitation as predicted for future; sea level predictions exclude global sea level rise but include other effects on tides and include extreme tides every 5 years, on average). A) – D) as described for Figure 1.

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B)

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C)

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D)

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**Summary and Conclusions**

This study has demonstrated the value of incorporating demographic processes into assessing impacts of climate change on long-term population viability. Even if habitat is available in the future, and of suitable condition for threatened populations such as tidal marsh Song Sparrows, low reproductive success resulting from climate change may lead to precipitous drops in population size, with extinction or near-extinction a likely result.

This study focused on reproductive success: here we have demonstrated that temperature, precipitation, and high tide levels all affect reproductive rates of a tidal marsh bird, in particular nest survival and number of nesting attempts per female per breeding season. Anticipated climate change will produce temperature and precipitation values that favor higher nest survival probability and longer breeding seasons, thus increasing reproductive rates, though climate change will also increase sea level thus decreasing nest survival. However, juvenile and adult survival is also likely to be influenced by both weather (Arcese et al. 1992) and extreme tides (Evens and Page 1986). We are currently applying simple population dynamic models for Black Rails and Clapper Rails to assess vulnerability to climate change; these models incorporate effects of winter-time extreme tides on survival of the two rail species.

The overwhelming factor influencing future population trajectory for this tidal marsh bird species is increasing water level due to global sea level rise. If the population can fully compensate for anticipated global sea level rise then the prospects for future population growth are very good. If the population cannot compensate for global sea level rise, then steep declines are expected, especially in 20 years or more when the accelerating increase in sea level is expected to be more evident. We expect that tidal marsh Song Sparrows lie somewhere in between these two extremes: there are some constraints on the ability of their habitat, including nesting habitat, to migrate in response to higher sea levels.

That said, any steps taken that can reduce the impact of projected sea level rise on these populations will have a major impact on their viability. Such steps can include reduction in the actual sea level rise experienced in the marsh or reduction in probability of flooding of nests, e.g., by construction of berms or provision of additional vegetation. An alternative approach is to implement compensatory measures that increase survival or other aspects of reproductive success, thus mitigating for the effects of climate change. The next iteration of our findings will include modeling results that incorporate alternative management actions, allowing assessment of the efficacy of such management.

We believe that our results are applicable to tidal marsh bird species more generally, in the San Francisco Estuary and throughout the world. The models developed here can be tailored to other species and other estuary habitat. Furthermore, the modeling approach, statistical methods, and modeling algorithms can be adapted to other species of concern, in other habitats. We will make our code freely available to others who wish to adapt our analytic and modeling approach.

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