SAN FRANCISCO BAY
BIRD OBSERVATORY

Review and analysis of historical phalarope population trends

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FINAL REPORT
April 21, 2023

Suggested citation: LaBarbera, K.., G. Burns, and N.D. Van Schmidt. 2023. Review and analysis of historical phalarope population trends. San Francisco Bay Bird Observatory. Report prepared for the South Bay Salt Pond Restoration Project.

EXECUTIVE SUMMARY

The South Bay Salt Pond Restoration Project (SBSPRP) is restoring over 15,000 acres of former salt evaporation ponds to a mix of tidal marsh and ponded wetland habitats. These wetlands provide habitat for many waterbirds, including migrating red-necked phalarope (*Phalaropus lobatus*) and Wilson's phalarope (*P. tricolor*). Sustaining baseline population goals for wildlife populations requires understanding how species are responding to restoration actions over time. If a species group is observed to drop below a sustained threshold or hit a single-year trigger point below that baseline, the Project is committed to evaluating available data and considering targeted management action. Part of this consideration is whether the decline is likely a result of restoration actions. In 2017, phalarope counts were below their assigned trigger point. Now we seek to understand how this observed decline in the salt ponds compares to broader population trends throughout the phalaropes' Western migration routes.

We reviewed a combination of existing scientific survey data and community science data to gain insight into phalarope abundance and how it has changed over time. In July 1986, coordinated Wilson's phalarope surveys across migration stopover sites yielded peak counts of 741,000, including 40,000 (5% of the total count) in South San Francisco Bay. By the early 1990's, peak Wilson's phalarope counts at the three largest migration sites had dropped by 50%. Range-wide data is not available for red-necked phalaropes, but it was estimated that 52,000–65,000 passed through Mono Lake each year during the early 1980's.

The next regular scientific surveys of phalaropes at migration sites began in 2019 and are ongoing. Counts have varied across years and no clear directional trends have emerged. The Wilson's phalarope peak count was highest in 2019 (370,770) and lowest in 2022 (just under 200,000). The red-necked phalarope peak count was highest in 2019 (296,731 birds) and lowest in 2021 (124,048). In 2021, counts from SFBBO's Phalarope Migration Surveys represented less than 1% of the total counts during peak periods. The 2022 peak count for Wilson's phalarope (735 birds) represents a decline of 98% from the 1986 survey data.

The time period of greatest interest for our purposes (2005–2018) is part of the gap between scientific surveys of phalarope numbers. To shed light on this period, we performed an analysis of community science data submitted to the eBird platform. We used negative binomial linear models to investigate trends in phalarope counts while controlling for survey effort at several geographic scales, ranging from three Bay Area counties to the state of California. We found that phalarope counts had declined steeply from the early 1970s to the late 1990s, and from then to the present showed a continuing but more shallow decline. The three Refuge counties (Alameda, San Mateo, and Santa Clara) had higher counts than the rest of California in the 1970s, but declined more steeply in the following two decades. Analysis of only the most recent 20 years (2002-2022) found no significant difference in estimated population trends between the Refuge counties and the rest of California, although the nature of eBird data makes this a relatively insensitive analysis.

All of our investigations showed evidence of significant phalarope decline since the 1970's, particularly in the South San Francisco Bay Area. The declines were greatest during the period of the 1970's-1990's, during which period the counties containing the SBSPRP area saw a much greater rate of decline than other geographies. Beginning in the early 2000's the rate of decline began to decrease and converge to its current steady low rate across geographies. The alignment of this timing with the beginning of restoration suggests that the worst of the declines are not attributable to management actions, but we cannot rule out that there is still a degree of negative effect from restoration on phalarope populations in the Bay Area. In any case, the severity of the >95% loss of Bay Area Wilson's phalaropes since 1986 strongly suggests the need for monitoring and management interventions, particularly as the saline lakes phalaropes depend upon for migration stopover sites elsewhere across Great Basin are severely threatened by water diversion and climate change. Suitable habitat in the Bay Area could become a refuge for phalaropes displaced by habitat loss elsewhere in their range. Additional years of high-quality survey data such as that generated by the Phalarope Migration Survey will make possible an analysis that could disentangle the impacts on phalaropes of various factors, including Project management actions.

INTRODUCTION

In 2003, the U.S. Fish and Wildlife Service (USFWS) and California Department of Fish and Wildlife (CDFW, formerly California Department of Fish and Game) entered into an historic agreement with Cargill Salt to acquire 15,100 acres of salt evaporator ponds in the south San Francisco Bay. The South Bay Salt Pond Restoration Project (SBSPRP) has begun to restore the area to a mix of tidal and ponded habitats while continuing to provide flood risk management and improved public access to many sites.

The SBSPRP has committed to restoring some ponds to tidal marsh, while retaining some pond habitat (as managed ponds) within the project area for waterbirds. Monitoring of waterbird populations is used to assess their effectiveness at achieving these goals. Waterbird surveys were conducted from 2005–2007 to determine population baselines before major restoration activities began. The baselines were used to set thresholds and trigger points for further investigation if the population of a particular species group dropped too low. Certain species groups, such as phalaropes *(Phalaropus spp.)*, were of particular note because their habitat needs are more aligned with the conditions of salt production ponds than restored tidal marsh (South Bay Salt Pond Restoration Project, 2007). In 2017, phalarope counts were 78% below the baseline value, which is well beyond the action trigger of 50% below the baseline of a monthly summer average of 3225 birds. The management criteria outlined in the Adaptive Management Plan seek to differentiate between observed declines that are likely the result of restoration actions versus reflective of broader population trends outside of the Project's control (South Bay Salt Pond Restoration Project 2007).

Phalarope Natural History

There are three species of phalarope, two of which (Wilson's and red-necked) migrate through the South Bay and are the focus of our research. Red-necked phalaropes breed in the arctic and winter in the waters off of South America, while Wilson's phalaropes breed in the northern US into southern Canada and winter in saline lakes in South America (Colwell & Jehl 2020, Rubega et al. 2020).

Little is known about their northward migrations in the spring, but during the fall both species congregate at staging areas on their way south (Lesterhuis & Clay 2009). Hypersaline lake environments are important to both species during their southbound fall migration each year (Carle et al. 2022). In Western North America, these staging sites are hypersaline lakes such as Great Salt Lake in Utah, Mono Lake in California, and Lake Abert in Oregon (Carle et al. 2022). More than 70% of the world population of Wilson's phalaropes and more than 10% of the world population of red-necked phalaropes utilize these lakes during their fall migration (Carle 2022). Wilson's phalaropes perform a full molt during their stopover–one of only two shorebird species to do so (Lesterhuis & Clay 2009). The creation of salt production ponds around San Francisco

Bay introduced habitat that also attracted phalaropes, although in lower numbers than the saline lakes (Jehl 1988, Winkler 1977).

Phalaropes also migrate through Eastern and Central North America, with the Bay of Fundy on the US-Canada border being a particularly notable stopover site (Hunnewell et al. 2016). These migration routes are used predominantly by red-necked phalaropes and red phalaropes (*P. fulicarius*), rather than Wilson's phalaropes (Brown et al. 2010, Hunnewell et al. 2016). We are not aware of any literature comparing the Eastern and Western migration routes, but a study of shorebird trends (including phalaropes) in the North Atlantic and Midwest regions concluded that the regional trends were divergent enough that individual regions should not be extrapolated to conclude rangewide trends (Bart et al. 2007).

There is a lack of consensus on the size of worldwide phalarope populations and what their conservation status should be. The IUCN list considers both species to be "Least Concern" with Wilson's phalarope reported to be slightly increasing and red-necked phalaropes decreasing in numbers (BirdLifeInternational 2016, 2019). However, researchers point out that their populations are difficult to study and poorly understood (Lesterhuis & Clay 2009, Rubega et al. 2020). Past population estimates have come primarily from Morrison et al. (2001), but their estimates were considered to have "significant uncertainty" and have not been comprehensively revisited since then (Brown et al. 2010).

Study Goals

There is a need to determine whether the decline in phalarope abundance within the SBSPRP management area is the result of restoration actions or simply reflective of broader population trends for these species. A third possibility, that the apparent decline is the result of sampling biases, is not supported by available data (covered in the Annual Report, Burns et al. 2023). Because there has not been a contemporary review of the scientific literature on phalarope trends since Morrison et al. (2001), which predated the project, we first conducted a review of published studies and datasets that used formal scientific coordinated surveys. Because we found a scarcity of data for the study area in general and the time period of the observed decline (mid-2000's) in particular, we supplement this review with an original analysis of community science data. We conclude by holistically discussing local and range-wide trends, and the degree to which local declines can be attributed to management actions by the Project.

COORDINATED SURVEY DATA

To compile this report, we searched broadly for and reviewed a variety of sources of data on phalarope numbers, including published scientific papers, publicly-available reports, and raw data. Historic coordinated scientific surveys across the western range were conducted primarily during the 1980's, with only scattered local surveys in the 1990s and 2010s until coordinated surveys across the western range began again in 2019.

Historical Stopover Site Counts (1980-2015)

Joseph R. Jehl, Jr did extensive research on phalarope migration in Western North America during the 1980's, particularly focusing on Wilson's phalaropes at Mono Lake and the other large stopover sites (Jehl 1988). In addition to his own direct studies, he compiled available count data from all other known migration sites in western North America (Jehl 1999). The largest sites with the most complete records were Mono Lake, Great Salt Lake, and Lake Abert. Throughout the 1980's, Jehl estimated peak migration counts of 500,000–600,000 Wilson's phalaropes across these major sites.

In 1986, concerted efforts were made to identify and survey additional staging sites and over 741,000 Wilson's phalaropes were recorded in July of that year. This included a peak count of 40,000 from South San Francisco Bay; elsewhere in California there were 56,320 in Mono Lake, 7,500 in San Diego Bay, 6,000 in Tulare Lake (and possibly up to 12,000 that were observed at other water bodies in 1987; Jehl 1988). This is our best estimate of the historic contribution of the SBSPRP area to the western migration route, indicating that it may have supported up to 5% of population and a third of the California population, nearly rivaling Mono Lake in size. Jehl (1988) estimated the true rangewide population size was roughly twice that which was counted, so there were potentially up to 80,000 phalaropes within the area, though he did not perform such an estimation for the Bay counts directly. We could not find information about the precise location or methodology for these counts, but all of the sites included in the study were at salt lakes or commercial salt works.

By the early 1990's, annual peak counts of Wilson's phalaropes at the three major stopover sites had dropped by half to around 250,000–300,000 per year (Jehl 1999). Counts began to increase in the mid-1990's, but not to previous levels. Most sites had no organized surveys after 1997.

There is less data available for red-necked phalaropes during the 1980's and 1990's. Jehl (1986) estimated that between 52,000 and 65,000 passed through Mono Lake each year from 1980-1984, with the exception of a low year in 1983 at only 36,000. Estimates at Great Salt Lake put numbers at up to 1 million red-necked phalaropes during 1982 migration, dwindling down to only 100,000–240,000 per year by 1994 (Jehl 1994). Jehl cautions that these estimates should be taken with a grain of salt because they were extrapolated from sample surveys conducted from shore and not a census of the entire lake. Data from the Bay of Fundy show a precipitous drop of red-necked phalaropes from the early 1980's to early 1990's, similar to the drop in Wilson's phalaropes observed in the Western sites (Duncan 1996, Hunnewell et al. 2016).

The only peer-reviewed data available between 1997 and 2019 is a set of survey data from Lake Abert from 2011–2015 (Larson et al. 2016). Annual census information from East Cascades Audubon Society show peak migration counts ranging from over 200,000 phalaropes (not identified to species) in 2012 and 2013 to just above 21,000 in 2014 and 13,000 in 2015 as the lake dried up, highlighting the severe impact of habitat loss.

Contemporary Phalarope Working Group Surveys (2019 onward)

More recent trends can be estimated from surveys by the The International Phalarope Working Group, which was established and began coordinated monitoring of phalarope staging sites in Western North America in 2019 (Carle et al. 2022). In 2019 there were three participating sites (Mono Lake, Great Salt Lake, Lake Abert) and beginning in 2020 surveys were also conducted at Owens Lake, Chaplin Lake, and South San Francisco Bay. The timing of surveys at each site are coordinated so that counts are conducted in the same week to reduce the chance of double-counting birds that may move between sites. Each location is internally consistent in their survey methods, but methods vary across locations. The surveys were initiated with the goal of replicating the coordinated surveys described by Jehl (1988), although the data cannot be directly compared between the historical and modern surveys due to methodological differences and environmental changes. For example, the water levels at Mono Lake have increased by eight vertical feet since Jehl's studies, which substantially increased the surface area and made it infeasible to continue surveying the entire lake. In other cases, such as South San Francisco Bay, there is no information available about the historical methods used.

Combined counts across all sites show a substantial degree of year-to-year variability in Wilson's phalaropes and substantial variability in red-necked phalaropes (Carle et al. 2022). For Wilson's phalaropes, the average peak count was 301,041, with individual year peak counts from 2019-2021 being 23% higher, 21% lower, and 2% lower, respectively. The standard deviation of the peak count across years was 67,306, or 22% of the mean peak count. For red-necked phalarope, the average peak count was 194,194, with individual year peak counts from 2019-2021 being 53% higher, 36% lower, and 17% lower, respectively. The standard deviation of the peak count was 90,783, or 47% of the mean peak count. Among the three years, the peak counts from 2019 were the highest for both species—despite 2019 being the year with fewer sites surveyed—with a count of 370,770 Wilson's and 296,731 red-necked phalaropes. These counts include the phalaropes that could not be visually identified to species and were classified based on the date of the survey as the two species have distinct migration peaks. Results from 2022 have not been published yet, but are on track to be the lowest annual peak count for Wilson's phalarope at just under 200,000 birds (Ryan Carle pers. comm.). The lowest annual peak count for red-necked phalaropes was a count of 124,048 birds in 2021 (Carle et al. 2022).

SFBBO conducted Phalarope Migration Surveys of the primary South San Francisco Bay habitats during this same time period, with partial surveys in 2019-2020 and full surveys in 2021-2022 (Burns et al. 2022). In 2021, South San Francisco Bay counts represented less than 1% of the total peak counts across the migration sites (0.08% for Wilson's and 0.74% for red-necked phalaropes). The large majority of phalaropes in contemporary surveys were observed at Great Salt Lake. In 2021, 95% of the combined Wilson's phalarope peak count were at Great Salt Lake as were 72% of the combined red-necked phalarope peak counts (Carle et al. 2022).

Comparing Historic and Contemporary Estimates

Cyclical population dynamics are common in wildlife populations and should be expected to some degree, which have the potential to exaggerate or mask local declines. Long-term trends can be estimated by examining if there have been nadir-to-nadir declines or peak-to-peak declines (i.e., are the lows getting lower; Coates et al. 2021). In the case of phalaropes, the available data suggests that their numbers have never again reached the peaks from the 1980's, pointing to a sustained decline rather than cyclical dynamics (Carle et al. 2023).

The peak migration of 735 Wilson's phalaropes in 2022, compared to 40,000 in 1986, indicates a 98% decline from historic levels within the South San Francisco Bay. For comparison, the rangewide estimated decline from 741,000 phalaropes in 1986 to an average of 301,041 in 2019-2021 indicates a decline of 59%. While direct comparisons of these numbers is problematic due to differences in the extent, timing, and protocols of different surveys, this large magnitude of difference strongly suggests that declines in the South San Francisco Bay have exceeded the general rate. The fact that all regions have seen substantial declines suggests that the San Francisco Bay phalaropes did not simply shift their migration route to new sites, though this cannot be determined definitively.

However, these scientific surveys alone cannot identify *when* the decline in South San Francisco Bay between 1986 to 2022 occurred or the relative rates of decline over time. The time period of greatest interest for our purposes is 2005–2018: the years during which baseline surveys and restoration activities were taking place, but SFBBO's Phalarope Migration Surveys had not yet begun. Because we were unable to find any published studies of phalarope numbers during that timespan outside of Lake Abert in Oregon, we turned to community science to get more information about that gap, as described in the next section.

COMMUNITY SCIENCE DATA

Data Sources

The best fit for our needs was the eBird community science platform (eBird 2022). The eBird platform allows any participant to submit checklists with their observational data including location, date/time, species abundance, and various measures of birding effort (Sullivan et al. 2009). eBird provides access to bird presence and abundance data that is unavailable from other resources (e.g., during migration season, which is not covered by the Christmas Bird Counts or Breeding Bird Surveys). Drawing conclusions from this data is complicated by the fact that it does not arise from a standardized survey protocol; rather, eBird data are potentially impacted by variation in observer skill and effort, and sample sizes (i.e., number of bird checklists available) vary widely and non-randomly across time and space (Grade et al. 2022). Any statistical analysis of this data should take effort into account, and the goal should be to discover trends in relative abundance, rather than absolute population sizes (Walker & Taylor 2017; Horns et al. 2018; Johnston et al. 2020). Nevertheless, changes in relative abundance can still identify when declines occurred and their relative magnitude in and outside of the counties of South San Francisco Bay.

The variation in survey effort inherent to eBird data has the potential to impact estimated counts of phalaropes in particular, as phalaropes on a migratory stopover site are spatially clumped (due to flocking behavior) and present for only short periods of time. At low levels of survey effort—i.e., low numbers of submitted checklists—stochastic sampling error becomes likely. This means that eBird data is likely to yield only coarse-scale insights into phalarope trends. Nevertheless, even coarse-scale insights are an improvement over a lack of information.

We considered, but did not use, data from three other community science sources: iNaturalist, Christmas Bird Count (CBC) surveys, and the American Breeding Bird Survey (BBS).

Similar to eBird, the iNaturalist website is another community science platform for reporting wildlife sightings (iNaturalist 2022). Unlike eBird, iNaturalist observations rarely include abundance data, and the platform does not provide tools to aggregate observations for analysis. Among the birding community, eBird is the more popular community science platform. iNaturalist included a relatively small number of phalarope observations in the Bay Area (just 204 for Wilson's phalarope and 785 for red-necked phalarope across all time). We therefore decided to focus exclusively on eBird for community science data because it was more detailed and in much greater quantity.

A common source of long-term bird population counts, Christmas Bird Count (CBC) surveys are conducted by the National Audubon Society each year from December 14 through January 5, primarily in North America. During this time of year both phalarope species have completed their fall migration and are in their wintering ranges (Colwell & Jehl 2020, Rubega et al. 2020), and are almost entirely absent from CBC data (National Audubon Society 2021). We therefore did not consider the CBC surveys to be a viable source of data for this analysis.

The other major source of long-term bird population counts in North America is the USGS North American Breeding Bird Survey (BBS). These surveys are conducted each June along designated driving routes throughout the United States and Canada (USGS 2018). Red-necked phalaropes breed outside of the BBS range, but there is some data available for Wilson's phalaropes. Pardieck et al. (2007) analyzed BBS data from 1966-2003 and calculated that over the whole time range, the population's mean percent change per year (r) was 0.4%, but narrowing to look only at more recent years shows a growing decline. For example, 2002-2003 had a value of -21.3%. However, in the past there has not been strong correspondence between trends in BBS data and trends at migration staging sites. For example, counts at Mono Lake and other major staging sites dropped by almost half between the 1980's and the 1990's, but BBS data from 1967-1992 showed only a sustained general decline with no corresponding jumps (Jehl 1999). Jehl (1999) raises two concerns about the BBS protocol: that it does not overlap with the full Wilson's phalarope breeding range and that the detection methods were designed originally for passerines and are inappropriate for Wilson's phalaropes (e.g., listening for song used in territory defense). Together, the poorly-suited survey methods and lack of congruence between BBS trends and migration surveys made us hesitant to take BBS data as a reliable indicator of phalarope populations during migration.

eBird Data Analysis

Data preparation

We first prepared the eBird data as follows: filtered out checklists that used the "Incidental" protocol; filtered out checklists lacking a value for the duration of the birding session; filtered out checklists that included presence but not abundance data for phalaropes; filtered out duplicate checklists using the Group Identifier; and filtered out checklists from outside the focal time period of June through September.

To model the eBird data, we summed phalarope observations across a given time period and location to permit a large-scale understanding of total population size trends. We summarized eBird data at the level of monthly counts, in order to be able to capture years and areas with few counts. We analyzed phalarope counts at four different spatial scales: the three SBSPRP counties only (Alameda, San Mateo, Santa Clara); the nine counties that compose the Bay Area (Alameda, Contra Costa, Marin, Napa, San Francisco, San Mateo, Santa Clara, Solano, Sonoma); California outside of the three SBSPRP counties; and all of California. The three SBSPRP counties were the closest we could get to modeling only the SBSPRP area itself: eBird checklists contain only a starting location, and even those starting locations are often too vague to differentiate between Project land and nearby non-Project areas. We analyzed the region *California outside of the* SBSPRP *counties* to compare it to the SBSPRP counties, since our other focal regions of analysis all included the SBSPRP and would therefore be impacted by whatever trends were present in the SBSPRP. For each geographic region, we trimmed the data to start on the first year that had five or more phalarope-sighting checklists, to avoid potentially large effects of a few checklists in early years. For the SBSPRP counties and the Bay Area, the data after trimming spanned 1973-2022; for outside the SBSPRP and all of California, the data after trimming spanned 1969-2022.

Variables assessed

A challenge in calculating survey effort for habitat specialists, such as phalaropes, is separating out effort spent in the focal species' habitat (Johnston et al. 2015). An eBirder could diligently bird Lake Elizabeth in Fremont for a month and observe zero phalaropes, but that is not a good measure of how many phalaropes are present in Alameda County, because that is not suitable habitat. Filtering checklists based on location for only those that are from suitable phalarope habitat would be inexact, since most checklists include only a starting location, which does not describe the entirety of the area covered by the list. We employed two approaches to accounting for effort. First, we used the total eBird checklists submitted by observers who had at some point reported a phalarope, as a metric of overall birding effort across all habitats. We limited this to observers who had reported a phalarope at some point because many beginner or backyard birders may not be capable of identifying a phalarope or ever bird in waterbird habitats; we wanted to count only effort by observers who were known to potentially be able to identify and record a phalarope. Second, we used the number of observers and the number of minutes spent observing *for checklists that observed phalaropes only*. Limiting these measures to only phalarope-positive checklists ensured that they represented effort spent in suitable phalarope habitat. This is an imperfect measure, certainly—some zero-phalarope checklists might have covered phalarope habitat, and some phalarope-positive checklists might have spent much of their time in unsuitable habitat—but it allows at least an approximation of this effort.

As with most analyses of long-term data, the relationship of interest—that between phalarope abundance and year—is potentially confounded by the correlation of other variables with year. For example, the number of eBird checklists submitted in the threeSBSPRP counties by observers who have at some point reported a phalarope is positively correlated with year (correlation coefficient = 0.69, $P < 0.001$; Fig. 1). This is consistent with the known history of eBird: it is a relatively recently-introduced tool that has seen increasing uptake among

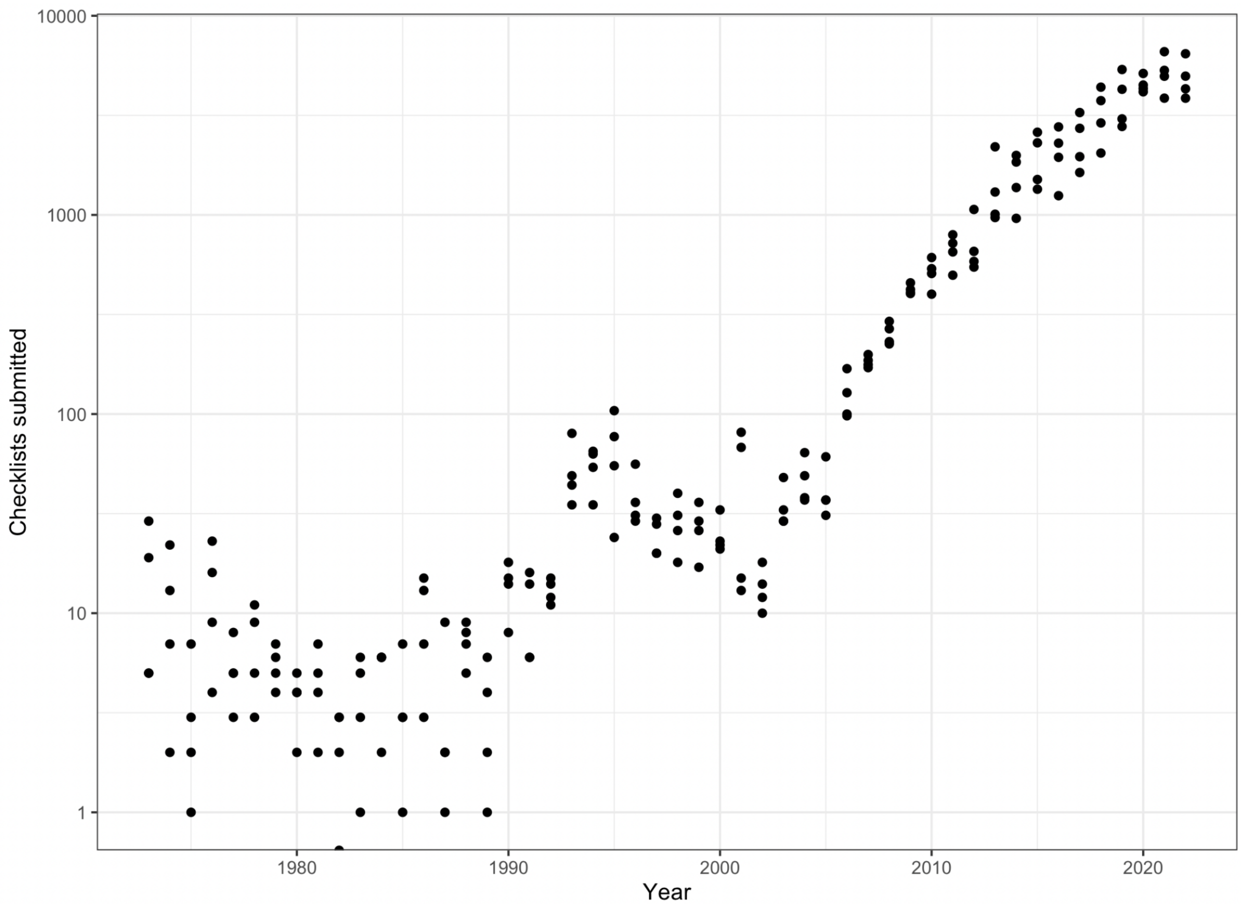

Figure 1. The number of checklists submitted in the SBSPRP counties by phalarope–identifying observers since 1973. Note the change in slope at 2002, the year of eBird's release.

community scientists over its lifespan (Sullivan et al. 2009). A clear change in slope in Figure 1 is evident at 2002, the year of eBird's release: checklists dated prior to 2002 are historical checklists, recorded in some other medium and then uploaded to eBird at any time since, and it is therefore unsurprising that there is not a strong correlation between the number of pre-2002 checklists and year. From 2002 on, the number of checklists grows exponentially over time.

To control for long-term trends in phalarope counts arising from long-term trends in birding activity, our statistical models included an offset of the log of the number of all eBird checklists submitted during that month in that area (including those that did not count any phalaropes) by observers who had ever submitted a list with phalaropes. An offset is a term included in a model of counts that describes the sampling effort. Including this term allows us to control for variation in total birding effort. Because all of our variables related to sampling effort were likely to be correlated with year, there was the potential for collinearity to impact our model results (York 2012). We tested for impacts of collinearity by calculating the variance inflation factor (VIF) for all models.

We modeled phalarope abundance in the given focal area (described below) with a generalized linear model of total phalaropes observed in one month, with fixed effects of: total number of observers from phalarope-sighting checklists that month, total observing minutes from phalarope-sighting checklists that month, year (as a continuous variable), month (as a continuous variable), and month (as a continuous variable) as a second order term to accommodate the expected quadratic shape of the relationship with month. Because we included an offset of a measure of birding activity, the model estimates a *rate* of observations: monthly counts per unit of effort (checklists). Hereafter we refer to this simply as "monthly counts" for brevity. We useda negative binomial distribution because this distribution is well-suited to overdispersed data such as phalarope counts (Burns & Van Schmidt 2023).

We additionally ran models comparing the SBSPRP counties to the rest of California, which were the same as the above-described models except with an additional term: the interaction between year and location, with location being a binary (SBSPRP *counties* vs. *non*-SBSPRP *counties*). We ran one of these models for the full timespan supported by the dataset (1973–2022) and a second one for only the most recent 20 years (2002–2022), to focus in on the timespan most relevant to the South Bay Salt Pond Restoration Project.

Finally, we ran a version of the model comparing the SBSPRP counties to the rest of California in 1973-2022 with year as a categorical variable, rather than continuous. This forces the model to calculate effect sizes for each year as an individual entity unrelated to other years, rather than calculating the effect size of year as a variable that can take on many different values. The advantage of this approach is that, unlike examining raw counts, it allows one to consider estimated phalarope counts with the effects of the several effort variables removed, and unlike the models with year as a continuous variable, without the concern that the counts are being impacted by the assumption of a linearity progression from year to year. The disadvantage of this approach, however, is that it is poorly suited to answering any question about multi-year trends: e.g., it can address questions like “Did the SBSPRP and outside-the-SBSPRP counts differ in 1996?” and “Were counts different in 1996 than in 1997?”, but cannot answer questions like “Are phalarope counts declining more quickly in the SBSPRP counties than outside of them?” We present it here as an additional lens through which to view the dataset.

Tests for statistical validity

We performed several tests on our models to ensure that assumptions of general linear models were not violated.

First, some early observations had exceptionally high counts of phalaropes that could have a large impact on the results. Outlying datapoints should only be omitted from analysis if they are irrelevant to the question being asked or indicative of an error in the data. (e.g., if the observer misidentified a different species as phalaropes). Detecting irrelevant datapoints becomes more difficult the greater the expected variance in the data is, as larger ranges of values become reasonable. The expected variance for phalarope counts is high: counts of zero phalaropes are plausible, as are counts of tens of thousands of phalaropes. One might expect a series of counts to go abruptly from very few to very many phalaropes and back down again as the birds’ large flocks move through the stopover area. Essentially, for this dataset the problem of detecting and excluding true outliers becomes both very difficult and high-stakes. Because very high historic counts corresponded with scientific studies described above and were therefore plausible, we did not exclude any datapoints for being “too high” from our main analyses. However, we did perform a secondary analysis in which we omitted the highest-count checklist for each of those months and reran all models to examine how robust our results were to the assumption that these counts were accurate.

Second, correlated variables can lead to collinearity in a model, whereby if correlations are high between specific independent variables it becomes difficult to attribute variation in the dependent variable (phalarope counts) . Problematic collinearity is generally defined as $R^2 \geq 0.6$ or variance inflation factor (VIF) ≥10 (Dorman et al. 2013; although see O’Brien 2007 and York 2012 for discussion of why such thresholds may be overly conservative). At all spatial and temporal scales examined, we found positive correlations between year and the two fixed effects representing survey effort, but these were in acceptable range (R^2 = 0.45-0.59). For all of our statistical models, we found VIF values <10 (except for variables in interaction terms or higher-order terms, which are expected to have high VIF and therefore not problematic; Francoeur 2013). Therefore, we retained all independent variables in our models.

eBird Results

The three SBSPRP counties

When corrected for effort, a decline is evident even by visually inspecting the raw phalarope counts (Fig 2). The model of the three SBSPRP counties detected significant relationships (all $P < 0.001$) of phalarope count with year and month (both the linear and quadratic term). Phalarope counts were negatively related to year (Fig 3).

As expected for migratory habitat use, phalarope counts showed a pattern of increasing from June to July, remaining at a high level through August, and then declining slightly in September (Fig. 4). This pattern held true for all other extents assessed as well (data not shown for brevity).

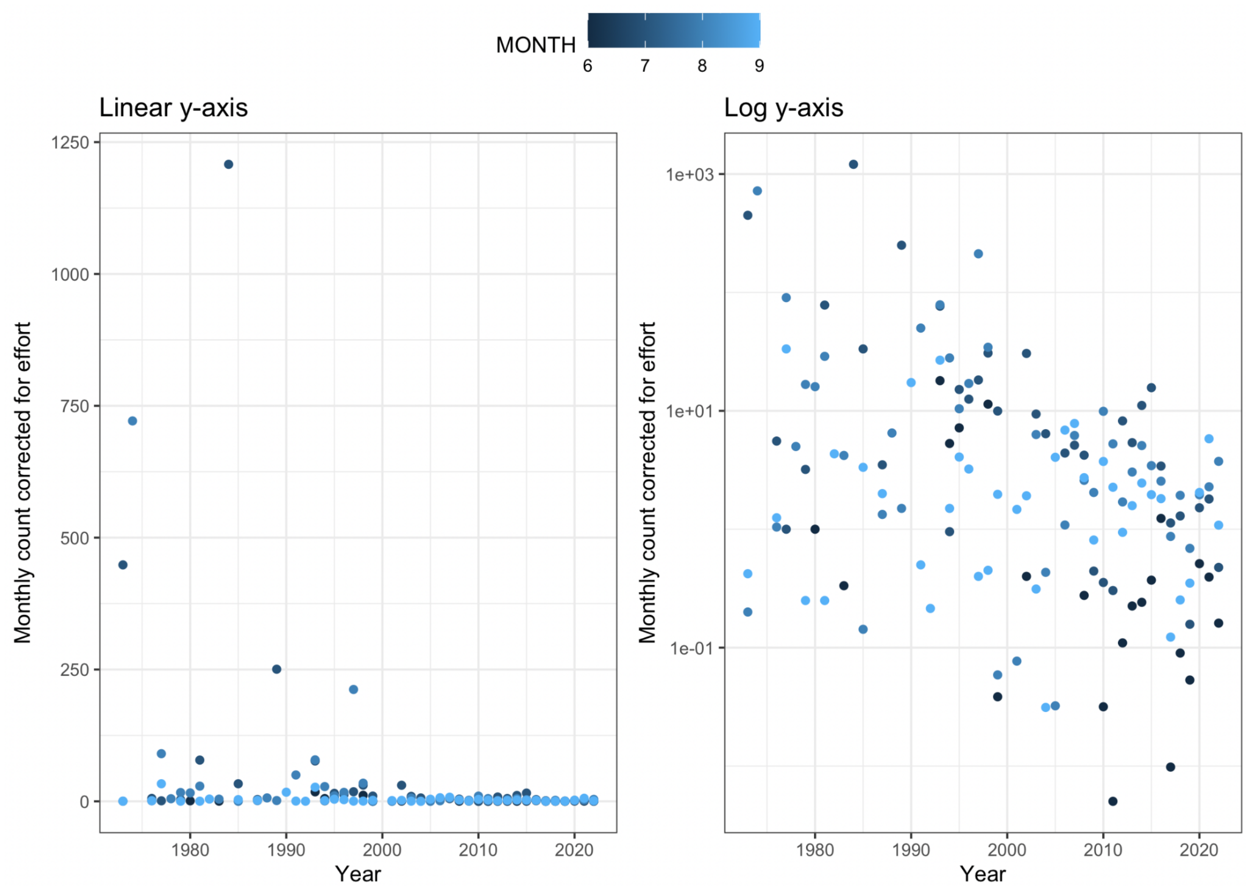

Figure 2. Total monthly phalarope count divided by all eBird checklists submitted by known phalarope-identification-capable observers, with month of the year indicated by color. A linear y-axis (left) makes it difficult to see most differences; on the logarithmic y-axis (right), an overall decline is apparent.

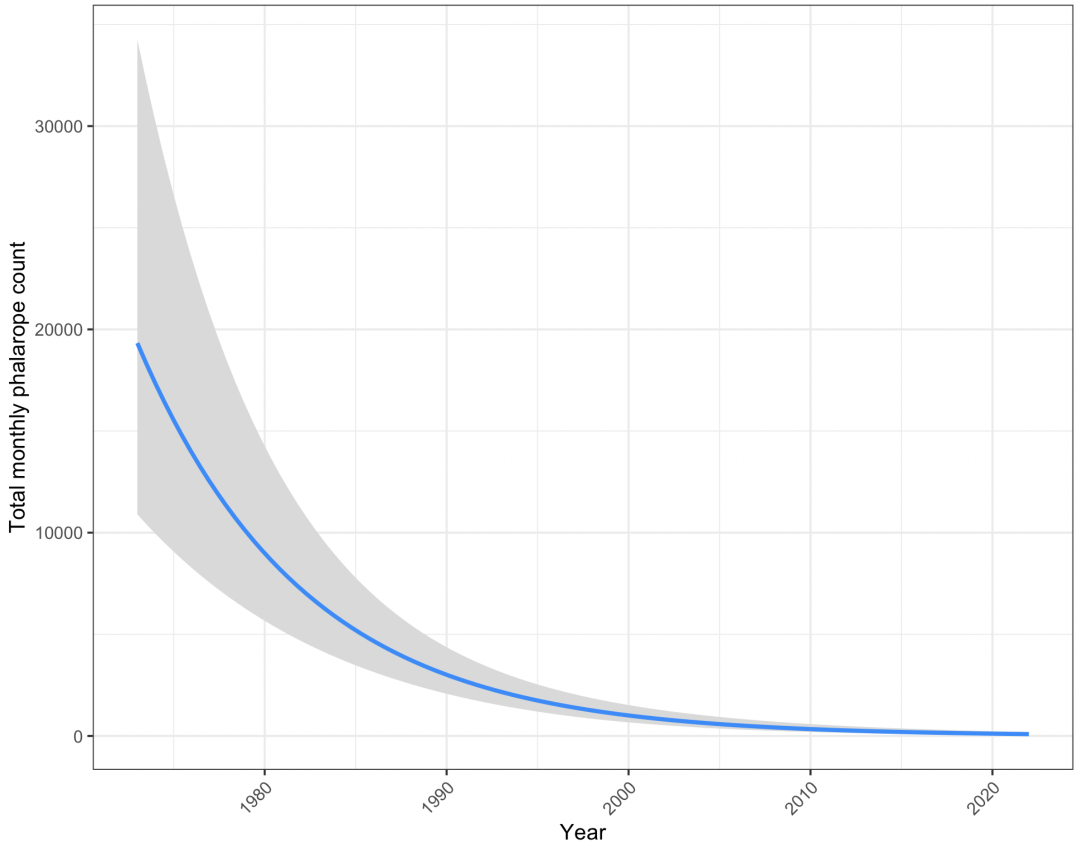

Figure 3. The modeled trend of total monthly phalarope count in the three SBSPRP counties in August from 1973-2022. The gray shaded area is the 95% confidence interval.

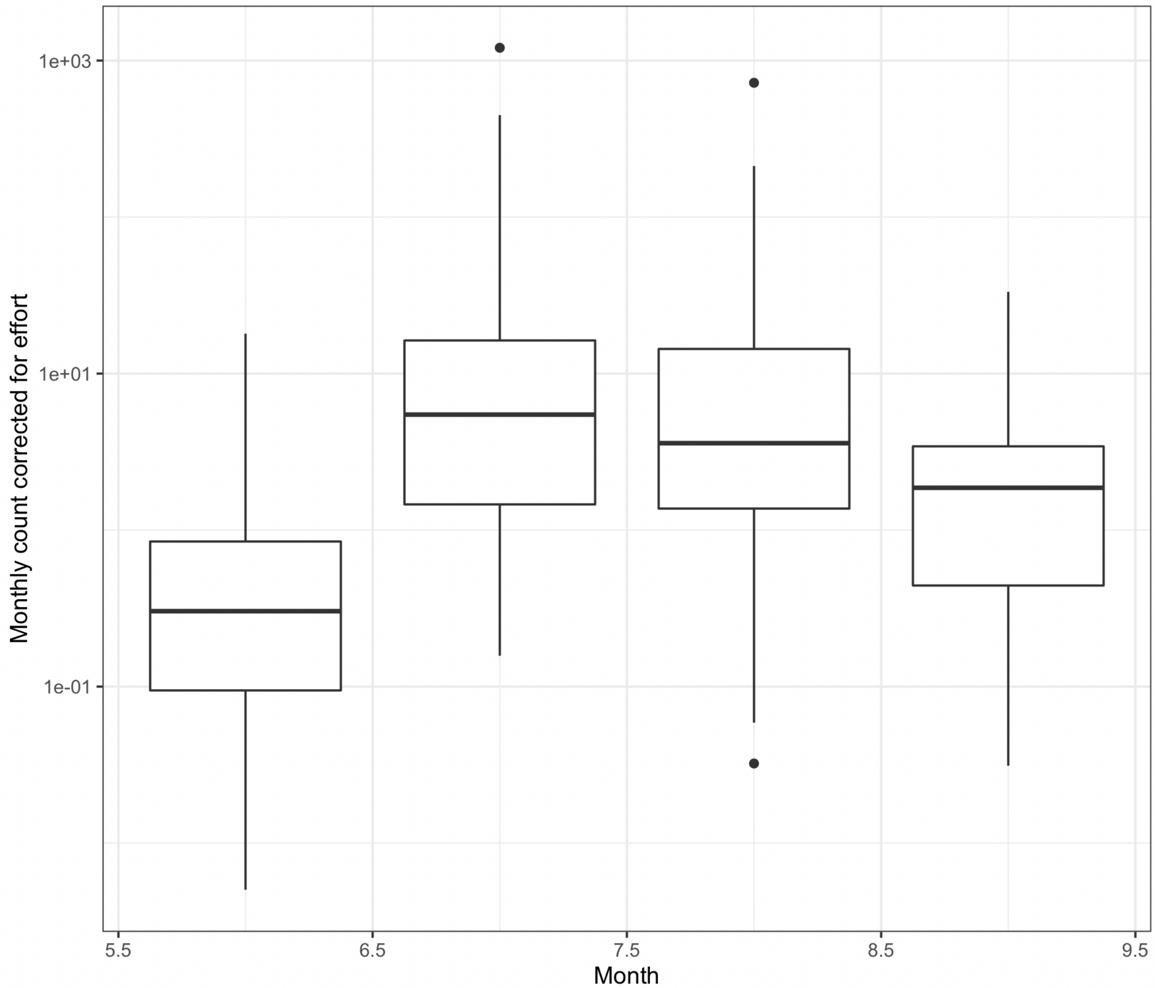

Figure 4. The modeled relationship between total monthly phalarope count in the three SBSPRP counties in each month of June-September. Boxes depict the median and 25th and 75th percentiles; "whiskers" extend from the box to the most extreme value no more than 1.5 times the interquartile range; values further than 1.5 times the interquartile range are shown as individual dots. Month is shown as a numerical value: 6=June, 7=July, 8=August, 9=September.

The nine Bay Area counties

Phalarope counts in the nine Bay Area counties were also negatively related to year, indicating a decline ($P < 0.001$; Fig 5). The model of the nine Bay Area counties detected significant relationships between phalarope count and year, month (both the linear and quadratic term), and total observing minutes.

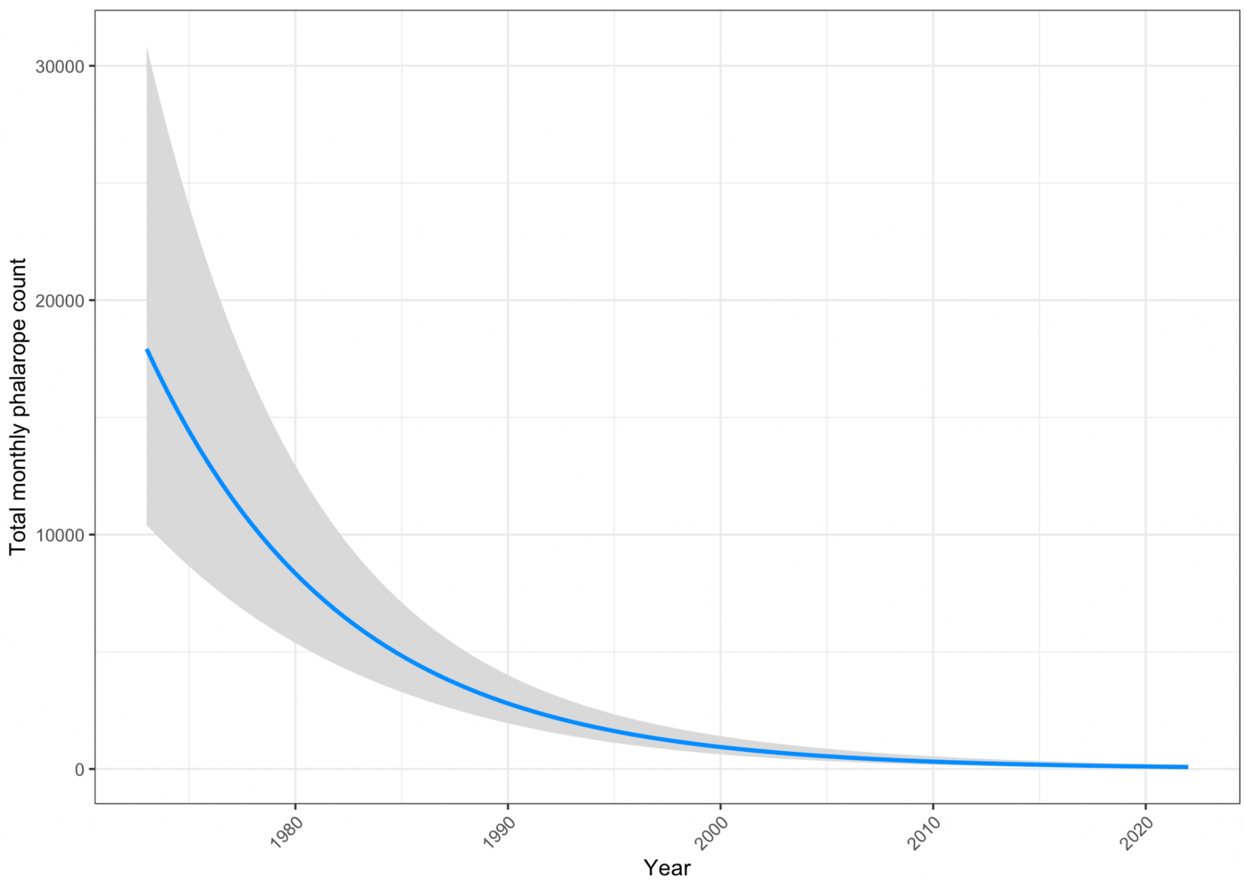

Figure 5. The modeled trend of total monthly phalarope count in the Bay Area in August from 1973-2022. The gray shaded area is the 95% confidence interval.

California excluding the three SBSPRP counties

The model of California excluding the three SBSPRP counties detected significant relationships (all $P < 0.001$) of phalarope count with year and month (both the linear and quadratic term). Phalarope counts were negatively related to year (Fig 6).

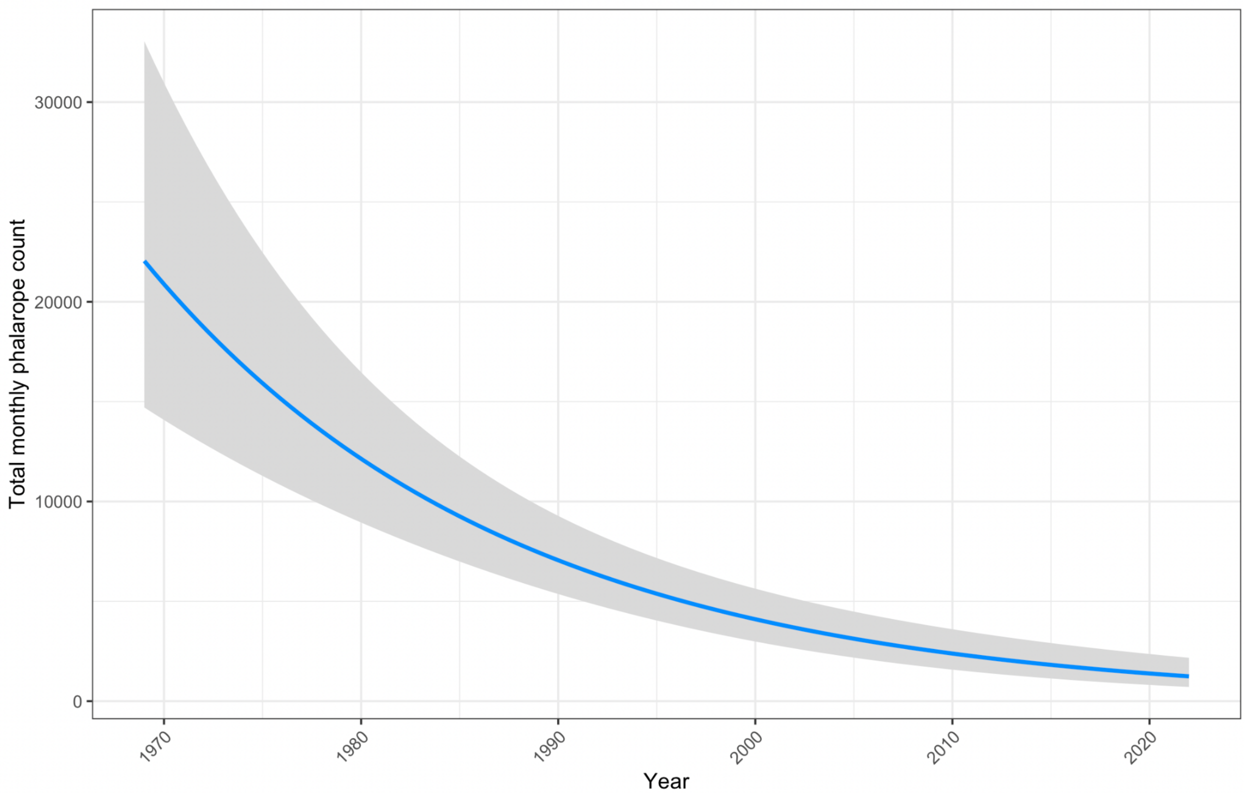

Figure 6. The modeled trend of total monthly phalarope count in California excluding the three SBSPRP counties in August from 1969-2022. The gray shaded area is the 95% confidence interval.

The state of California

The model of California detected significant relationships (all $P < 0.001$) of phalarope count with year and month (both the linear and quadratic term). Phalarope counts were negatively related to year, as in the previous models (Fig 7).

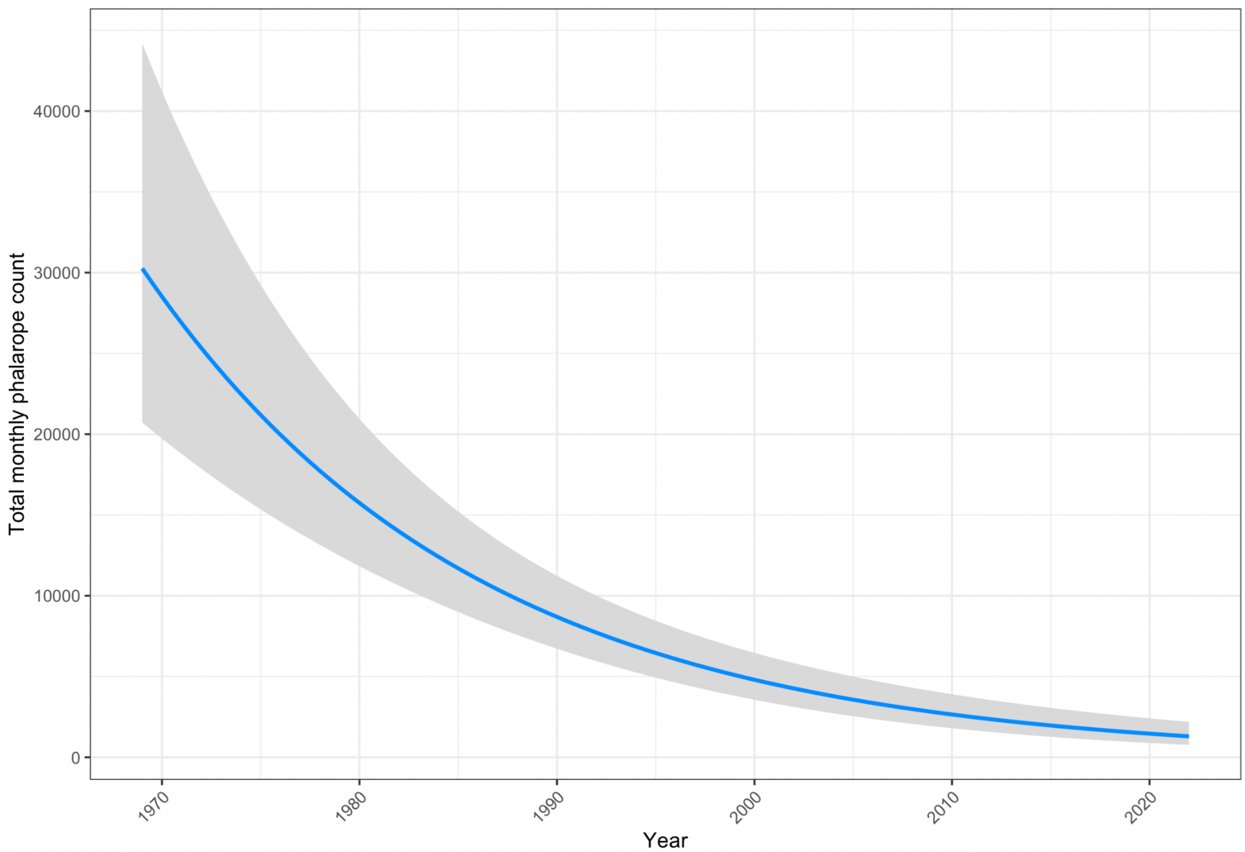

Figure 7. The modeled trend of total monthly phalarope count in California in August from 1969-2022. The gray shaded area is the 95% confidence interval.

Comparing the SBSPRP *counties to the rest of California*

The visualized raw counts from the SBSPRP counties and the rest of California show that the highest counts come from theSBSPRP counties prior to 2000, and that counts across both regions appear to have declined over time (Fig. 8).

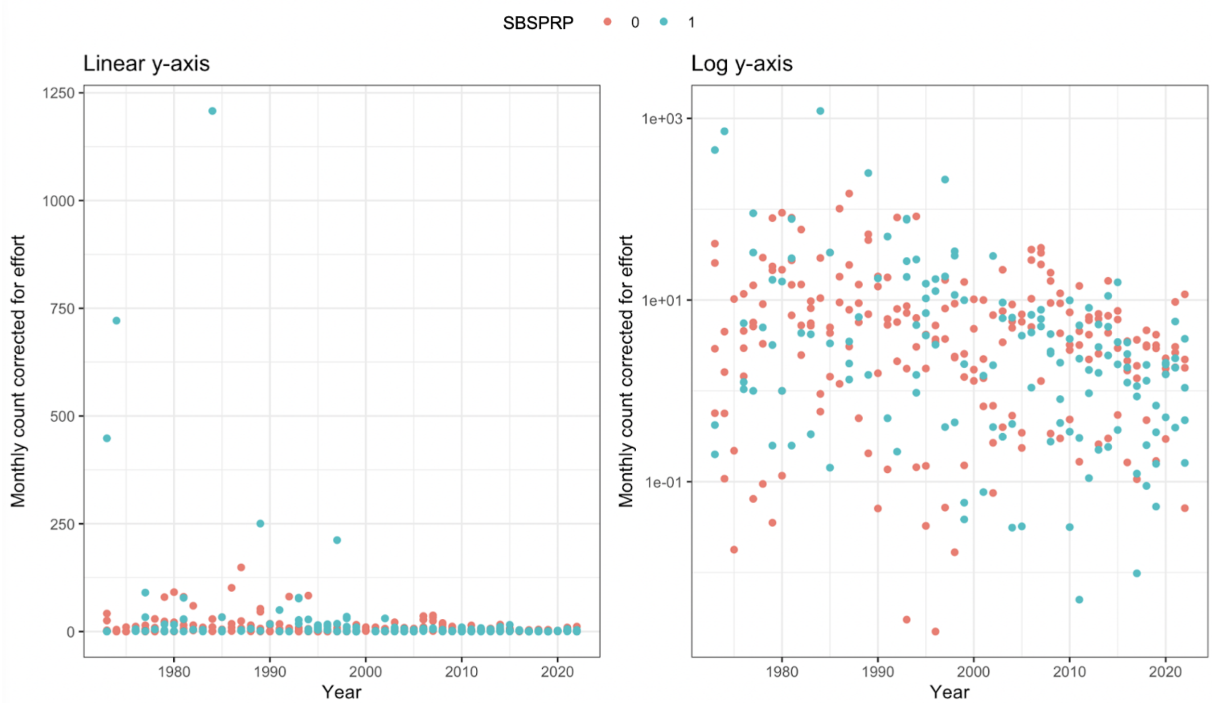

Figure 8. Total June-September phalarope counts divided by all eBird checklists submitted by known phalarope-identification-capable observers. The SBSPRP counties are shown in aqua, and the rest of California is shown in pink.

The model comparing trends in the three SBSPRP counties to the rest of California reported a significant relationship with month (both the linear and quadratic term), and significant interaction between year and location ($P < 0.001$). The SBSPRP counties showed a more severe decrease in phalarope counts than did the rest of California (Fig. 9). eBird counts in the rest of California are lower than peak counts compared to scientific surveys, which had 56,320 Wilson's phalaropes historically (Jehl 1988) and up to 45,143 to as recently as 2021 (Carle et al. 2023), likely because scientific surveys at Mono Lake also survey areas far from shore by boat. The key comparison between areas is not the absolute numbers but the change in numbers of time.

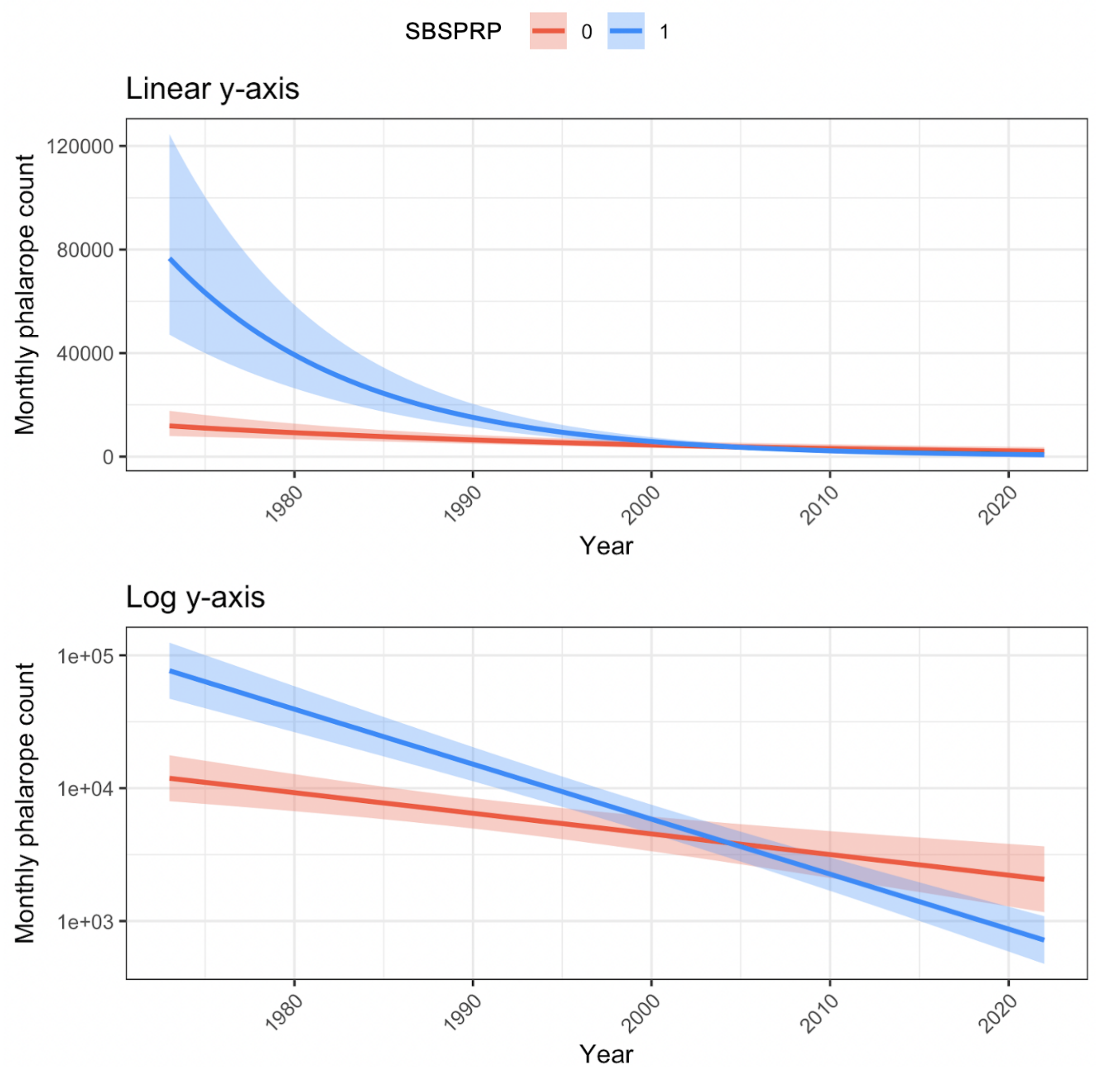

Figure 9. The modeled relationship between total monthly phalarope count in August and year, with the three SBSPRP counties (Alameda, Santa Clara, San Mateo) shown in blue and the rest of California shown in red.

The model of those data restricted to only the most recent 20 years (2002-2022) found significant relationships with year and month (both the linear and quadratic term), but no effect of location or the year-by-location interaction (Fig. 10).

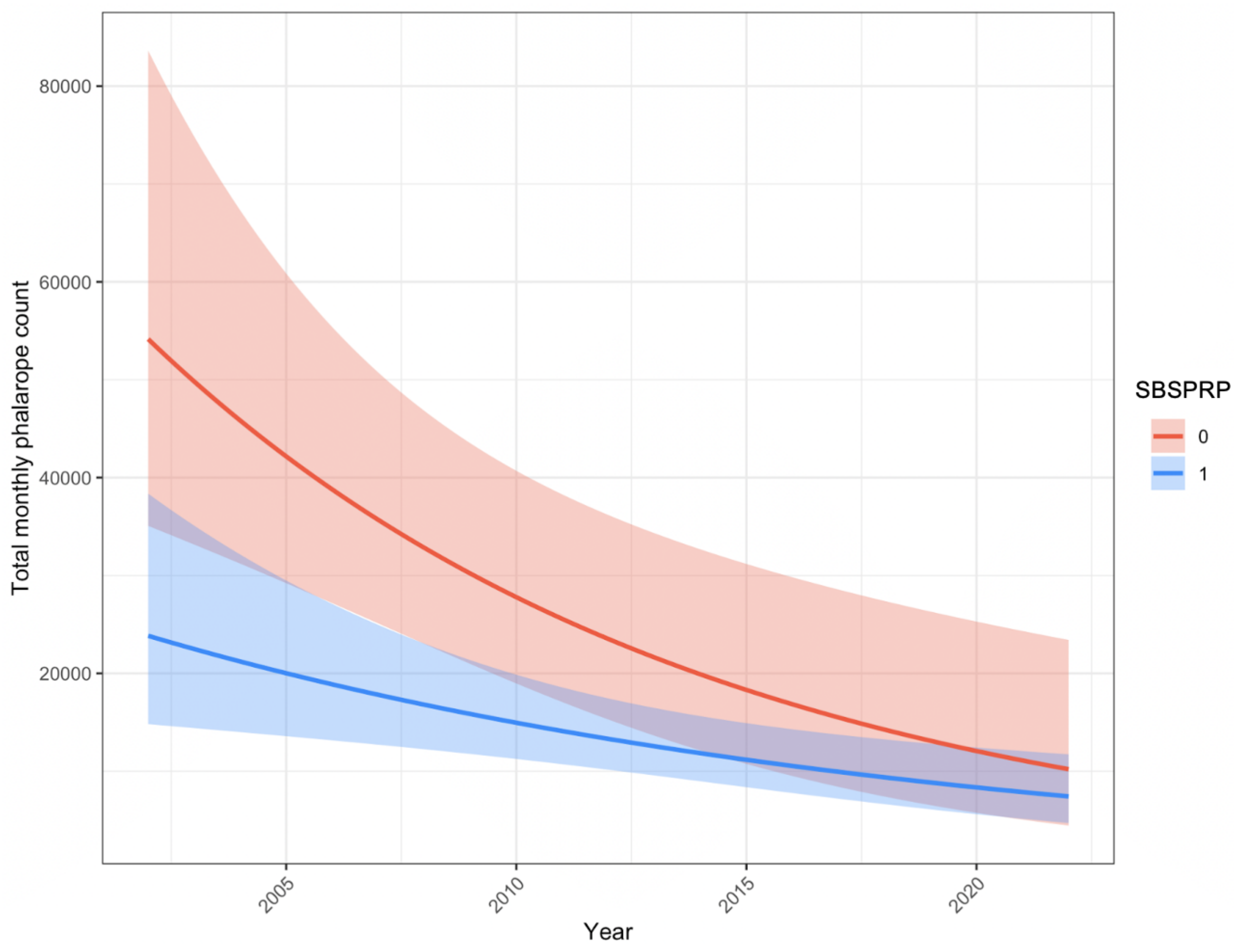

Figure 10. The modeled relationship between total monthly phalarope count in August and year, with the three SBSPRP counties (Alameda, Santa Clara, San Mateo) shown in blue and the rest of California shown in red, for only the years 2002-2022. Lines show predicted means, shading shows 95% confidence intervals.

To examine the effects of the assumption of a log-linear trend on the model, we reran the model of 1973-2022 with the variable of *year* as a factor rather than a continuous variable. This forces the model to calculate separate effects for each year. Like the previous models, this model reported a significant relationship with month as both a linear and quadratic term. Visualizing the results of this model (Fig. 11) reveals support for the overall trends observed in the model of year as a continuous variable: phalarope counts within the SBSPRP counties show the highest values in the 1970s-1980s, and as time goes on, counts in the SBSPRP counties become more similar to those outside the SBSPRP counties. This model also shows considerable year-to-year variability in phalarope counts, especially in the SBSPRP counties; this variability appears to decline over time.

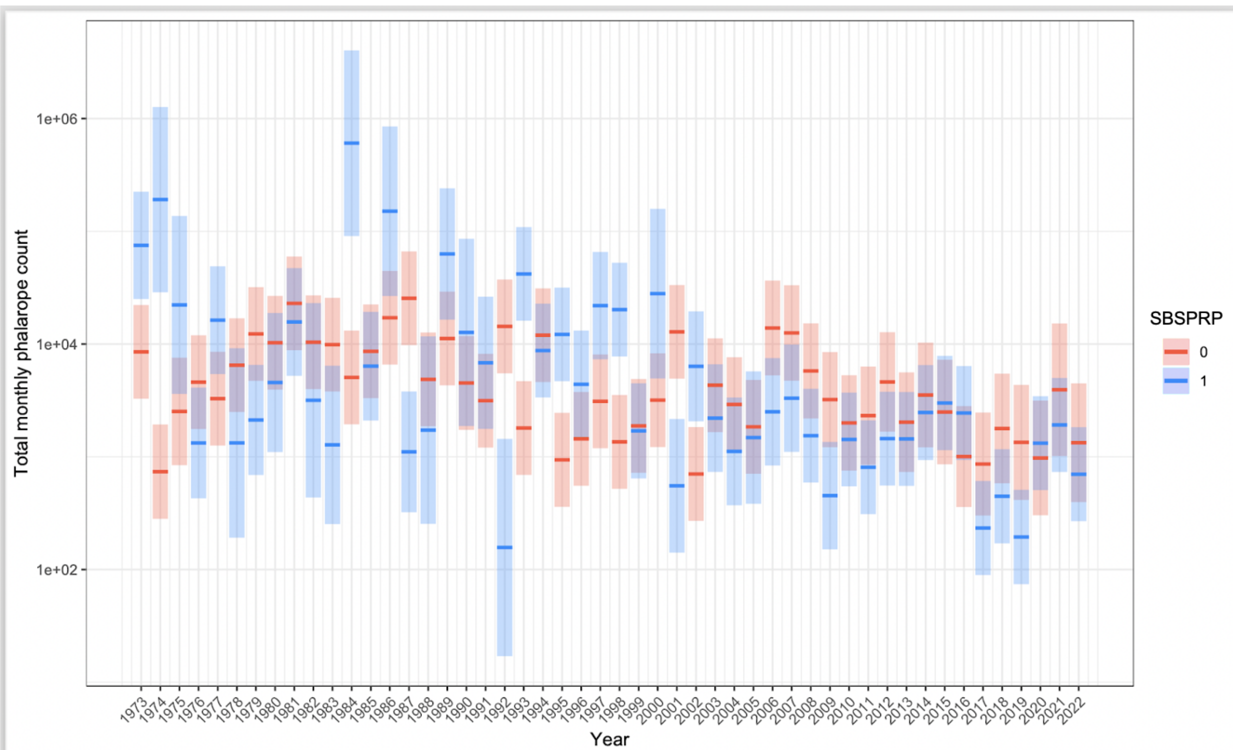

Figure 11. The modeled total monthly phalarope count in June-September for each year from 1973-2022, with the three SBSPRP counties (Alameda, Santa Clara, San Mateo) shown in blue and the rest of California shown in red. Note that the y-axis is on a logarithmic scale. Lines show predicted mean, bars show 95% confidence intervals.

Effects of omitting potential outliers

From the graphs of monthly counts (Fig. 2, Fig. 8) we identified three months whose counts appeared especially high in the SBSPRP counties: July 1973, August 1974, and July 1984. Examination of the checklists contributing to these counts revealed no obvious cause for concern, but the location of these high counts early in our focal timespan meant that they could potentially have a large impact on our model results. To test the robustness of our results, we reran analyses with the highest checklist from each of the concerning months omitted. The omitted counts were: July 1973, 10,000 phalaropes; August 1974, 15,000 phalaropes; July 1984, 3900 phalaropes.

Omitting those checklists did not qualitatively change our results. No variables in the models changed significance or the direction of their estimated effect. Unsurprisingly, the estimated counts for the earliest years were reduced by the omission of these high counts (Fig.12).

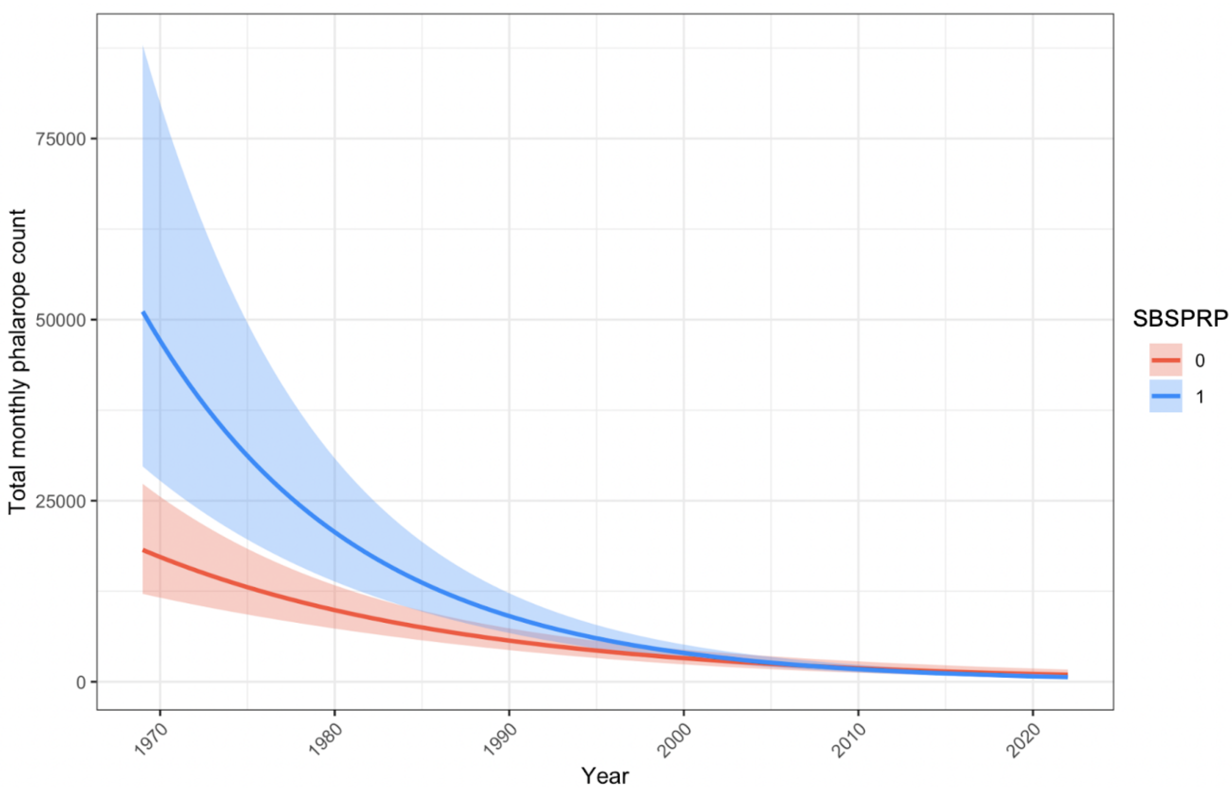

Figure 12. The same model results shown in Figure 9, but from a dataset with the three highest month counts reduced by the omission of their highest-count checklist. The modeled relationship between total monthly phalarope count in August and year, with the three SBSPRP counties (Alameda, Santa Clara, San Mateo) shown in blue and the rest of California shown in red. Lines show predicted means, shading shows 95% confidence intervals.

DISCUSSION

Trends in phalarope abundance during migration

Systematic historic surveys concluded that phalarope populations in the western United States declined by half from the 1980s to the 1990s (Jehl 19999) and have continued to decline at a lesser rate in recent years (Carle et al. 2023). Our eBird data broadly agrees with this trend (Fig. 9). At all spatial scales we investigated, from the three SBSPRP counties to the entire state, we found evidence that phalarope observations during fall migration have been declining since the 1970s. While analysis of community science datasets is always complex (Horns et al. 2018, Grade et al. 2022), the evidence for an overall declining trend is substantial. It is important to note that the numbers between the eBird and scientific survey datasets are not comparable. eBird data represent monthly counts per checklist (i.e. average counts) and the scientific surveys represent peak counts. Further, eBird surveys are opportunistic whereas the phalarope surveys specifically aim to maximize phalarope counts and utilize different methods. For example, scientific surveys at Mono Lake include boat surveys due to the lake's large size, opening up areas that eBird data are unlikely to cover. Estimated population size in the 1980s, based on counts per checklist, was roughly 20,000 individuals or fewer, but scientific surveys over this period had peak counts of up to 40,000–70,000 phalaropes on Mono Lake (Jehl 1999). The key comparison is relative decline within each dataset, and both eBird and scientific surveys show steeper declines in the SBSPRP counties than elsewhere.

The comparison of fall migration phalarope count trends over time in the SBSPRP counties to trends outside the SBSPRP counties strongly supports a difference between the two regions, with phalarope counts declining more steeply in the SBSPRP counties than elsewhere in both coordinated surveys and community science datasets. Scientific surveys found 1986 populations in South San Francisco Bay nearly rivaled Mono Lake in size, with a peak count of 40,000, indicating the area may have supported up to 80,000 Wilson's phalaropes over the course of migration–a third of California's migratory population at the time. In 2022 South San Francisco Bay had a peak count of 735 Wilson's phalaropes, a 98% decline from the peak historic count of 40,000 that greatly outpaced the 59% rangewide decline.

However, the eBird trends differ most in the earliest years of our analysis (the 1970s–80s), prior to the start of the SBSPRP (Fig. 9, top panel). In the model restricted to the years 2002–2022, the difference between the SBSPRP counties and the rest of the state was relatively small and decreased over time (Fig. 10). Some of these trends may be attributable to the log-linear model we fit the data, which assumes a constant rate of change over the survey period at the log scale (Fig. 9, bottom panel). However, more flexible model formulations that fit year-specific annual population sizes still showed a trend towards less divergence between the populations and reduced declines since the 2000s (Fig. 11). This time period also corresponds with the launch of eBird in 2002, which could be a confounding factor as the higher variability in historic rates could be attributable to this difference. However, we feel this trend is likely reasonably accurate given that (1) the scientifically conducted surveys generally corroborated the eBird data where comparisons could be made, and (2) the log-linearity in rates of decline and reduced variability as populations approach zero are expected by population biology theory (Sibly & Hone 2002). Overall our results therefore suggest that while the two regions have followed different trajectories, since the beginning of the SBSPRP they appear to have converged on shallow declining trends. It is worth noting that the convergence corresponds with the beginning of the SBSPRP project, indicating management actions could have actually stabilized the preexisting decline.

This analysis was limited to the relatively coarse geographic resolution of eBird data, which did not allow us to separate out either Salt Ponds generally or individual Salt Ponds specifically. Recent Phalarope Migration Survey data shows that large numbers of phalaropes are counted in sites within the SBSPRP counties but not in the Project area itself, such as the Sunnyvale Water Pollution Control Plant (Burns et al. 2023). The degree to which such extra-Project sites contribute to the trends detected in our analysis is unknown. Of the 140 starting locations given for Santa Clara county checklists that observed phalaropes, nearly half (47%) were insufficiently detailed to classify as *Salt Pond* or *not Salt Pond*, even if one could assume that the observers did not travel far from that starting location (a problematic assumption). Additionally, eBird data is by nature "noisy" and best-suited to detecting large-scale trends (Horns et al. 2018). Systematic survey data with fine-scale location information, such as that generated by the Phalarope Migration Survey, will be better able to detect differences in phalarope count trajectories in the Salt Ponds, once sufficient years of data are available.

Drivers of the decline

At the coarse scale of eBird data, with its inherently high level of uncertainty, we find no definitive evidence that restoration actions have caused a divergence in the trajectories of phalarope counts in the SBSPRP counties compared to elsewhere in California. However, it is important to note that our comparison models cannot rule out a difference in phalarope population trends between the Salt Ponds and other areas, nor can it rule out an effect of restoration actions on phalaropes. There are four reasonable interpretations of the observed trends, which are not mutually exclusive and could be acting synergistically.

The first possibility is that phalaropes are not declining, but are simply experiencing cyclical population changes. Cyclical changes are expected for bird populations, but long-term declines can still be detected by comparing nadir-to-nadir trends (i.e., are the lows getting lower; Coates et al. 2021). In the historic period, Wilson's phalaropes at Mono Lake showed cyclical patterns, but also a long-term decline. Jehl (1999) compiled a 15-year dataset with three peaks and two nadirs, which shows a nadir of ~35,000 phalaropes in 1984 to a nadir of ~5,000 phalaropes in 1993. Contemporary surveys of Mono Lake from 2019–2022 have also found nadir counts of <10,000 phalaropes (Carle et al. 2023). Data in the SBSPRP counties (Fig. 11) likewise show patterns of cyclical population dynamics (e.g., nadirs in 1996, 1999, 2004, 2009, and 2017), with generally lower nadirs over time. Even after accounting for this variability, however, our models showed a clear long-term decline (Fig. 9). The hypothesis that trends *only* reflect cyclical changes is unsupported, though and strongly unsupported within the Bay Area.

The second possibility is that the decline in migratory populations in South San Francisco Bay and the rest of the west could be jointly driven by climate conditions, or conditions on shared breeding or wintering grounds. Data from BBS on abundance in phalaropes' breeding grounds also indicated a general decline, but could not determine whether availability of habitat in the breeding range was the causative factor (Jehl 1999). However, until high-quality annual population data becomes widely available it may be difficult to determine the relative influence of annual climate on observed declines. Red-necked phalarope populations stopping over at the Bay of Fundy declined by over 99% in the 1980's from total counts of 2-3 million birds to peak counts of 20 in 1989 (Nisbet & Veit 2015). The leading explanation for this decline is food web disruption caused by the major El Niño event in 1982-83 and continued by the less extreme one in 1986-87. The limited information available from the breeding grounds for red-necked phalaropes show that some populations rebounded from this decline within a few years. However the counts at Bay of Fundy have never recovered to pre-crash levels (Hunnewell et al. 2016) and no new major stopover sites have been identified (Nisbet & Veit 2015), suggesting that there is much that is still not understood about the dynamics between breeding ground, migration stopover, and overall populations. Scientific surveys (Carle et al. 2022) and eBird data (Fig. 11) also suggest high variability in population size in the western United States, which could be related to annual variability in weather. El Niño has been implicated in driving dramatic shifts in abundance of Eared Grebes at Mono Lake due to loss of winter food supplies, but these quickly recovered (Jehl et al. 2002). Major El Niño years during the period of decline (1982-1983, 1987-1988, 1991-1992) do align with declines in SBSPRP counties (Fig 11), though 1997-1998 saw an increase in phalaropes. However, the following years see rapid recovery as in Jehl et al. (2002), and the SBSPRP and non-SBSPRP counties do not show synchrony in trends across years as would be expected if the population variability was climate-driven. Given the substantial variability and uncertainty in historic eBird data, it would be premature to draw firm conclusions from these trends. However, ongoing coordinated annual survey efforts (i.e. the Phalarope Migratory Surveys and the International Phalarope Working Group surveys) are very likely to be able to identify the role of annual weather once enough years of data have been collected.

A third possibility is that the decline is largely driven by migratory habitat degradation *outside* of South San Francisco Bay (areas that historically contained 95% of the migratory population), which has caused spillover effects on populations in the bay. A significant threat to phalaropes and potential contributor to their population decline is the loss of the saline lake habitats that they rely on during migration (Carle et al. 2022). All of the major saline lakes in western North America are facing the combined threat of climate change and water diversion for agriculture and other human uses (Null & Wurtsbaugh 2020). Despite increased awareness and efforts to preserve habitats (e.g., Herbst & Prather 2014), Lake Abert, one of the major stopover sites for phalaropes, virtually dried up during the summer of 2021 (Carle et al. 2022). Great Salt Lake hosts the majority of observed phalaropes during coordinated regional surveys (Carle et al. 2023) and is under substantial threat (Null & Wurtsbaugh 2020). Even if a lake does not dry up completely, a reduction in water volume may render it too salty to support the invertebrates that phalaropes and other waterbirds rely on (Senner et al. 2018). Juvenile phalaropes are less likely to forage in hypersaline environments, potentially due to a lower ability to handle an osmotic stress (Jehl 1988), which could also impact the population. Because there is a clear mechanism driving this decline, we find this theory more plausible. However, this hypothesis does not explain why South San Francisco Bay populations have experienced a *more* severe historical decline than saline lake populations.

The fourth possibility is that declines are being driven by degradation of migratory habitats within *both* South San Francisco Bay and saline lakes. If this is the case, rangewide recovery would require rangewide management changes. It is unlikely that habitat management actions taken by the Project are the primary driver of phalarope declines, given that the most severe declines predate the SBSPRP. The steep declines in counts in the 1980s-2000s are likely the result of the suite of factors that caused a decline in habitat quality in South San Francisco Bay during that time period. The ongoing, but shallower, declines observed since the start of the SBSPRP lend plausibility to two opposing possibilities. Because declines have continued, it cannot be ruled out that the conversion of high-salinity salt evaporation ponds to a diversity of ponds supporting different salinities may have negatively impacted phalarope populations. However, because the decline is less severe after the Project's inception, it is also plausible that the transition of the ponds from being managed for salt production to being managed for wildlife mitigated the preexisting decline. Additional studies modeling habitat use and changes in abundance at the site-level could shed light on these questions and guide future management. While it is perhaps disappointing to not have a definitive answer yet, the analyses in this report lay the foundation for such efforts.

CONCLUSIONS

The exceptionally severe decline in phalarope populations within San Francisco Bay–losses exceeding 95% since the 1980s–strongly suggests the need for monitoring and management interventions, regardless of the causative factors. There appears to have been a major collapse of a migratory stopover point that at one point rivaled Mono Lake in importance. All available data show that phalarope populations have declined across their migration range over the last few decades. Survey results from 2021 suggest that phalaropes may have enough flexibility to choose new migration stopover sites when habitat conditions are unfavorable (Carle et al. 2022). When Lake Abert dried up and Great Salt Lake hit historically low levels, Mono Lake saw a substantial increase in the number of Wilson's phalaropes compared to the two previous years. If plasticity in stopover site choice exists and saline lakes continue to decline, then quality phalarope habitat in South San Francisco Bay could be a refuge for migrating birds. While the fact that other populations are concurrently declining provides evidence that the decline is not driven by past management actions by the SBSPRP, the dramatic decline of this species across the west highlights the importance of conserving and improving remaining habitats for phalaropes in the San Francisco Bay.

Studying the population dynamics of migratory birds is challenging in many ways and phalaropes are no exception. Survey and eBird data from the 1970s-80s provide evidence for a much larger phalarope population that dropped precipitously and was already at relatively low levels in the early 2000s, when the Restoration Project began. However, there is little data available to understand what was happening in the 2005–2018 period that would be most informative for understanding the observed decline in phalarope counts in Salt Pond Survey data. Data from eBird suggest a shallower ongoing decline since the 2000s, but the magnitude of that trend is sufficiently small that the limitations to eBird data become concerning: the variability in survey effort inherent to eBird data mean that eBird data is poorly suited to detect trends of less-than-massive scale for a highly mobile flocking species on its migratory stopover site—phalaropes in the Bay. We can conclude that phalaropes are not experiencing order-of-magnitude-level declines in the three SBSPRP counties, but we cannot distinguish with confidence between, e.g., a decline of 10% per year or 50% per year, either of which would be of pressing conservation concern. Population trends within the SBSPRP counties follow the same direction as those outside—a decline—but we do not have the resolution, for 2000-2019, to detect less-than-extreme differences in the magnitude of that decline.

Fortunately, the availability of fine-resolution data on phalarope numbers is rapidly improving, thanks to the implementation of International Phalarope Working Group surveys in 2019 and SFBBO's improved Phalarope Migration Survey protocol, which includes expansion of the surveys to several non-Project sites, in 2020. These studies have shown there is a substantial degree of variability in the year-to-year survey counts (Carle et al. 2022) and we need more years of study to understand if the populations are continuing to decline or currently holding steady at these low numbers. The gaps documented by our review show the necessity of continuing the Phalarope Migration Surveys for further years, and should provide assurance that they are not replicating information that is already available, but instead generating sorely-needed data to fill an important gap in our understanding of phalarope declines. In the near future we will then be able to compare counts within the Project sites to those at sites in the immediate area of South San Francisco Bay but not subject to restoration actions, and to phalarope trends across their other major Western migratory stopover sites.

Lastly, in order to develop management strategies to recover these populations it is necessary to conduct more complex analyses that use these new datasets to understand not just the spatial pattern of the decline but also the *drivers* of this decline, as well as habitat use trends. Analysis of the first years of Phalarope Migration Survey data have shown counterintuitive results suggesting phalaropes may not be using high-salinity ponds to the degree their natural history would lead us to expect (Burns et al. 2022). More information is needed to understand the drivers of phalarope habitat selection and survivorship during migration. With sufficient additional data, analyses could test for significant relationships between declines and management actions, natural changes in habitats, and weather. These in turn could inform habitat management strategies to help stop declines and recover phalarope populations.

ACKNOWLEDGEMENTS

Thank you to the California Wildlife Foundation, the U.S. Fish & Wildlife Service, the California State Coastal Conservancy, and the Santa Clara Valley Water District (Valley Water) for coordinating and funding this work. We would like to thank Rachel Tertes at the Refuge for help with coordinating site access. We would like to acknowledge the South Bay Salt Pond Restoration's Pond Management Working Group that has recommended and implemented many management changes over the years as they relate to specific pond systems. Thank you to Dave Halsing of the South Bay Salt Pond Restoration Project and John Krause with the CDFW Eden Landing Ecological Reserve. We could not have done this work without our dedicated field crews that worked on these surveys over the years.

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