Research Article

Trends in Tricolored Blackbird Colony Size: 2008 Through 2017

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ABSTRACT Tricolored blackbird (*Agelaius tricolor*) is a colonial breeder, largely restricted to grasslands, wetlands, and agricultural areas of California, USA. Tricolored blackbird abundance declined considerably during the twentieth century. Recent trends have been less clear, however, hindering efforts to evaluate the conservation needs of the species. We assessed trends in tricolored blackbird colony size using 2008, 2011, 2014, and 2017 Triennial Tricolored Blackbird Statewide Survey, a community-science effort involving hundreds of volunteer observers. After accounting for variation in observer characteristics and survey effort, we found a clear, statistically significant decrease in average colony size of approximately 5% per year, which translated to a decrease in average colony size of approximately 40% between 2008 and 2017. This decrease in colony size matches the overall decline in abundance reported in another recent study and reinforces the conclusion that tricolored blackbird is in need of protection and recovery efforts.

KEY WORDS *Agelaius tricolor*, California, colony size, population trend, Triennial Tricolored Blackbird Statewide Survey.

Tricolored blackbird (*Agelaius tricolor*) is a colonial nesting species, restricted to wetland, grassland, and agricultural areas, and a near endemic of California, USA (Beedy et al. 2018). As a colonial nester, tricolored blackbird is particularly vulnerable to population declines and extinction because relatively few large colonies comprise a significant proportion of the total population (Cook and Toft 2005). The global abundance of tricolored blackbird declined considerably over the twentieth century, with counts declining by 89% (Beedy et al. 1991) and average colony size declining by 63% (Graves et al. 2013) from the 1930s through the 1970s. Historically, tricolored blackbird nested in the large wetland complexes of cattails (*Typha* spp.) and bulrushes (*Schoenoplectus* spp.) that occurred throughout California's Central Valley (Cook and Toft 2005, Graves et al. 2013, Meese 2014). However, an estimated 95% of wetlands were lost between the 1930s and 1980s (Frayer et al. 1989). Habitat loss and declines in insect prey availability, both consequences of agricultural intensification (Habel and Schmitt 2018), are likely causes of population declines (Beedy et al. 2018).

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The restricted geographic range, colonial nesting habit, long-term population decline, and reliance on shrinking breeding habitats make the tricolored blackbird a species of conservation concern. The species was recently assigned Threatened status under the California Endangered Species Act and is currently being considered for listing under the United States Endangered Species Act (Beedy et al. 2018). Status reviews have sought to evaluate whether declines in abundance or colony size have leveled off in recent decades. Graves et al. (2013) reported that trends in the average colony size between 1980 and 2009 were not statistically significant, possibly because of the heterogeneous nature of the data assembled for analysis. They pointed to the need for more years of standardized data collection before recent trends would become clear.

The Triennial Tricolored Blackbird Statewide Survey (i.e., Triennial Survey) was initiated during the 1980s to collect periodic data on breeding tricolored blackbirds. The Triennial Survey was designed as a community science (a more inclusive term for citizen science) survey that benefits from the engagement of trained volunteers. Since 1994, the survey has been the primary source of information on tricolored blackbird distribution during the breeding season (Meese 2017). Over the years, the nature of the survey has evolved, with participation increasing and protocols becoming more standardized. Surveys since 2008 are characterized by hundreds of volunteers counting hundreds of thousands of breeding tricolored blackbirds at hundreds of colony sites using a consistent protocol (Kelsey 2008, Meese 2017). Despite the increased effort, standardization, and quality of the survey, inference about the population status of tricolored blackbird remains challenging. These challenges are similar to those encountered when working with data from other community science monitoring programs, such as the United States Geological Survey's North American Breeding Bird Survey (Sauer and Link 2011) and the National Audubon Society's Christmas Bird Count (Link et al. 2006, Soykan et al. 2016).

Challenges surrounding analysis of data from programs such as the Triennial Survey arise from several sources. First, volunteers, with varying expertise and effort within and among years, conduct the surveys. When expertise and effort vary randomly, noise is added to data, but when these factors vary systematically, they can bias analysis results (Sauer et al. 1994, Link and Sauer 1998). Second, tricolored blackbird breeding biology makes monitoring their populations a challenge. For example, the species breeds in colonies with upward of 20,000 individuals, which makes it difficult to estimate precise counts in the field, and produces skewed count distributions that make statistical analysis challenging. Also, colonies move to new locations frequently, with 60% of breeding colonies relocating the year after a given breeding season (Holyoak et al. 2014). Tricolored blackbird also has 2 breeding pulses, the first in early spring in the southern part of the species range, and a later pulse in the northern part, which necessitates a limited survey window to avoid double-counting of birds (Hamilton 1998). These factors challenge classical sampling designs and present analytical problems that can be remedied, in part, by careful consideration of survey effort, thoughtful data selection, and appropriate choice of statistical methods (Sauer and Link 2011, Hochachka et al. 2012).

Previous research has pointed to several practices that facilitate extracting robust trend estimates from community science data. An established way of dealing with the heterogeneity in observer expertise is to model counts with a statistical model that incorporates random effects for unique observers (Sauer et al. 1994, Sauer and Link 2011). Heterogeneity in observer effort can be accounted for directly by including effort metrics as explicit predictors of counts (Link and Sauer 1999, Soykan et al. 2016). Skewed count distributions can be dealt with effectively by including observation-level random effects (Harrison 2014, 2015).

We estimated trends in colony size derived from an analysis of count data collected at breeding colonies during 4 Triennial Tricolored Blackbird Statewide Surveys conducted between 2008 and 2017. The 2 goals of the study were to quantify patterns in survey effort and then to model the temporal trend in tricolored blackbird colony size over the study period using established statistical approaches designed to account for variation in survey effort.

STUDY AREA

Data used for this study came from Triennial Surveys conducted in 44 counties located in the Central Valley, surrounding foothills, and coastal and inland regions of southern and central California (Fig. 1; Kelsey 2008; Kyle and Kelsey 2011; Meese 2014, 2017). The elevation of colonies ranged from near sea level to approximately 1,700 m. The study area has a Mediterranean climate with warm, dry summers and cool, wet winters. The geographic extent of the survey area changed little between 2008 and 2017 (Fig. 1). For example, 38 counties were surveyed in 2008 and 44 counties were surveyed in 2017. Of the 6 counties that were surveyed in 2017 and not 2008, Orange, Glenn, and Tahoma counties fell within the 2008 extent, whereas only Humboldt and Modoc counties fell outside of that extent. Further, only 2 colonies were reported from Humboldt and Modoc counties during 2017 (Meese 2017), so the influence in this small change in extent was not likely to have a large effect on average colony size. The majority of birds occurred in colonies located in the San Joaquin and Sacramento Valleys, followed by the Central Sierra Foothills and Central Coast regions of the state (Fig. 1). Colonies were generally located in open seminatural and agricultural areas, where common nesting substrates included bulrush, cattail, Himalayan blackberry (*Rubus armeniacus*), mallow (*Malva* spp.), mustard (*Brassica* spp.), stinging nettle (*Urtica dioica*), and triticale (*Triticum* × *Secale*; Kelsey 2008; Kyle and Kelsey 2011; Meese 2014, 2017).

METHODS

Triennial Surveys included in this study occurred between 2008 and 2017; survey protocols remained consistent during this period (Kelsey 2008; Kyle and Kelsey 2011; Meese 2014, 2017). Each year, official counts were conducted during a prescribed 3-day window during April. For a given survey, a state coordinator recruited county coordinators, who recruited local volunteers and assigned them to a study area comprising a portion of a county. Priorities for study area coverage were to survey previous colony locations, to survey suitable land cover types in the vicinity of previous colony locations, and to survey suitable land cover types elsewhere in the study area. Thus the sampling design, although not formally structured or consistently executed, was most analogous to an adaptive sampling scheme commonly used to sample elusive and clustered species (Smith et al. 2004). Volunteers were given study area maps, detailed instructional materials, and offered multiple training sessions at multiple sites around the state to refine tricolored blackbird identification and counting skills. Counts were typically preceded by scouting trips that helped volunteers become familiar with previous colonies and discover new ones. Volunteers counted birds from distances of 20–100 m, which prevented colony disturbance, and were encouraged to spend approximately 15 minutes at sites with suitable nesting vegetation to determine occurrence. Less time was spent at sites when a location was obviously unsuitable, and more time was spent as necessary to estimate the number of birds. Observers were instructed to count individual birds for smaller colonies (<500 individuals) and to conduct scanning surveys (multiples of 5 or 10) for larger colonies. Large colonies with >5,000 individuals were reported to coordinators for follow-up counting by expert observers. Full details of the Triennial

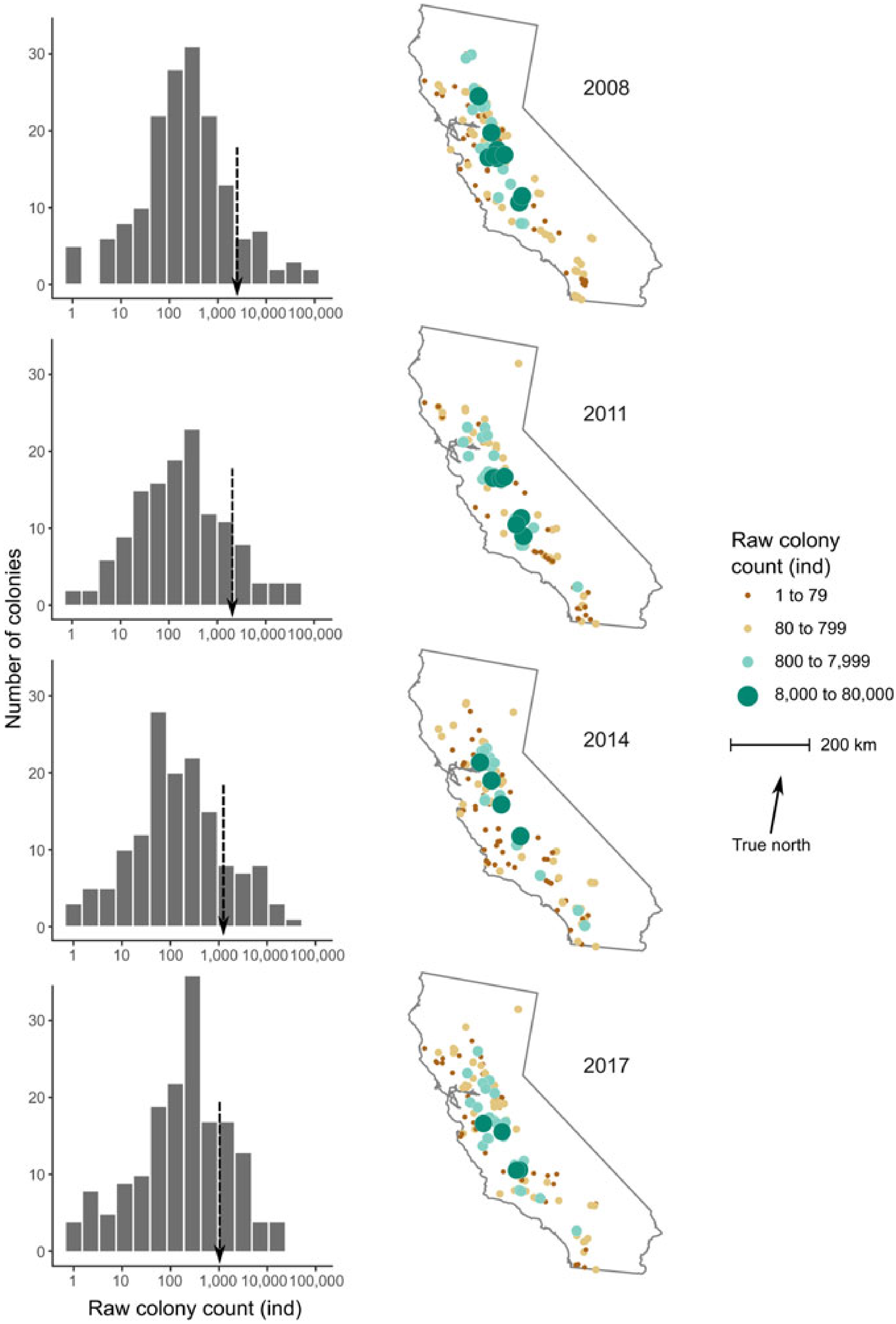

Figure 1. Tricolored blackbird raw colony counts (number of individuals [ind]) recorded during 4 Triennial Tricolored Blackbird Statewide Surveys conducted during 2008, 2011, 2014, and 2017 across much of the species' geographic range in California, USA. Vertical arrows on the histograms show the annual means of raw counts.

Survey protocol can be found in annual reports (Kelsey 2008; Kyle and Kelsey 2011; Meese 2014, 2017).

We obtained raw data for this analysis via the Tricolored Blackbird Portal, a publicly accessible website that serves as a central repository for information on the species (http://tricolor.ice.ucdavis.edu, accessed 29 May 2018). Before the analysis, we filtered the raw data, keeping only the maximum count per location per year. We retained the maximum count to reduce the possibility that observers underestimated colony size because of birds foraging away from the colony during repeat visits. After filtering, we computed averaged and summed metrics related to survey effort and blackbird occurrence, to look for systematic patterns of variation among the 4 surveys. Averaged effort metrics included the mean number of observers participating in the maximum count, per location and year, and the mean duration (min) of the maximum count, per location and year. Summed metrics included the number of unique observers per year, the number of unique locations visited per year, and the number of occupied locations visited per year.

After quantifying patterns in survey effort and occurrence, we assessed temporal trends in the size of tricolored blackbird colonies using a hierarchical modeling approach that is commonly used for the analysis of count data produced by community science programs (Kéry and Schaub 2011, Sauer and Link 2011, Soykan et al. 2016). For this analysis, we filtered the data set so that it included all records with a tricolored blackbird count >0. If a location was visited during 2 Triennial Surveys, and it was occupied both times, then we included both records in the analysis. If a location was visited during 2 surveys and it was occupied 1 time, then we included only the record with a count >0 in the analysis. Thus, the data set included observations from locations occupied only once (singletons) and observations from locations that were occupied repeatedly (repeats). By including all available non-zero counts, the analysis incorporated the greatest information content. We accounted for the lack of statistical independence among repeats in the statistical model used to analyze the data set.

We modeled maximum non-zero tricolored blackbird counts using a hierarchical statistical model that included a temporal trend and several terms to account for spatial and temporal variation in survey characteristics (Kéry and Schaub 2011, Sauer and Link 2011, Soykan et al. 2016). The model took the form:

$$c_{i,j} \sim \text{Poisson}(\lambda_{i,j}),\ \log(\lambda_{i,j}) = \mu_{i,j},$$

$$\mu_{i,j} = \alpha + \beta_1 Y_i + \beta_2 \log(D_i) + \beta_3 \log(T_{i,j}) + o_{k(i,j)} + \nu_j + \eta_j + \varepsilon_{i,j}.$$

We modeled a blackbird count (c) during year i at location j as coming from a Poisson distribution with an expected value ($\lambda_{i,j}$). The linear predictor ($\mu_{i,j}$) for the natural log of $\lambda_{i,j}$ included several fixed effects, including a global intercept (α), a global log-linear effect (β_1) of year (Y_i), a global power-law effect (β_2) for the number of occupied locations surveyed during a year (D_i), and a global power-law effect (β_3) for the amount of time spent during the count per location and year ($T_{i,j}$). A log-linear year effect is common in this type of analysis because it is simple and fits expectations based on population growth (Kéry and Schaub 2011). We selected flexible power-law effects for the number of occupied locations and survey duration because it is common for effort effects to be nonlinear, with diminishing returns for increased effort (Link and Sauer 1999).

Before analysis, we transformed the variables related to global fixed effects for computation and interpretation reasons. We scaled year such that 2008 through 2017 was set to 0–9. We scaled the number of occupied locations surveyed and the duration of surveys such that minimum values were set to 1. With these transformations, α represented the natural log of the expected count during 2008, assuming 133 occupied colonies were surveyed for 1 minute by a typical observer. Because of the arbitrary nature of these units, expected counts from this analysis should be considered as relative colony size indices (Kéry 2010, Kéry and Schaub 2011, Sauer and Link 2011, Soykan et al. 2016). These indices should not be interpreted as true colony size, although they are thought to be proportional to one another (Link and Sauer 1998, Sauer and Link 2011). When confounding factors are properly accounted for, however, temporal trends in indices are expected to follow trends in true colony size (Link and Sauer 1998, Sauer and Link 2011).

The linear predictor also included 4 exchangeable random effects, including an exchangeable random intercept per the kth observer ($o_{k(i,j)}$) an exchangeable random intercept per location (υ_j), an exchangeable random deviation from the global year effect per location (η_j), and an overdispersion term ($\varepsilon_{i,j}$). Given this formulation, the year effect for any given location was the sum of β_1 and η_j. We modeled random effects with normal distributions with mean = 0 and precisions (inverse of variances) τ_o, τ_υ, τ_η, and τ_ε, respectively. We added the random observer effect to account for variation in counts related to volunteer experience and ability (Sauer et al. 1994, Sauer and Link 2011). Individual observers tended to conduct observations in the same part of the state across years, so the observer effect is partially confounded by variation attributable to the region. We added random intercepts and year deviations to the model to allow the year effect to vary across colony locations and to account for the correlation between repeat measurements (Zuur et al. 2009). We added the overdispersion term so that overdispersed count data could be modeled using the Poisson distribution (Harrison 2014).

Inference on model parameters followed a Bayesian framework as implemented in the R-INLA package (Rue et al. 2017) for R statistical computing software (R Version 3.3.1, www.r-project.org, accessed 21 Jun 2016). Prior distributions for global fixed effects were normal distributions with mean = 0 and precision = 0.001. Priors for τ_o, τ_υ, τ_η, and τ_ε were gamma distributions with parameter values shape = 1 and rate = 0.5. We drew inference using 20,000 samples from the joint posterior distribution. When we provide numerical summaries for estimates of model parameters, point estimates are posterior medians with symmetric 95% credible intervals bounded by the 0.025th and 0.975th quantiles of marginal posterior distributions.

RESULTS

The raw data consisted of 2,713 records from 1,455 locations across 4 annual surveys spanning 10 years. Annual means for the number of observers participating in the maximum count per location, and the duration of the maximum count per location, did not vary systematically across the 4 surveys (Table 1). In contrast, the number of observers conducting surveys and the number of locations visited increased by approximately 25% and 150%, respectively (Table 1). Despite the increasing numbers of observers and the number of locations visited, there was no systematic variation in the number of locations with tricolored blackbirds detected (Table 1). Indeed, blackbirds were detected at 165 locations during 2008 and 168 locations during 2017.

Of the 1,455 locations visited during the study period, 471 had blackbirds detected ≥1 time. The 612 counts from these 471 locations suggested that average colony size had declined over the 4 surveys (Fig. 1).

The output from the model analysis gave a posterior median of −0.050 for β_1 (the global effect of the year), with a 95% credible interval of −0.106 to 0.006 (Table 2). Although the symmetric credible interval included zero, the posterior probability that β_1 was ≥0 was 0.038. The posterior median converted to an annual decrease in colony size of approximately 5% per year. When scaled over the study period, that annual rate translated to an approximate 40% decrease in colony size between 2008 and 2017.

The posterior median value for β_2 (the effect of the number of count locations) was −0.052 (−0.178, 0.075; Table 2). Given the wide credible interval encompassing zero, there was little evidence that observed blackbird counts were related to the number of occupied colonies surveyed in a given year. The posterior median value for β_3 (the effect of survey duration) was 0.437 (0.285, 0.590; Table 2). Given that the credible interval did not encompass zero, there was evidence for a positive relationship between observed blackbird counts and count duration. The value of 0.437 could be interpreted as an exponent for an effort-correction function with a power law form. The exponent between 0 and 1 indicated a positive effect of count duration, but that continued increases in count duration yielded diminishing returns.

Regarding random effects, median values for τ_o, τ_υ, τ_η, and τ_ε were 1.082, 2.226, 27.877, and 0.431, respectively. These values, converted to a standard deviation scale, were 0.961, 0.670, 0.189, and 1.523, respectively. Credible intervals for all forms of τ did not include zero, so all random effects were useful components of the model. In terms of highest to lowest variation explained, random effects ranked ε, o, υ, and η. Thus, the random observer effect (o) explained more variation than the colony location effect (υ) and the random year effect per location (η). The importance of ε indicated that the colony counts were overdispersed relative to a Poisson distribution, which was not surprising given the colonial nature of the species.

DISCUSSION

Tricolored blackbird populations in California declined considerably during the twentieth century (Beedy et al. 1991, Graves et al. 2013). Analysis of more recent trends, using heterogeneous data collected from the peer-reviewed and gray literature, has yielded results that are less clear (Graves et al. 2013), hindering efforts to evaluate the conservation needs of the species. We found a clear decline in average colony size of approximately 5% per year, which translated to a decrease in colony size of approximately 40% between 2008 and 2017.

Tricolored blackbird is listed as Endangered by the International Union for Conservation of Nature. The Partners in Flight Landbird Conservation Plan lists the species on its Red Watch List, with an estimated species half-life of approximately 50 years (Rosenberg et al. 2016). The 5% annual decrease in colony size observed during this study was statistically indistinguishable from a 6% annual decrease in overall abundance recently reported by Robinson et al. (2018), who evaluated an integrated population model that used an independent set of count data from the eBird program (Sullivan et al. 2014). The similarity in annual declines across the 2 different studies is intriguing, and suggests that colony size is declining in proportion to overall tricolored blackbird abundance. If these estimates for colony size and abundance declines are accurate, then tricolored blackbird could have a species half-life closer to 15 years than 50 years. Thus, the outlook for this species could possibly be worse than assumed.

The proportional declines in colony size and overall abundance documented in this study and that of Robinson et al. (2018), respectively, suggest that tricolored blackbird is struggling. It is possible, however, to imagine scenarios where this conclusion would be incorrect. For example, both this study and that of Robinson et al. (2018) focused on tricolored blackbird observations from California. If the geographic range of the species were shifting outside of the state, it could look as if the species was declining overall, when it was leaving the sampling area over time. Currently, there are few data available to evaluate this possibility. Second, this study and that of Robinson et al. (2018) considered changes in averages of colony size and relatively abundance, respectively. It is possible that the species has changed its behavior over the last 10 years, and is now aggregating in a greater number of colonies and flocks of

Table 1. Summary of effort and occurrence during 2008, 2011, 2014, and 2017 Triennial Tricolored Blackbird Statewide Surveys, California, USA.

Survey characteristic	2008	2011	2014	2017
Number of observers participating in maximum count	1	1	1	1
Maximim count duration (min)				
$\bar{x}$	23.79	15.48	19.61	17.95
SD	27.88	21.25	23.15	23.39
Number of observers	71	69	91	89
Number of locations surveyed	359	612	804	878
Number of locations occupied by tricolored blackbirds	165	133	157	168

Table 2. Summaries of marginal posterior distributions for global fixed effects from the hierarchical model of colony size counts of tricolored blackbirds, California, USA, 2008–2017.

Model parameter	Posterior median	Lower credible limit	Upper credible limit	Probability estimate ≥0
Global intercept, α	3.951	3.339	4.554	>0.999
Survey year effect, β_1	−0.050	−0.106	0.006	0.038
log(locations occupied), β_2	−0.052	−0.178	0.075	0.212
log(count duration), β_3	0.437	0.285	0.590	>0.999

smaller average sizes, creating an illusion of overall declines. Although this scenario cannot be ruled out, it does not appear to be the most likely scenarios for 2 reasons. First, if there were increasing numbers of colonies on the landscape, we might expect the Triennial Survey to detect them, given the 25% increase in observers participating and 150% increase in locations visited over the past decade. However, despite an increased number of observers and site visits, the number of reported colonies has remained steady. Second, although the current study relied strictly on colony counts, trends from Robinson et al. (2018) were also informed by productivity estimates and survival information from banding data.

It is possible that methodological variation in the Triennial Survey, within and across years, could have influenced observed trends, if not properly accounted for (Sauer et al. 1994, Link and Sauer 1998). A systematic change in average observer ability, as new observers joined the survey, could have resulted in an apparent trend in blackbird counts. We reduced the possibility for this confounding effect by including observer identity directly into the model and note that estimates of observer effects could have also included a signal related to regional variation in counts. It is conceivable that an apparent decline in colony size could be influenced by a gradual increase in the number of colonies counted, under the assumption that large colonies would be found and counted before small ones (Rosenstock et al. 2002). This possibility was not likely to affect our results because there was not an apparent increase in the number of occupied colonies and because the number of occupied colonies was incorporated directly into the model. Third, the amount of time spent during colony counts varied considerably within and across surveys. Systematic declines in count duration across years could have resulted in an apparent decrease in colony size. This possibility was unlikely to influence our results because we explicitly modeled count duration in our analysis.

MANAGEMENT IMPLICATIONS

Management activities over the past few decades have been insufficient to stop the long-term decline in average colony size for tricolored blackbird in California. Our results say little about how a decline in colony size could be stopped. Conservation programs that increase productivity, such as payments to farmers in California's Central Valley to delay harvest of silage and grain crops when fields are occupied by tricolored blackbird nestlings (Arthur 2015), could possibly reverse the negative trends in colony size observed in the Triennial Survey.

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