Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Short communication

Composite population trends reveal status of wintering diurnal raptors in the Northwestern USA

Christopher J.W. McClure [a,*], Brian W. Rolek [a], Jeff Fleischer [b]

[a] *The Peregrine Fund, Boise, ID, United States of America*
[b] *East Cascades Audubon Society, Bend, OR, United States of America*

ABSTRACT

Integrated models can combine data from disparate monitoring programs to improve inference into population dynamics because trends in disparate datasets can be interpreted using a single index. We present a composite index of raptor population trends that combines data from two monitoring programs into a single estimate. The National Audubon Society's Christmas Bird Count and the East Cascade Audubon Society's Winter Raptor Survey use different methods to monitor the same populations of wintering raptors. Observers record all birds detected within 452 km^2 'circles' during the Christmas Bird Count, and during the Winter Raptor Survey observers count raptors along roadways. We present the results of a joint likelihood model that combines trends of raptors counted during both programs into a single population trend from 2005 to 2020. Population indices of the Bald Eagle (*Haliaeetus leucocephalus*), Ferruginous Hawk (*Buteo regalis*), Cooper's Hawk (*Accipiter cooperii*), Red-shouldered Hawk (*Buteo lineatus*), and Red-tailed Hawk (*Buteo jamaicensis*) increased over the course of our study, whereas Prairie Falcon (*Falco mexicanus*) and White-tailed Kite (*Elanus leucurus*) population indices declined. Further, the composite index for White-tailed Kite declined at a rate of 22 % (80 % CRI = 17 %–28 %) per year—supporting evidence of declines from breeding season surveys. We recommend further research into population trends of this species within its core California range. Our study advances efforts to combine trends in datasets collected using differing methodologies to estimate large-scale population trends from disparate data sets.

1. Introduction

Monitoring is necessary for biological conservation (Lovett et al., 2007; Nichols and Williams, 2006; Wiens, 1984) and can prevent extinction when conservationists become aware of population losses with enough time to implement countermeasures (Lindenmayer et al., 2013; Martin et al., 2012; Woinarski et al., 2017). Ideally, common species should be monitored (Gaston and Fuller, 2008) so that when declines occur, the species can be recovered while still relatively abundant. For example, the White-rumped Vulture (*Gyps bengalensis*) was once thought to be the most abundant large raptor on Earth (Houston, 1985), yet nearly went extinct within a decade during the late 1990s and early 2000s (Pain et al., 2008). Long-lived and slowly reproducing species such as raptors are especially susceptible to precipitous declines (Ogada et al., 2022, 2016; Pain et al., 2008), and may require intensive monitoring to expeditiously counteract population declines.

Few monitoring exercises are true population censuses, most programs therefore make statistical and methodological assumptions regarding the representativeness of samples to actual populations. Because of these assumptions, monitoring programs might have strengths and weaknesses such that evidence from multiple programs bolsters the case for a hypothesized population decline. Reliance on a single population indicator for policy or management should be avoided, when possible (McClure et al., 2022). For example, the case for a population decline of American Kestrels (See Table 1 for scientific names of focal species) across the northeastern USA is strong because multiple lines of evidence provide the same conclusion. These lines of evidence include nest box studies, breeding counts, migration indices, and historical records (Farmer and Smith, 2009; McClure et al., 2017; McClure and Schulwitz, 2022; Smallwood et al., 2009).

Integrated modeling, or data integration, is a framework that helps combine inference from multiple monitoring programs into a single source of inference (Zipkin et al., 2021). Such analysis often uses a joint

---

* Corresponding author.
E-mail address: cmcclure@peregrinefund.org (C.J.W. McClure).

Table 1

Common and scientific names for focal raptor species as well as the number of individuals counted within Christmas Bird Count circles (CBC Counted) and along Winter Raptor Survey routes (WRS Counted). For all species except the Northern Harrier, the probability of decline is derived from the composite index of the CBC and the WRS models using the region-wide mean annual population growth rates. The probability of decline for the Northern Harrier is derived from only the WRS model.

Common name	Scientific Name	CBC counted	WRS counted	Probability of decline
American Kestrel	*Falco sparverius*	40,804	24,443	0.405
Bald Eagle	*Haliaeetus leucocephalus*	52,801	8216	0.000
Cooper's Hawk	*Accipiter cooperii*	8595	734	0.070
Ferruginous Hawk	*Buteo regalis*	454	731	0.006
Golden Eagle	*Aquila chrysaetos*	2990	1465	0.389
Northern Harrier	*Circus hudsonius*	25,476	7428	0.633
Prairie Falcon	*Falco mexicanus*	2232	1189	0.940
Red-shouldered Hawk	*Buteo lineatus*	2903	760	0.133
Red-tailed Hawk	*Buteo jamaicensis*	95,013	50,615	0.090
Rough-legged Hawk	*Buteo lagopus*	12,698	8443	0.280
White-tailed Kite	*Elanus leucurus*	1073	523	0.999

likelihood that links datasets so that single parameters are informed by multiple sources of data (Farr et al., 2021; Fletcher et al., 2016). For example, researchers have estimated migratory connectivity across the Western Hemisphere by integrating tracking data with band-reencounters (Meehan et al., 2022), and improved population trend estimation by integrating North American Breeding Bird Survey with targeted surveys for Common Nighthawks (*Chordeiles minor*; Knight et al., 2021). Integrated modeling is growing increasingly popular in part because the incorporation of multiple data sources often decreases uncertainty while increasing accuracy of estimated parameters (Zipkin et al., 2021).

Raptor populations are of global conservation concern (Buechley et al., 2019; McClure et al., 2018; McClure and Rolek, 2020), but are generally considered secure within the USA with a few exceptions

(McClure et al., 2022). We use a joint likelihood model to estimate population trends of diurnal raptors wintering in the northwestern USA by combining the National Audubon Society's Christmas Bird Count (CBC; Butcher, 1990) with the East Cascades Audubon Society's Winter Raptor Survey (WRS). Within the regions where the two programs spatially overlap, these two programs monitor the same populations of raptors, albeit with different methodologies. Combining these datasets into a composite index will likely improve inference into population trends because trends in both datasets can be interpreted using a single index. We perform this analysis for 11 species of diurnal raptors (Table 1) across the states of Washington, Oregon, and Idaho (Fig. 1). Given the generally favorable conservation status of raptor populations across the USA (McClure et al., 2022), we predict that most species increased or remained stable over the course of our study.

2. Methods

2.1. Christmas Bird Count

The CBC (Butcher, 1990) consists of hundreds of 452 km² 'circles' throughout North America in which volunteers record the birds they encounter during surveys. We analyzed data from the 126 circles within our study area (Fig. 1). Volunteers surveyed using a motorized vehicle, walking, or various other types of transportation. CBC surveyors recorded distance traveled by foot and vehicle, along with the duration of survey. These surveys were conducted on single days between the dates 14 December and 5 January.

2.2. Winter Raptor Survey

The creation of WRS surveys in northwestern USA began during the winter of 2004–2005 within a small region of Oregon. These surveys gradually expanded throughout Oregon by the winter of 2010–2011, into Idaho by the winter of 2011–2012, and into Washington by the winter of 2019–2020. These efforts resulted in routes throughout Oregon, Idaho, and Washington by 2020–2021. WRS surveyors had previous experience identifying raptors and drove preassigned routes that varied in distance (12–294 km). Surveyors used binoculars and were encouraged to use a spotting scope. Surveyors were instructed to stop their vehicle to improve identification of raptors when safe. Surveyors recorded distance driven and duration of survey. We restricted these
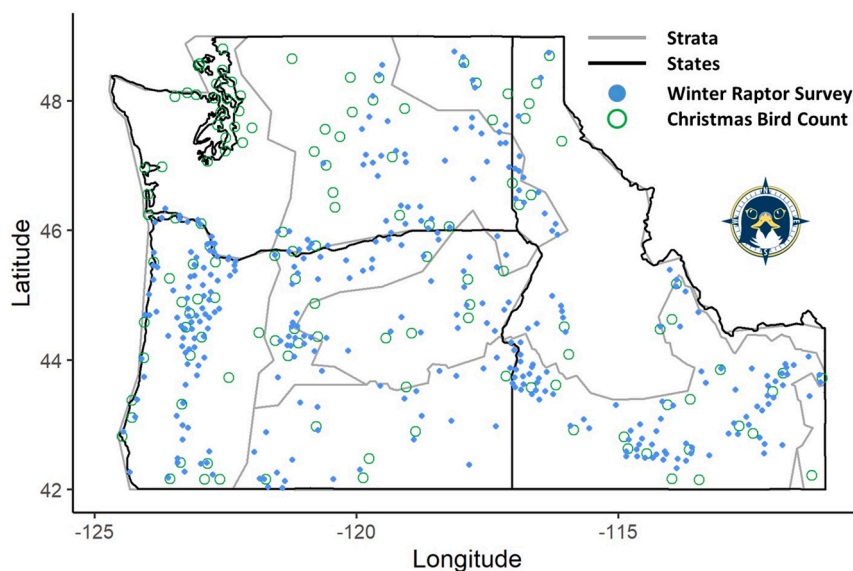

Fig. 1. Map of our study region depicting the boundaries of spatial strata, locations of Christmas Bird Count circles, and beginning locations of Winter Raptor Survey routes.

data to routes that were surveyed for ≥ 2 years matching the seasonal time period of the CBC. In total, we analyzed 328 WRS routes within our study area (Fig. 1).

2.3. Data

We evaluated population trends for the eleven species having >500 detections during WRS surveys (Table 1). We restricted raptor count data to include surveys conducted within the states of Washington, Oregon, and Idaho and included Bird Conservation Regions five, nine, and ten, because WRS and CBC data overlap spatially within these regions. Additionally, we restricted data between dates of 14 December and 05 January each year, when WRS and CBC overlap seasonally. We analyzed data from the winters of 2004–2005 to 2019–2020 because the two datasets overlapped during these years.

We assigned a spatial unit (hereafter "stratum") to each CBC and WRS route using shapefile polygons that corresponded to Bird Conservation Regions subdivided by state boundaries (Link and Sauer, 2007; Fig. 1). We slightly modified strata boundaries to include several islands within Puget Sound, Washington that would have been excluded otherwise. We used these strata during the modeling process (detailed below) to group population growth rates into spatial units and integrate models for WRS and CBC data.

2.4. Model framework

We used a Bayesian framework with single-species hierarchical models to create integrated and state-space models to estimate population growth rates for raptors using CBC and WRS data. We assumed that these two survey protocols would have different scales of abundance indices and observation errors because of inherent differences in survey protocols (e.g. number of surveyors, skill of surveyors, and method of travel). To integrate models using the two datasets, we circumvented data harmonization and linked the data sets by including stratum-level population growth rates as a shared parameter. Although our model accounts for differences in observation error between sampling protocols, other integration efforts were able to more directly model the observation process (Barry et al., 2021; Pacifici et al., 2019); however, these studies were conducted at much smaller spatial extents than ours. We lacked the computing resources necessary to implement such spatially explicit modeling for these datasets at a large spatial scale, and present a more computationally tractable model.

We assigned count data to come from either a Poisson, zero-inflated Poisson, or a negative binomial distribution. We applied goodness-of-fit tests to select a good-fitting distribution as some function, $g(\mu)$, where μ represented an estimated mean abundance index having some variance from the aforementioned distributions. Notably, when $g(\mu)$ represented negative binomial or zero-inflated distribution this function included two parameters that accounted for the mean and variance, while the Poisson had a single parameter where the variance was assumed equal to the mean, consistent with standard parameterizations of these distributions. We used mean absolute error as the discrepancy statistic to calculate Bayesian *P*-values (Besbeas and Morgan, 2014). We selected distributions providing Bayesian P-values near 0.5, and we tended to select simpler distributions having fewer parameters (i.e. Poisson) when distributions had similar Bayesian P-values. Good-fitting distributions tended to be consistent for WRS and CBC data; therefore, we used the same distribution for data from both survey protocols. Bayesian P-values tend to be biased toward suggesting a good fit (0.5); however, this measure remains valuable for detecting an extreme lack of fit (Conn et al. 2018).

2.5. Process submodels of abundance and dynamics

We specified abundance indices for WRS surveys during the first year ($\log N_{WRS,\,t=1,\,i}$) as model-estimated parameter for each WRS route (i)

and time step (t). We included survey route-level population dynamics so abundance indices were an autoregressive Markovian process because abundance during future time steps ($t + 1$) depends on abundance during the previous time step and survey route-specific population growth rate (r_{WRS}). We used the exponential growth model on the log scale (Lande et al., 2003) as $\log N_{WRS,\,t+1,\,i} = \log N_{WRS,\,t,\,i} + r_{WRS,\,t,\,i}$. The submodel for abundance using CBC data was identical in form to the WRS submodel and specified as $N_{CBC,\,t=1,\,j}$ and $\log N_{CBC,\,t+1,\,j} = \log N_{CBC,\,t,\,j} + r_{CBC,\,t,\,j}$ for each CBC survey route (j).

2.6. Observation submodels

We integrated two disparate survey protocols; therefore, we specified two separate observation submodels by simply replicating code for each survey protocol with some modifications to indices. Other studies could use indexing to simplify code, and this approach would be advantageous when including many survey protocols. Here, we specified separate observation submodels for each protocol to allow each data set to have different observation error and covariates.

We modeled count data ($y_{WRS,\,k}$) for each WRS survey (k) as a function of some good-fitting distribution, $y_{WRS,\,k} \sim g(\mu_{WRS,\,k})$, where $\mu_{WRS,\,k}$ remained confounded with observation error. To account for observation error, we estimated the abundance index ($\log N_{WRS,\,t,\,i}$) with observation error (σ_{WRS}). We used the log-link function and included an offset for distance driven (x_{WRS}) per 100 km during each survey where the number of individuals counted is indexed by survey year (t) and route (i). We included a covariate for average driving speed (SPEED, scaled and centered) because it influences the number of raptors counted during road surveys (McClure et al., 2021b). We specified this regression as $\log \mu_{WRS,\,k} \sim \text{normal}(\log N_{WRS,\,t[k],\,i[k]} + \log x_{WRS,\,k} + \beta_{WRS} \times \text{SPEED}_{WRS,\,k}, \sigma_{WRS})$. Centering and scaling the SPEED covariate ensured that the intercept provided an abundance index when a route was surveyed at the mean SPEED (Schielzeth, 2010). We included a separate submodel for CBC data that was nearly identical to the WRS likelihood in form except that average speed data were unavailable thereby excluding this covariate. We simply modified indexing and excluded the SPEED covariate to obtain the CBC observation submodel specified as $y_{CBC,\,l} \sim g(\mu_{CBC,\,l})$ and $\log \mu_{CBC,\,l} \sim \text{normal}(\log N_{CBC,\,t[l],\,j[l]} + \log x_{CBC,\,l}, \sigma_{CBC})$ for CBC survey (l).

2.7. Integration of population growth rates

To estimate composite population growth rates from CBC and WRS data for each raptor species, we assumed that survey locations within each spatial stratum shared a mean population growth rate, regardless of survey protocol. This formulation allowed sites with similar spatial and physiographic regions to share partially-pooled information about population growth rates without the need to harmonize detection and abundance data. More explicitly, we integrated model estimates from CBC and WRS datasets by introducing shared parameters of average population growth rates (ρ) in each stratum (s) having some process error (δ) as $r_{WRS,\,t,\,i} \sim \text{normal}(\rho_{t,\,s}, \delta)$ and $r_{CBC,\,t,\,j} \sim \text{normal}(\rho_{t,\,s}, \delta)$ thereby partially pooling estimates within each stratum. This formulation links the likelihoods for both datasets and allows abundance indices to scale separately for each protocol. We allowed these averaged stratum-level population growth rates to share partially-pooled information that came from a normally-distributed grand mean among strata ($\bar{r}$) as $\rho_{t,s} \sim \text{normal}(\bar{r}, \nu)$. We therefore considered $\bar{r}$ to be a composite index of the region-wide mean population growth rates ("population trends" hereafter) that combines inference from both the WRS and CBC.

2.8. Model implementation and inference

We implemented models in Just Another Gibbs Sampler (JAGS) v4.3.0 (Plummer, 2003) with R statistical software v4.0.2 (R Core Team,

2021) and the package jagsUI v1.5.1 (Kellner, 2016) as interfaces. We implemented each model with four chains each having ≥10,000 adaptation, ≥ 400,000 burn-in, and ≥ 100,000 posterior iterations. We thinned each chain by retaining one of 400 iterations to alleviate autocorrelation between posterior draws and to improve effective sample size from the posterior. This implementation yielded a total of 1000 iterations for each posterior distribution. We assessed convergence of posterior chains using traceplots, density plots, and the Gelman-Rubin diagnostic ($\hat{R}$, Gelman and Rubin, 1992), and we assigned adequate convergence when $\hat{R} < 1.1$ and traceplots of parameters did not visually appear to drift. All data, metadata, R code, and JAGS code needed to reproduce the analyses are available at: https://github.com/The-Peregrine-Fund/northwest-trends.

We interpreted modeling outputs using both 95 % credible intervals and 80 % credible intervals, which are commonly used for management purposes (Miller et al., 2019, 2016). We also calculated the probability of direction (Makowski et al., 2019) as the proportion of iterations of the composite index that were <0 to determine the probability that the composite index was negative. We refer to this value as the 'probability of decline'. We determined the probability of decline to indicate a negative trend with values <0.10 and a positive trend when >0.90. We mapped the probability of decline across strata per species to visualize the spatial heterogeneity in the composite index. To place the population indices of the CBC and WRS on the same level (Fig. 3), we used the exponentiated cumulative sum of $\bar{r}_t$ over years. This calculation scales population indices as a percentage of the first, or base, year of analysis for each survey protocol.

3. Results

Eleven species were detected ≥500 times on WRS surveys (Table 1).

See Appendix A for results of goodness-of-fit tests. Both the CBC and WRS models converged for all species except the Northern Harrier, for which only the WRS models converged. We therefore only used the WRS model for inference into population trends of the Northern Harrier. CBC and WRS population trends tended to match (i.e. share signs) between survey protocols with the exceptions of the Cooper's Hawk and Golden Eagle, where the median CBC estimate tended toward increases and the median WRS estimate suggested either declines or stability (Figs. 2, 3, Fig. S1), although confidence intervals greatly overlapped and population trends tended to be small in magnitude. Species having increasing population trends included the Bald Eagle, Ferruginous Hawk, Cooper's Hawk, Red-shouldered Hawk, and Red-tailed Hawk (Table 1; Figs. 2, 3, 4, Fig. S1). Species having declining population trends included the Prairie Falcon and White-tailed Kite (Table 1; Figs. 2, 3, 4, Fig. S1). The composite index for White-tailed Kite indicated a population decline of 22 % (80% CRI = 17 %—28 %) per year. There was spatial heterogeneity across strata in the probability of decline both among and within species (Fig. 4). Yet, species that were increasing or declining tended to do so across our study region.

4. Discussion

The most salient of our results is the apparently declining trend of wintering White-tailed Kite populations within northwestern USA. This apparent decline is supported by two monitoring programs implemented using disparate methodologies, and is therefore difficult to dismiss as an artefact of sampling methodology (e.g. changing visibility along roadsides). The first known White-tailed Kite nest in Oregon was confirmed in 1977 (Henny and Annear, 1978). The apparent declines we observed might therefore be an artefact of the species retracting to its historical California range. However, the North American Breeding Bird Survey shows declines of this species within California (Sauer et al., 2020) and
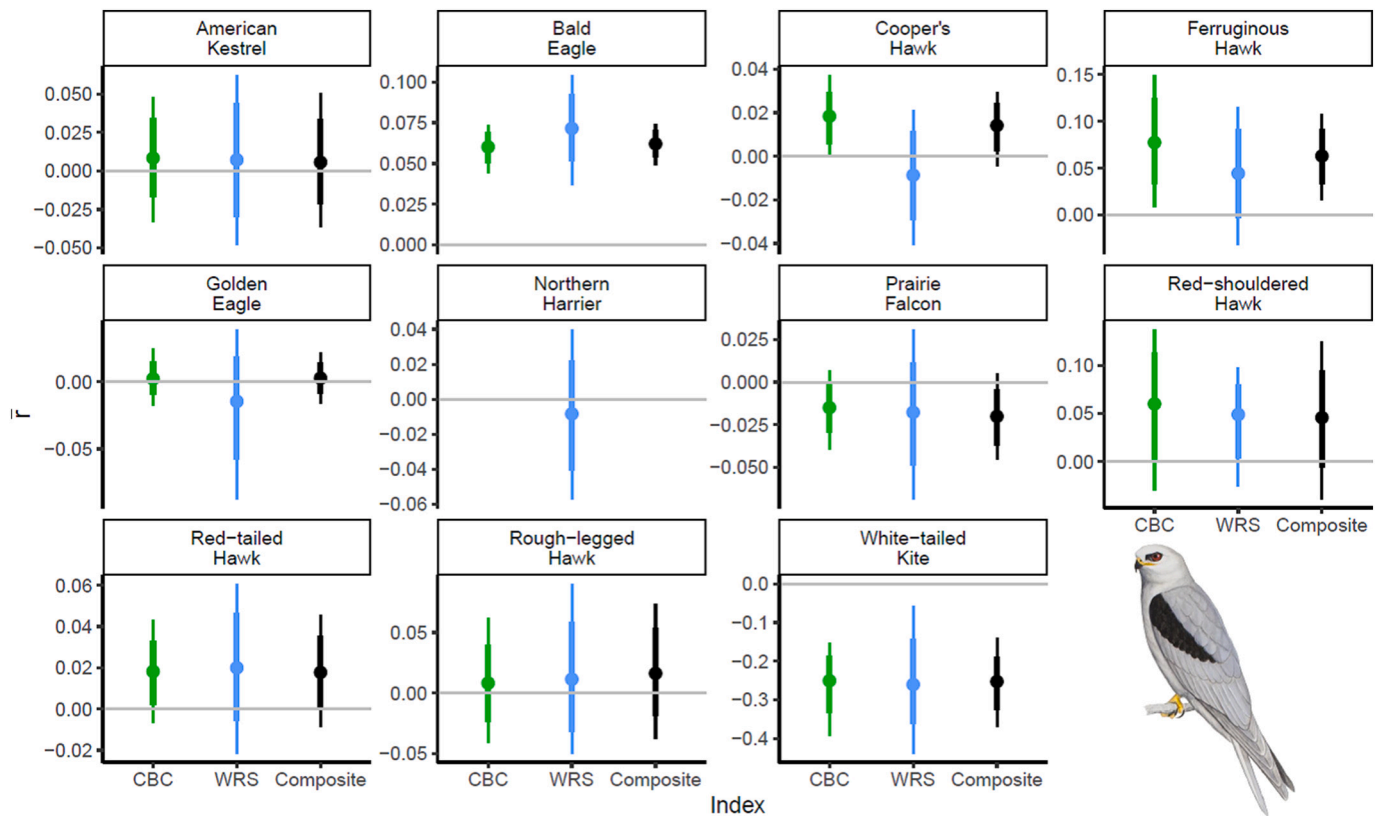

Fig. 2. Caterpillar plots of region-wide mean annual population growth rates ($\bar{r}$) from the Christmas Bird Count (CBC) Winter Raptor Survey (WRS) and a composite of the two programs (Composite). Points depict medians, thick lines depict 80 % credible intervals, and thin lines depict 95 % credible intervals. See Table 1 for scientific names. Only the WRS model converged for the Northern Harrier. Illustration by Bryce Robinson.
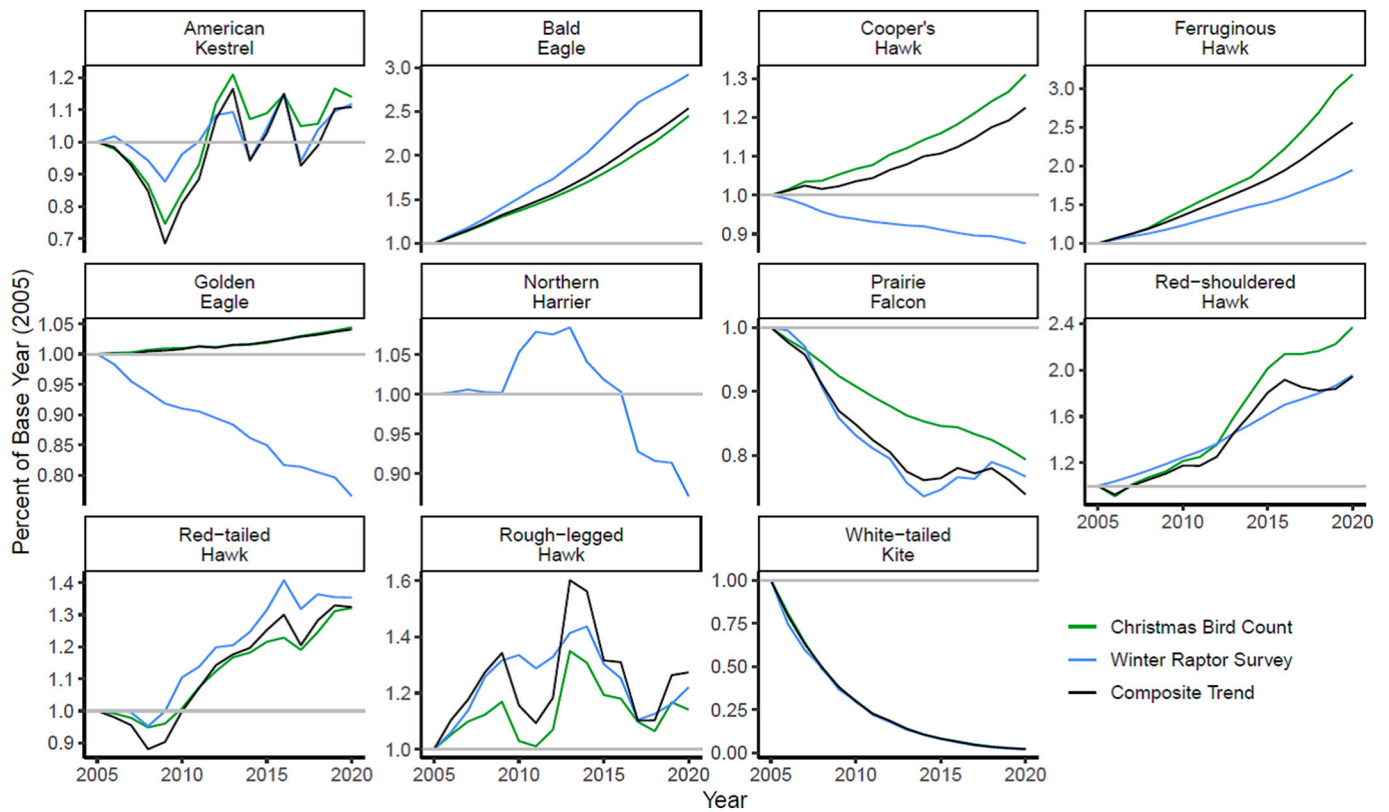
Fig. 3. Population indices as a mean percentage of the first year of surveys analyzed (2005). This index is the exponentiated cumulative sum of the yearly population growth rate. The composite trend is an integration of the Christmas Bird Count and the Winter Raptor Survey. See Table 1 for scientific names. Only the WRS model converged for the Northern Harrier.
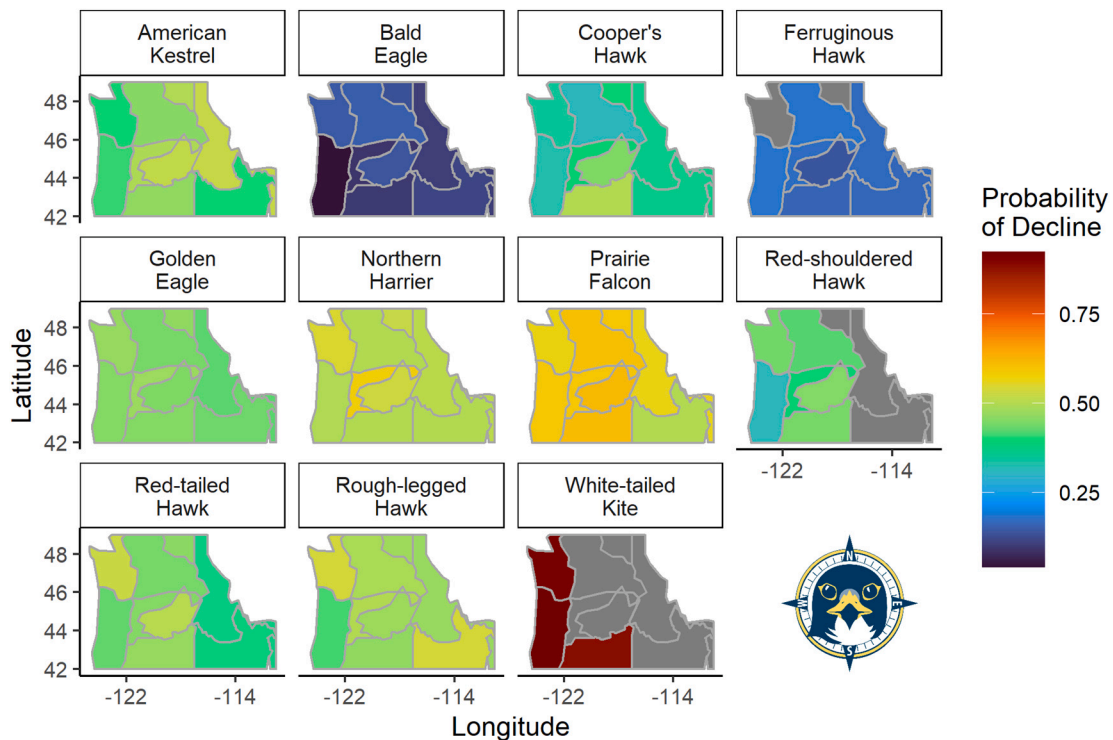

Fig. 4. Maps of the probability of decline for each species within the strata of our study region. See Table 1 for scientific names. Gray polygons depict strata that were surveyed but had no detections; therefore, we omitted these strata from analyses. Only the WRS model converged for the Northern Harrier, so results from that model are shown.

Rosenberg et al. (2019) estimated a loss of >12,000 individuals across North America since 1970. Our study region is outside the core California range of the White-tailed Kite (Dunk, 2020). Future studies should integrate the CBC, WRS, Breeding Bird Survey, and local datasets into a composite population index for the White-tailed Kite across its range within the western USA. If the population decline is apparent within the core of the species' North American range, conservationists should immediately undertake efforts to remediate the declines before rarity decreases the chances of a population rebound.

The Prairie Falcon also appears to be declining across our study region during winter. However, Miller et al. (2019) noted an apparent increase in wintering Prairie Falcons along road transects in Nevada from 2013 to 2018, and this time span coincides with a peak in population growth rates during our study. Anecdotal observations and unpublished analyses have led to a general sense among some experts that the species is in decline across the western USA (CJWM Personal Observation). In response, a working group for the species is currently discussing ways to elucidate the conservation status of this species. Our results suggest that the efforts of the Prairie Falcon working group are justified and should be supported.

Populations of other species appeared stable or increasing. For example, Bald Eagle populations have more than doubled. Other studies have demonstrated drastic increases in Bald Eagle populations (Farmer et al., 2008; McClure et al., 2021b; Watts et al., 2008) likely due to a continuing rebound from the DDT era (Grier, 1982; Postupalsky, 1978; Smith et al., 2016). Our results also support the assertion that Cooper's Hawk populations are generally increasing across the USA and Canada (McClure et al., 2022; Rosenberg et al., 2019; Smallwood et al., 2009). The observation that Ferruginous Hawks are apparently increasing across our study region is encouraging, given that this is a species of conservation concern (McClure et al., 2022). The conservation status of common wintering diurnal raptors across the northwestern USA is therefore generally secure, with the exceptions of the Prairie Falcon and White-tailed Kite.

Our model provided a composite population index that effectively combined inference from two disparate monitoring programs to elucidate population trends of raptors across a large region. Our model further has several advantages compared to many current data integration models. This model is both practical and conceptually simple to implement across large spatial extents compared to more spatially explicit models. The integrated model generally performed as we expected, with biologically realistic estimates and reasonable levels of precision. However, we did not formally test our integrated model via simulation. We therefore acknowledge some uncertainty regarding the statistical properties of our model and plan to test the model in the future. We also plan to expand and improve this index. For simplicity, we constrained our analysis to the spatial and temporal scales common to the two focal monitoring programs. Future analysis will incorporate data spanning different spatial and temporal scales. Further, we analyzed each species separately, but a single model could be developed that combines results for all species into a single index of trend for the full suite of raptors examined. Eventually, our composite population index will integrate as many datasets as possible for raptor species across the globe.

Raptor researchers must collaborate to accomplish this ambitious goal of monitoring the world's raptors (McClure et al., 2021a). Data sharing should be a priority because multiple lines of evidence can bolster confidence in apparent population trends. Composite indices calculated using integrated modeling will provide a mechanism through which researchers can work together to ensure raptors thrive into the Anthropocene.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2022.109861.

CRediT authorship contribution statement

Christopher J.W. McClure: Conceptualization, Writing – original draft, Visualization, Funding acquisition. **Brian W. Rolek:** Formal analysis, Data curation, Writing – review & editing. **Jeff Fleischer:** Data curation, Supervision, Writing – review & editing.

Declaration of competing interest

Brian Rolek reports financial support was provided by McClure Family Foundation.

Data availability

We have provided a link to the data.

Acknowledgements

Appendix A. Bayesian *P*-values to assess goodness-of-fit for Winter Raptor Survey (WRS) and Christmas Bird Count (CBC) data using integrated state-space models with three statistical distributions: Poisson, negative binomial, and zero-inflated Poisson. Bayesian P-values in bold indicate statistical distributions selected for use in the final model implementation and used for further inference.

Species	Data set	Poisson	Negative binomial	Zero-inflated Poisson
American Kestrel	WRS	0.20	0.20	**0.44**
	CBC	0.06	0.05	**0.46**
Bald Eagle	WRS	0.32	0.30	**0.50**
	CBC	0.00	0.00	**0.56**
Cooper's Hawk	WRS	**0.43**	0.41	0.82
	CBC	**0.67**	0.68	0.86
Ferruginous Hawk	WRS	**0.31**	0.42	0.61
	CBC	**0.38**	0.43	0.56
Golden Eagle	WRS	**0.41**	0.39	0.60
	CBC	**0.67**	0.66	0.81
Northern Harrier	WRS	0.33	0.36	**0.59**
	CBC	0.00	0.00	**0.01**[a]
Prairie Falcon	WRS	**0.52**	0.50	0.84
	CBC	**0.76**	0.79	0.81

(*continued*)

Species	Data set	Poisson	Negative binomial	Zero-inflated Poisson
Rough-legged Hawk	WRS	**0.40**	0.48	0.58
	CBC	**0.52**	0.49	0.76
Red-shouldered Hawk	WRS	**0.47**	0.52	0.74
	CBC	**0.16**	0.16	0.34
Red-tailed Hawk	WRS	0.14	0.10	**0.33**
	CBC	0.00	0.00	**0.16**
White-tailed Kite	WRS	**0.48**	0.54	0.65
	CBC	**0.33**	0.41	0.50

[a] Northern Harrier had no good-fitting distribution using CBC data, so we excluded these data from inference.

References

Barry, B.R., Moriarty, K., Green, D., Hutchinson, R.A., Levi, T., 2021. Integrating multi-method surveys and recovery trajectories into occupancy models. Ecosphere 12, e03886. https://doi.org/10.1002/ecs2.3886.

Besbeas, P., Morgan, B.J.T., 2014. Goodness-of-fit of integrated population models using calibrated simulation. Methods Ecol. Evol. 5, 1373–1382. https://doi.org/10.1111/2041-210X.12279.

Buechley, E.R., Santangeli, A., Girardello, M., Neate-Clegg, M.H., Oleyar, D., McClure, C. J.W., Şekercioğlu, Ç.H., 2019. Global raptor research and conservation priorities: tropical raptors fall prey to knowledge gaps. Divers. Distrib. 25, 856–869. https://doi.org/10.1111/ddi.12901.

Butcher, G.S., 1990. Audubon christmas bird counts. In: Sauer, J.R., Droege, S. (Eds.), Survey Designs and Statistical Methods for the Estimation of Avian Population Trends, U.S. Fish and Wildlife Service, Biological Report, 90(1), pp. 5–13.

Dunk, J.R., 2020. White-tailed kite (Elanus leucurus), version 1.0. In: Poole, A.F., Gill, F. B. (Eds.), Birds of the World. Cornell Lab of Ornithology, Ithaca, NY. https://doi.org/10.2173/bow.whtkit.01.

Farmer, C.J., Smith, J.P., 2009. Migration monitoring indicates widespread declines of american kestrels (Falco sparverius) in North America. J. Raptor Res. 43, 263–273.

Farmer, C.J., Goodrich, L.J., Inzunza, E.R., Smith, J.P., 2008. Conservation status of North America's birds of prey. In: State of North America's Birds of Prey. Series in Ornithology, 3, pp. 303–420.

Farr, M.T., Green, D.S., Holekamp, K.E., Zipkin, E.F., 2021. Integrating distance sampling and presence-only data to estimate species abundance. Ecology 102, 1–9. https://doi.org/10.1002/ecy.3204.

Fletcher, R.J., McCleery, R.A., Greene, D.U., Tye, C.A., 2016. Integrated models that unite local and regional data reveal larger-scale environmental relationships and improve predictions of species distributions. Landsc. Ecol. 31, 1369–1382. https://doi.org/10.1007/s10980-015-0327-9.

Gaston, K.J., Fuller, R.A., 2008. Commonness, population depletion and conservation biology. Trends Ecol. Evol. 23, 14–19. https://doi.org/10.1016/j.tree.2007.11.001.

Gelman, A., Rubin, D.B., 1992. Inference from iterative simulation using multiple sequences. Stat. Sci. 7, 457–472.

Grier, J., 1982. Ban of DDT and subsequent recovery of reproduction in bald eagles. Science 218, 1232–1235. https://doi.org/10.1126/science.7146905.

Henny, C.J., Annear, J.T., 1978. A white-tailed kite breeding record for Oregon. Western Birds 9, 131–133.

Houston, D., 1985. Indian white-backed vulture Gyps bengalensis. In: Newton, I., Chancellor, R.D. (Eds.), Conservation Studies on Raptors. International Council for Bird Preservation, Cambridge, pp. 465–466.

Kellner, K., 2016. jagsUI: A wrapper around "rjags" to streamline "JAGS" analyses. In: R Package Version 1.4.2.

Knight, E.C., Smith, A.C., Mark Brigham, R., Bayne, E.M., 2021. Combination of targeted monitoring and Breeding Bird Survey data improves population trend estimation and species distribution modeling for the Common Nighthawk. In: Ornithological Applications, 123, pp. 1–14. https://doi.org/10.1093/ornithapp/duab005.

Lande, R., Engen, S., Saether, B.E., 2003. Stochastic Population Dynamics in Ecology and Conservation. Oxford University Press, Oxford., UK.

Lindenmayer, D.B., Piggott, M.P., Wintle, B.A., 2013. Counting the books while the library burns: why conservation monitoring programs need a plan for action. Front. Ecol. Environ. 11, 549–555. https://doi.org/10.1890/120220.

Link, W.A., Sauer, J.R., 2007. Seasonal components of avian population change: joint analysis of two large-scale monitoring programs. Ecology 88, 49–55. https://doi.org/10.1890/0012-9658(2007)88[49:SCOAPC]2.0.CO;2.

Lovett, G.M., Burns, D.A., Driscoll, C.T., Jenkins, J.C., Mitchell, M.J., Rustad, L., Shanley, J.B., Likens, G.E., Haeuber, R., 2007. Who needs environmental monitoring? Front. Ecol. Environ. 5, 253–260. https://doi.org/10.1890/1540-9295(2007)5[253:WNEM]2.0.CO;2.

Makowski, D., Ben-Shachar, M., Lüdecke, D., 2019. bayestestR: describing effects and their uncertainty, existence and significance within the Bayesian framework. J. Open Source Softw. 4, 1541. https://doi.org/10.21105/joss.01541.

Martin, T.G., Nally, S., Burbidge, A.A., Arnall, S., Garnett, S.T., Hayward, M.W., Lumsden, L.F., Menkhorst, P., Mcdonald-Madden, E., Possingham, H.P., 2012. Acting fast helps avoid extinction. Conserv. Lett. 5, 274–280. https://doi.org/10.1111/j.1755-263X.2012.00239.x.

McClure, C.J.W., Rolek, B.W., 2020. Relative conservation status of bird orders with special attention to raptors. Front. Ecol. Evol. 8, 593941.

McClure, C.J.W., Schulwitz, S.E., 2022. Historical accounts provide inference into population dynamics of American kestrels (Falco sparverius) in the northeastern USA. J. Raptor Res. 56, 89–94.

McClure, C.J.W., Schulwitz, S.E., Buskirk, R.Van, Pauli, B.P., Heath, J.A., 2017. Commentary: research recommendations for understanding the decline of american kestrels (Falco sparverius) across much of North America. J. Raptor Res. 51, 455–464.

McClure, C.J.W., Westrip, J.R.S., Johnson, J.A., Schulwitz, S.E., Virani, M.Z., Davies, R., Symes, A., Wheatley, H., Thorstrom, R., Amar, A., Buij, R., Jones, V.R., Williams, N. P., Buechley, E.R., Butchart, S.H.M., 2018. State of the world's raptors: distributions, threats, and conservation recommendations. Biol. Conserv. 227, 390–402. https://doi.org/10.1016/j.biocon.2018.08.012.

McClure, C.J.W., Anderson, D.L., Belthoff, J.R., Botha, A., Buechley, E.R., Buij, R., Davies, R.A.G., Dunn, L., Glowka, L., Goodrich, L., Gurung, S., Heath, J.A., Henderson, M.T., Hinchliffe, S., Loercher, F., McCabe, J., Méndez, D., Miranda, E.B. P., Oleyar, M.D., Phipps, W.L., Rayner, A.P., Marques Reyes, C., Robinson, B.W., Rolek, B.W., Schulwitz, S.E., Slater, S., Spurling, D.P., Subedi, T.R., Sumasgutner, P., Sutton, L.J., Tavares, J., Therrien, J.-F., Trice, S.R., Vargas, F.H., Virani, M.Z., Watson, R.T., 2021a. Commentary: the past, present, and future of the global raptor impact network. J. Raptor Res. 55, 605–618.

McClure, C.J.W., Rolek, B.W., Grove, G.W., Katzner, T.E., 2021b. Yearly temperature fluctuations and observer speed drive counts of wintering raptors during road surveys. Ibis 163, 593–606. https://doi.org/10.1111/ibi.12914.

McClure, C.J.W., Dunn, L., Buechley, E.R., Juergens, P., Oleyar, D., Goodrich, L.J., Therrien, J.-F., 2022. Conservation assessment of raptors within the USA and Canada. Biol. Conserv. 272, 109633.

Meehan, T.D., Saunders, S.P., DeLuca, W.V., Michel, N.L., Grand, J., Deppe, J.L., Jimenez, M.F., Knight, E.J., Seavy, N.E., Smith, M.A., Taylor, L., Witko, C., Akresh, M.E., Barber, D.R., Bayne, E.M., Beasley, J.C., Belant, J.L., Bierregaard, R.O., Bildstein, K.L., Boves, T.J., Brzorad, J.N., Campbell, S.P., Celis-Murillo, A.H.A.C., Domenech, R., Goodrich, L., Gow, E.A., Haines, A., Hallworth, M.T., Hill, J.M., Holland, A.E., Jennings, S., Kays, R., King, D.T., Mackenzie, S.A., Marra, P.P., McCabe, R.A., McFarland, K.P., McGrady, M.J., Melcer, R., Norris, D.R., Norvell, R. E., Rhodes, O.E., Rimmer, C.C., Scarpignato, A.L., Shreading, A., Watson, J.L., Wilsey, C.B., 2022. Integrating data types to estimate spatial patterns of avian migration across the Western hemisphere. Ecol. Appl. 32, e2679 https://doi.org/10.1002/eap.2679.

Miller, R.A., Paprocki, N., Stuber, M.J., Moulton, C.E., Carlisle, J.D., 2016. Short-eared owl (Asio flammeus) surveys in the North American intermountain west: utilizing citizen scientists to conduct monitoring across a broad geographic scale. Avian Conserv. Ecol. 11 (1), 3. https://doi.org/10.5751/ace-00819-110103.

Miller, R.A., Carlisle, J.D., Barnes, J.G., Haley, R.D., Jeffress, M.R., 2019. Winter distributions and habitat associations of raptors across Nevada. Western Birds 50, 114–141. https://doi.org/10.21199/WB50.3.1.

Nichols, J.D., Williams, B.K., 2006. Monitoring for conservation. Trends Ecol. Evol. 21, 668–673.

Ogada, D., Shaw, P., Beyers, R.L., Buij, R., Murn, C., Thiollay, J.M., Beale, C.M., Holdo, R. M., Pomeroy, D., Baker, N., Krüger, S.C., Botha, A., Virani, M.Z., Monadjem, A., Sinclair, A.R.E., 2016. Another continental vulture crisis: Africa's vultures collapsing toward extinction. Conserv. Lett. 9, 89–97. https://doi.org/10.1111/conl.12182.

Ogada, D., Virani, M.Z., Thiollay, J.M., Kendall, C.J., Thomsett, S., Odino, M., Kapila, S., Patel, T., Wairasho, P., Dunn, L., Shaw, P., 2022. Evidence of widespread declines in Kenya's raptor populations over a 40-year period. Biol. Conserv. 266, 109361 https://doi.org/10.1016/j.biocon.2021.109361.

Pacifici, K., Reich, B.J., Miller, D.A.W., Pease, B.S., 2019. Resolving misaligned spatial data with integrated species distribution models. Ecology 100, 1–15. https://doi.org/10.1002/ecy.2709.

Pain, D.J., Bowden, C.G.R., Cunningham, A.A., Cuthbert, R., Das, D., Gilbert, M., Jakati, R.D., Jhala, Y., Khan, A.A., Naidoo, V., Lindsay Oaks, J., Parry-Jones, J., Prakash, V., Rahmani, A., Ranade, S.P., Sagar Baral, H., Ram Senacha, K., Saravanan, S., Shah, N., Swan, G., Swarup, D., Taggart, M.A., Watson, R.T., Virani, M.Z., Wolter, K., Green, R.E., 2008. The race to prevent the extinction of south Asian vultures. Bird Conserv. Int. 18, S30–S48. https://doi.org/10.1017/s0959270908000324.

Plummer, M., 2003. JAGS: A Program for Analysis of Bayesian Graphical Models Using Gibbs Sampling.

Postupalsky, S., 1978. The bald eagle returns. Nat. Hist. 87, 62–63.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. Vienna. Austria.

Rosenberg, K.V., Dokter, A.M., Blancher, P.J., Sauer, J.R., Smith, A.C., Smith, P.A., Stanton, J.C., Panjabi, A., Helft, L., Parr, M., Marra, P.P., 2019. Decline of the North American avifauna. Science 366, 120–124. https://doi.org/10.1126/science. aaw1313.

Sauer, J.R., Link, W.A., Hines, J.E., 2020. The North American Breeding Bird Survey, Analysis Results 1966 - 2019: U.S. Geological Survey Data Release. https://doi.org/10.5066/P96A7675 [WWW Document].

Schielzeth, H., 2010. Simple means to improve the interpretability of regression coefficients. Methods Ecol. Evol. 1, 103–113. https://doi.org/10.1111/j.2041-210X.2010.00012.x.

Smallwood, J.A., Causey, M.F., Mossop, D.H., Klucsarits, J.R., Robertson, B., Robertson, S., Mason, J., Maurer, M.J., Melvin, R.J., Dawson, R.D., 2009. Why are american kestrel (Falco sparverius) populations declining in North America? Evidence from nest-box programs. J. Raptor Res. 43, 274–282.

Smith, N.R., Hess, T.J., Afton, A.D., 2016. History and nesting population of bald eagles in Louisiana. Southeast. Nat. 15, 12–25. https://doi.org/10.1656/058.015.0102.

Watts, B.D., Therres, G.D., Byrd, M.A., 2008. Recovery of the Chesapeake Bay bald eagle nesting population. J. Wildl. Manag. 75, 152–158.

Wiens, J.A., 1984. The place of long-term studies in ornithology. Auk 101, 202–203.

Woinarski, J.C.Z., Garnett, S.T., Legge, S.M., Lindenmayer, D.B., 2017. The contribution of policy, law, management, research, and advocacy failings to the recent extinctions of three Australian vertebrate species. Conserv. Biol. 31, 13–23. https://doi.org/10.1111/cobi.12852.

Zipkin, E.F., Zylstra, E.R., Wright, A.D., Saunders, S.P., Finley, A.O., Dietze, M.C., Itter, M.S., Tingley, M.W., 2021. Addressing data integration challenges to link ecological processes across scales. Front. Ecol. Environ. 19, 30–38. https://doi.org/10.1002/fee.2290.