Supporting Information. Daniel Fink, Tom Auer, Alison Johnston, Viviana Ruiz-Gutierrez, Wesley M. Hochachka, and Steve Kelling. 2020. Modeling avian full annual cycle distribution and population trends with citizen science data. *Ecological Applications.*

Appendix S5: Estimating Area of Occurrence

To estimate the Area of Occurrence (AOO) we tested the binary occupied versus unoccupied state for each week and prediction location using both the 2.8km and 25.2km spatial grids, described above. The resulting set of AOO values provides detailed information about the distributional range of a species and can be used to generate fine-scale range boundaries throughout the year.

At the base model level, a location was considered to be occupied if the predicted occurrence probability was above the kappa-maximized threshold for that base model. Aggregating across the ensemble, a location was considered to be occupied if at least 1/7 of base models predicted it was occupied. This is equivalent to an expert observer detecting the species at least once during 7 adjacent days of standardized surveys (estimated probability of detecting species per survey >= 1/7), taking account of the variation across base models. The un/occupied status was estimated for all weeks using both the 2.8km and 25.2km spatial grids, described above.

Formally, let $m_{s,k}$ be the estimated occurrence rate at spatiotemporal location s from base model k, $k = 1, \dots N_s$, and $Kappa_k$ be the kappa-maximized occurrence threshold for base model k, where N_s is the ensemble support, the number of overlapping base model estimates of location s. The indicator

$$Y_{s,k} = I(\, m_{s,k} > Kappa_k \,)$$

is used to estimate the binary occurrence for location s for base model k. The sum measures how frequently the site was estimated to be occupied, $S_s = \sum_k^{N_s} Y_{s,k}$. Using the fact that overlapping base models are trained using independent subsamples, we model $S_s \sim Binomial(N_s, \mu)$ where μ is the probability of detecting at least one individual of the species on a standardized survey. To infer if the location was occupied we conducted a binomial test $H_0\!: \mu < 1/7$. This testing value was motivated by the practical consideration that a site should be considered to be occupied by a species if an expert observer can detect the species at least once during 7 adjacent days of standardized surveys.

To estimate the AOO across each species' range for a given week often requires conducting these tests across a large number of locations. In order to identify as many occupied locations as possible while still maintaining a low false positive rate, we used False Discovery Rate (Benjamini & Hochberg 1995) thresholding to control for multiple comparisons. The q-value was set 0.01, limiting the expected proportion of falsely occupied locations to 1%. One benefit of this ensemble estimator of AOO is that it naturally adapts to regional and seasonal variation in species prevalence and detectability.

Literature Cited

Benjamini, Y., and Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society Series B, 57, 289–300. http://www.jstor.org/stable/2346101.