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Analysis and Summary of Christmas Bird Count Data

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Abstract – All large-scale surveys need to be better focused on environmental decision making, and statistical developments in recent years have aided this process through development of predictive models and by producing summaries of results to better inform us about the consequences of management (e.g., land use, pollution-abatement, etc.) decisions with regard to bird populations. We describe recently-developed analysis methods for the Christmas Bird Count, and explain how these approaches assist in summarizing the data and better integrating the survey into bird conservation activities. Hierarchical models, fit using Bayesian methods, provide estimates of population change that accommodate effort adjustments. Multispecies summaries of change can also be modeled hierarchically, resulting in state of the birds status summaries. Finally, integration of Christmas Bird Count data with North American Breeding Bird Survey data enhances the quality of estimation of change for North American birds.

INTRODUCTION

Modern conservation requires increasingly focused use of monitoring information. Bird population data are used to develop models that link bird populations to both controllable and uncontrollable features of the environment, and the models are then used to predict the consequences of natural and human-induced environmental changes on bird populations. For environmental features that we can manage, these models permit us to assess the consequences of alternative management activities and make optimal decisions based on our best understanding of the systems. Monitoring allows us to directly assess population status and response to management, and to evaluate the predictions of the models and increase our understanding of the systems (Nichols and Williams 2006). Evaluation of change in population status of species over time is also used as an overall index to system status, or state of the birds, which can also be used as a response variable for changes in the common environmental features (Gregory *et al*. 2005). We have been developing quantitative approaches for the analysis of Christmas Bird Count data (CBC, Butcher 1990), with the intent of more fully integrating the CBC into bird conservation activities. The CBC is the only extensive, long-term data set that provides information for wintering North American Birds, and development of procedures to estimate regional population change in wintering birds has been an important focus of research in recent years (e.g., Link *et al*. 2006). Hierarchical models presently used to analyze CBC data allow association of covariates with wintering bird abundance and population change (Sauer *et al*. 2004), as well as analysis of composite change for a collection of species (e.g., Sauer and Link 2002). These analyses extend traditional analyses of CBC data, and make the data more relevant for information needs of modern conservation. Here, we extend these analytical approaches to address two emerging uses of CBC data: 1) state of the birds summaries, and 2) composite analyses of CBC data with data from the North American Breeding Bird Survey (BBS, Sauer *et al*. 2003), a long term monitoring program based on point count routes conducted in early summer.

HIERARCHICAL MODELS FOR CHRISTMAS BIRD COUNT DATA

Started in 1900 at a single site in New York, USA, the survey has grown to become hemispheric in scope with over 2060 sites sampled in 2005-2006 (the 106th count). Sample units for the CBC are circular plots, 24.1 km in diameter, in which observers count birds over a single day selected within a count period near 25 December. Participation and organization varies greatly among circles, and selection of circle locations is not random, complicating inference from the CBC. See Sauer *et al*. (2004) for a summary of issues related to varying observer effort and circle location.

Analysis of the CBC is controversial: Sauer *et al*. (2004) described some of the limitations associated with nonrandomly-selected sites and indices that are poorly tied to underlying populations. There are also many issues associated with early-winter counts; distributions change yearly and on longer time scales, making population definitions vague. We have begun the process of evaluating the CBC by developing methods for controlling for changes in counting effort over time and space.

Link *et al*. (2006) proposed analyzing CBC data using a hierarchical log-linear model that assumes that counts follow an overdispersed Poisson distribution:

$$\log(\lambda_{i,j,t}) = S_i + \beta_i (t - t^*) + \omega_j + \gamma_{i,t} + B_i (\xi_{i,j,t}\, p_i - 1)/p_i + \varepsilon_{i,j,t} ,$$

where the log of the expected count is a linear function of a stratum-specific intercept (S_i), a stratum-specific slope (β_i) indexed by year minus a base year t^* ($t - t^*$), circle effects (ω_j), year effects ($\gamma_{i,t}$), effort adjustment and its coefficient B_i ($\xi_{i,j,t}\, p_i - 1)/p_i$, and overdispersion ($\varepsilon_{i,j,t}$). This model contains effort (number of party-hours) taken to the power (p_i), along with a coefficient to assess the weight of the effort adjustment. The exponent p_i defines the shape of the relationship of counts to effort, and B defines the strength of the relationship. The form of the effort adjustment allows a logarithmic adjustment as p approaches 0, and effort is scaled to the mean effort. Annual indices are defined as exponentiated model components:

$$n_{i,t} = z_i \exp\left(S_i + \beta_i (t\text{-}t^*) + \gamma_{i,t} + 0.5^*(V(\omega) + V(\varepsilon))\right)$$

where z_i is a scaling factor introduced to accommodate the proportion of circles in the region on which the species was not observed, and variances are added so that the mean rather than the median of the counts is the quantity estimated. Annual indices for groups of strata are defined as area-weighted regional estimates. Interval-specific population change (trend) from times t_a to t_b is estimated as:

$$B_i = \left\{ \frac{n_{i,\,t_b}}{n_{i,\,t_a}} \right\}^{\frac{1}{t_b - t_a}}$$

We fit this model using Bayesian methods, in which we treat all the quantities as random variables, make distributional assumptions about the variable (i.e., define their prior distributions and likelihoods), and use Markov-chain Monte Carlo (MCMC) methods to simulate the posterior distributions (Spiegelhalter *et al*. 1999). Inference is then based on the posterior distributions, and means and credible intervals are estimated from the simulated results. We treat year, stratum, and circle effects as normal random variables with mean 0, and use standard vague priors to conduct an objective Bayesian analysis. In fitting this model, we use a 10,000 iteration "burn-in" period to permit time for the estimates to become stationary, and evaluate stationarity of results through visual observation of autocorrelation in replicates.

Using strata in the analysis partially accommodates spatial deficiencies in the sample design, as large regional differences occur in the number and consistency of samples. We use Bird Conservation Regions (BCRs) as fundamental strata for analysis, as these regions are consistent with patterns of vegetation and climate associated with bird distributions (Sauer *et al*. 2004).

SUMMARY OF RESULTS: STATE OF THE BIRDS ANALYSES

We have fit the model to more than 500 species, and are using the information to address specific conservation questions associated with individual species (Link *et al*. 2006) and groups of species (Niven *et al*. 2004). Although the CBC results often reflect patterns displayed in BBS results (Dunn and Sauer 1997), we acknowledge concerns that CBC patterns can be influenced by distributional changes associated with climate change and other issues. Interpretation of CBC data requires an understanding of species natural history, and evaluation of species-specific concerns forms an important part of any summary of the data.

One analysis suggested by Gregory *et al*. (2005) with European data has been state of the bird summaries, in which a group of birds species is selected to reflect some common environmental dependency (e.g. dependence on a specific habitat for breeding), and a common trajectory of population change is estimated for these species that can be used both to evaluate the common status of these species and to reflect changes in the underlying environmental feature. Although the usefulness of these state of the birds summaries as environmental indicators remains to be fully evaluated, the analyses form a convenient summary of common change for groups of species. State of the bird summaries can be defined in terms of a hierarchical model for summary of trends described in Sauer and Link (2002). We provide hereafter a brief summary of the approach.

Hierarchical model for state of the birds - For each spe-

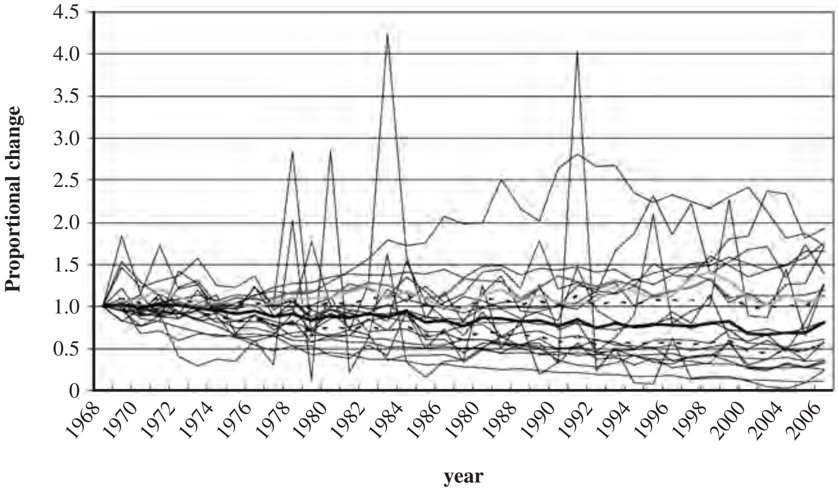

Figure 1. Population year effects for 20 North American grassland-breeding species, scaled to show proportional change, as estimated from CBC data. We do not identify individual species trajectories in the Figure; see Table 1 for a summary of overall change by species. Thicker line and dashed lines show the median of the posterior distributions of the estimated mean of the change for the collection of species, and 2.5% and 97.5% credible intervals.

cies in the collection, we first estimate trend from year 1 to years 2,..., N. The quantity of interest is the total change over the interval, which is estimated by the ratio $n_{i,t}$ / $n_{i,1}$. This quantity is estimated from the population change model for each species. Then we used modified version of the hierarchical model of Sauer and Link (2002) to estimate the mean rate of change across species over years 1 through y, with $y = 2, 3,..., N$. The logarithm of each rate of change is assumed to be normally distributed with a species-specific mean and variance (Gregory *et al*. 2005). See Sauer and Link (2002) for a detailed technical description of the yearly summary procedure; the analysis described here differs from their account in that total change over an interval (rather than yearly change) is the quantity that is summarized, and here the logarithm of the species-specific trend is treated as a normally-distributed random variable. Composite estimate of change for the collection of species is estimated as the exponentiated hierarchical mean of the log-species trends.

We apply this approach to estimate a composite summary of changes for a collection of 20 species of North American grassland birds (Fig. 1), as estimated from CBC data. We used the hierarchical model described above to estimate annual indices of abundance for each species at the continental scale, then estimated total change by year to construct scaled population changes from the base year (Fig. 1). Note that over the considered interval 1968-2006 the trajectories varied greatly among species, from estimated declines of almost 90% for Chestnut-collared Longspur *Calcarius ornatus* to estimated increases of 91% from Henslow's Sparrow *Ammodramus henslowii* (Table 1). Patterns of population change over time also varied among species (Fig. 1).

We applied the hierarchical model to estimate the posterior distribution of the mean of the log transformed yearly total changes for each species. We used program BUGS (Spiegelhalter *et al*. 1999), used a "burn-in" period of 30,000 iterations to allow the Markov chain to reach a stationary state, then based the inference on 20,000 additional iterations. The median of the posterior distributions of the estimates, presented with 2.5% and 97.5% credible intervals, indicate a general declining status of this group of species, with an increase in the final year (Fig. 1). This summary measure of population change for the collection of species appears to provide a useful summary of the original species data (Fig. 1), and the credible intervals seem quite precise, given the variable nature of the original surveys.

COMBINING CBC DATA WITH BBS DATA TO DERIVE A COMPOSITE ANALYSIS OF POPULATION CHANGE OF NORTH AMERICAN BIRDS

Because the CBC monitors change in wintering populations, it has a clear use associated with modeling and evaluation of changes associated with regional wintering populations. This information, both for modeling individual species and for assessing overall status of species groups,

Table 1. Estimated total population changes (total percentage change, along with a 95 % credible interval based on a hierarchical model), 1968-2006, for 20 species from the Christmas Bird Count.

Species	**Total Change** (%)	**95% CI**
Northern Harrier *Circus cyaneus*	11.76	(1.32, 23.72)
Ferruginous Hawk *Buteo regalis*	73.81	(27.09,128.43)
American Kestrel *Falco sparverius*	19.6	(11.84, 28.55)
Prairie Falcon *Falco mexicanus*	65.93	(42.07, 97.28)
Ring-necked Pheasant *Phasianus colchicus*	-40.62	(-57.87,-20.13)
Sharp-tailed Grouse *Tympanuchus phasianellus*	25.84	(-68.58,202.43)
Greater Prairie-Chicken *Tympanuchus cupido*	-40.14	(-91.45,408.14)
Barn Owl *Tyto alba*	71.94	(34.50,120.72)
Short-eared Owl *Asio flammeus*	-66.74	(-76.60,-53.43)
Horned Lark *Eremophila alpestris*	-64.5	(-80.04,-45.98)
Sprague's Pipit *Anthus spragueii*	-44.23	(-72.60, 57.00)
Cassin's Sparrow *Aimophila cassinii*	26.93	(-51.28,226.47)
Vesper Sparrow *Pooecetes gramineus*	-18.25	(-50.22, 37.40)
Lark Bunting *Calamospiza melanocorys*	-76.33	(-96.19, 21.52)
Savannah Sparrow *Passerculus sandwichensis*	76.57	(41.50,119.44)
Grasshopper Sparrow *Ammodramus savannarum*	40.12	(-25.63,150.46)
Henslow's Sparrow *Ammodramus henslowii*	91.09	(-21.88,319.66)
Chestnut-collared Longspur *Calcarius ornatus*	-88.28	(-98.26,-27.48)
Eastern Meadowlark *Sturnella magna*	-74.71	(-79.49,-69.11)
Western Meadowlark *Sturnella neglecta*	-64.02	(-72.20,-54.06)

provides input to regional conservation planning but also plays a critical role in evaluating range-wide issues such as global changes that influence continental-scale populations. However, aggregation of CBC data with additional information, such as breeding-season data from the BBS, provides an opportunity to both strengthen inference with additional data and to estimate additional parameters associated with seasonal population change. This aggregation is complicated by technical and logistical issues. In particular:

1. Sampled populations differ between surveys, and often the target population is not covered by either survey. Neither the BBS or the CBC provides range-wide estimates of change for most species, as the BBS does not cover boreal regions and the CBC does not cover tropical regions. Consequently, for migratory species, each survey could cover different proportions of the species range, and the actual overlap of species coverage between the surveys is unknown.

2. Surveys are offset by 6 months. Two complications must be considered in aggregating results from the surveys: (i) for migratory species, population changes between summer and fall are confounded with changes in the populations that are sampled; (ii) even for nonmigratory species in which both surveys provide data for comparable regions, the count data collected in both surveys are both indices of the actual population. Analyses that control for factors influencing detectability tend to adjust the survey indices to be internally consistent, to permit estimation of temporal or spatial change, but differences in the baseline abundance indices between surveys cannot be estimated.

Two approaches have been considered for aggregate analysis of BBS and CBC data. One of these approaches is focused on composite summary of long-term trend estimation, while the other provides composite annual indices of abundance and permits evaluation of seasonal components of population change.

Composite summary of long-term trends - Because the CBC and the BBS include differing portions of breeding and wintering ranges of species, we have used proportion of range covered by each survey as weights in aggregation of long-term (i.e., 40 year) trend estimates from the surveys. The use of the long-term trend estimates in the analysis reduces difficulties associated with seasonal differences, as the effects of the 0.5 year differences on the edge is small in a long-term analysis. Estimates from each survey can also be weighted by estimated precisions. For example, the CBC covers 70.2% of the Loggerhead shrike *Lanius ludovicianus* winter range, and the BBS covers 84.3

% of the shrike breeding range. The CBC trend, over the 40 year interval ending the 2004, is -2.3 %/yr (-2.6,-2.0), while the BBS trend, for 40 years ending in 2005, is -3.7 %/yr (-4.4, -3.0). The combined estimate using area and precision weights is -3.07 %/yr (-3.5, -2.7). This approach, while limited to interval summaries in which the seasonal differences in survey timing are unlikely to be an important consideration, accommodates differences in survey coverage of the target population and precision of estimates. It also uses trend estimates based on statistical models that control for effort and observer effects in the surveys.

Composite hierarchical model analysis of BBS and CBC data - Link and Sauer (2007) and Link *et al*. (2008) propose an approach for composite summary of BBS and CBC population change for species that are nonmigratory. For these species, changes from year to year, when properly controlled for factors influencing detectability of counts, represent (on the log scale) the sum of seasonal changes for winter/spring (January to June, W_{y+1}) and summer/autumn (July to December, S_{y+1}),

$$\mu^{CBC}_{y+1} = \mu^{CBC}_{y} + W_{y+1} + S_{y+1}$$

$$\mu^{BBS}_{y+1} = \mu^{BBS}_{y} + S_{y} + W_{y+1}$$

Unfortunately, a consequence of our inability to define the difference in baseline abundances between surveys is that W and S are not directly estimable. However, we can estimate the relative magnitude of the W's and S's, and we can also estimate the relative variation in W and S, as

$$P_s = \frac{\sigma^2_s(W)}{\sigma^2_s(W) + \sigma^2_s(S)}$$

See Link and Sauer (2007) and Link *et al*. (2008) for details of model fitting. In Link *et al* (2008), we provide an example of the composite analysis for Northern Bobwhite *Colinus virginianus*. The composite analysis shows that bobwhite were declining over the interval 1966 – 2002 with a rate -3.56 %/yr (-3.8, -3.32), and most of the variation in population change occurred in winter (P_s = 0.747, SE = 0.162).

DISCUSSION

The CBC contributes to our understanding of distribution changes, area-specific population change, and environmental associations of abundance and change in wintering birds. Hierarchical models applied to CBC data provide a variety of opportunities for (**1**) better controlling for nuisance variables such as effort in the analysis to lessen the extent of bias in estimates from the survey; (**2**) implementing estimation of change at a variety of geographic scales; (**3**) combining change estimates for collections of species; and (**4**) incorporating additional information on change from other surveys to increase precision of estimates and better use information from species breeding and wintering ranges. Using statistical models similar to those described in this paper, we are implementing analyses designed to evaluate the consequences of changing weather, habitat, and other large-scale environmental effects on bird populations. We are also more fully exploiting the CBC as a data source for bird conservation, both in assessing bird population status in conjunction with the BBS and in developing models that allow us to predict the effects of habitat change on wintering bird populations.

Managers are now starting to use these results to enhance management of wintering birds. We expect the value of the CBC survey to increase as methods are developed and implemented to better integrate winter survey data with breeding season survey data.

Of course, it is important to view any ongoing survey with a critical eye. Due to its ad-hoc development and primary historical focus as a recreational event for bird watchers, the CBC is particularly vulnerable to criticisms of inappropriate site selection and of the influence of additional uncontrolled effort effects. A recent review of the CBC highlighted these constraints, and attempted to identify reasonable approaches to mitigating them (Francis *et al*. 2004). One important outcome of this review is the recognition of the model-based nature of CBC analyses. Although marginal improvements can be made by better recording effort and partitioning sampling effort within the CBC circles, the need will always exist to control for effort and other factors influencing the counting process. Improvements in statistical models that implement these controls, in conjunction with on-the-ground methodological innovations, allow better recording of information at local scales, will make the CBC are more reliable source of information on bird population change.

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