

# Density estimation in wildlife surveys

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and C. John Ralph*

**Abstract** Several authors have recently discussed the problems with using index methods to estimate trends in population size. Some have expressed the view that index methods should virtually never be used. Others have responded by defending index methods and questioning whether better alternatives exist. We suggest that index methods are often a cost-effective component of valid wildlife monitoring but that double-sampling or another procedure that corrects for bias or establishes bounds on bias is essential. The common assertion that index methods require constant detection rates for trend estimation is mathematically incorrect; the requirement is no long-term trend in detection "ratios" (index result/parameter of interest), a requirement that is probably approximately met by many well-designed index surveys. We urge that more attention be given to defining bird density rigorously and in ways useful to managers. Once this is done, 4 sources of bias in density estimates may be distinguished: coverage, closure, surplus birds, and detection rates. Distance, double-observer, and removal methods do not reduce bias due to coverage, closure, or surplus birds. These methods may yield unbiased estimates of the number of birds present at the time of the survey, but only if their required assumptions are met, which we doubt occurs very often in practice. Double-sampling, in contrast, produces unbiased density estimates if the plots are randomly selected and estimates on the intensive surveys are unbiased. More work is needed, however, to determine the feasibility of double-sampling in different populations and habitats. We believe the tension that has developed over appropriate survey methods can best be resolved through increased appreciation of the mathematical aspects of indices, especially the effects of bias, and through studies in which candidate methods are evaluated against known numbers determined through intensive surveys.

**Key words** bias, density estimation, distance methods, double-observer, double-sampling, estimation, indices, surveys, trends

Anderson (2001, 2003) recently called attention to the limitations of using index methods to estimate population trends and recommended that density-estimation methods be used instead. These comments have initiated a constructive dialogue providing different perspectives on the use of indices and density estimates to monitor bird populations (Ellingson and Lukacs 2003; Hutto and Young 2002, 2003). Anderson and others (Rosenstock et al. 2002, Diefenback et al. 2003,

Norvell et al. 2003) also have suggested that alternate methods usually are available to provide reliable, inexpensive density estimates and that index methods should therefore seldom be used.

We believe the emphasis, in designing trend-estimation surveys, should be on providing the most accurate estimates possible with available resources. Accuracy of the trend estimate may be defined as the mean square error of the estimate (Cochran 1977) or by calculating power using an

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expression that acknowledges potential bias (Bart et al. 2004). In either case, accuracy includes both bias and variance (Levy and Lemeshow 1991), so a biased estimator may be more accurate than an unbiased one if the biased estimator has smaller variance. Thus, pointing out that indices are often biased is not sufficient grounds for claiming that they are necessarily less accurate than surveys that estimate density. Furthermore, we believe that bird density seldom can be estimated without bias and that trend estimates based on these surveys may also have significant bias. Choosing between index methods, and methods that estimate density, thus requires consideration of the variance and potential bias inherent in both approaches.

We believe that double-sampling provides a general approach for investigating how to allocate resources between variance reduction and bias reduction. As Anderson (2001:1296) pointed out, “double-sampling has been used in many biological fields for decades to provide a rigorous means of making valid estimates of population parameters based on empirical relationships between index values and estimates of actual parameter values.” In this commentary, we discuss ways to maximize the accuracy of bird surveys using a double-sampling approach. We emphasize bias and ways to reduce it. Specifically, we clarify the mathematical conditions in which bias occurs, propose a classification of sources of bias in bird surveys, discuss ways of minimizing each source of bias including recently proposed methods, and conclude by re-emphasizing the need to devote more resources to estimating and reducing bias as Anderson and others have recommended.

### Defining the parameter

Defining the population parameter is an important component of study design. Each population parameter and sampling plan has potential sources of bias, and the nuances of how particular survey methods measure a parameter can significantly influence the bias. Additionally, the relationship between the measured parameter and the goal of estimating total population size requires serious consideration. For example, estimating the number of territorial birds provides no information on the nonbreeding component of the population. A long-term change in the proportion of nonbreeders would cause bias in estimates of change in total population size if only territorial birds were surveyed.

The definition of number of birds “in” a plot should ensure that summing the number of birds across all possible plots yields population size. Failure to do this makes it nearly impossible to decide whether a method yields unbiased estimates of density. A rule must be adopted that assigns each bird in the population to exactly 1 plot. We refer below to the number of birds assigned to a plot as the number of “resident birds.” Different assignment rules may be used, depending on the natural history traits of the species and logistic constraints. For example, if the number of nonbreeders is negligible, the number of resident birds might be defined as the number of territorial males, and their mates, whose first nest of the season, or territory centroid for non-nesters, is within the plot. Alternatively, birds could be assigned on the basis of singing locations, with the assignment rule based on the centroid of all singing perches used during the breeding season. Either definition satisfies the requirement that summing the number of resident birds across all plots in the study area yields population size. In contrast, defining the number of resident birds as those that are present at the time of a single visit to the plot meets the same requirement only if all birds that breed in the study area are present during every survey. In most studies, some birds are not yet present or have already left the study area when some surveys are conducted.

### The requirement for unbiased trend estimates

Writers criticizing indices (e.g., Nichols et al. 2000; Anderson 2001, 2003) frequently assert that indices cannot be reliable because they require the assumption of constant detection rates. This assumption, however, is not necessary for estimating population change. Indices are unbiased if there is no long-term (i.e., non-zero) trend in the “index ratio” (Bart et al. 1998), defined as the ratio (survey result)/(parameter of interest). Even sizable variation in detection rates between observers, weather conditions, and other factors does not necessarily produce bias in trend estimates, although large variation reduces precision of population change estimates. This point can be demonstrated mathematically (Bart et al. 1998) but also is intuitive. For example, suppose the only potential source of bias is that observers do not detect all birds present and that the population is stable. If there is no long-term trend in observer ability, then

the expected trend in sample results will also be zero regardless of how much ability varies among observers. Thus, the trend estimate will be unbiased. Often accepting a small amount of bias can result in a more accurate estimate if the variance is smaller than the variance of alternate estimators for the available resources.

## Bias in estimating density

### *Sources of bias*

Some authors (Nichols et al. 2000, Farnsworth et al. 2002, Rosenstock et al. 2002) argue that rapid inexpensive methods exist to estimate bird density, but we believe that density estimation for breeding birds actually is very difficult in most studies. Four sources of bias in density estimation may be distinguished (Table 1): coverage, closure, surplus birds, and detection rates. Coverage refers to how completely the sampling frame covers the population of interest. Closure refers to how many of the target birds are in the study area during the study period. Surplus birds are birds in the study area during the study period that we do not wish to include in the count—for example, because they are migrants. The detection rate is the ratio (number of target birds recorded on the survey or estimated to be present from the survey)/(number of target birds in the surveyed area at the time of the survey). Incomplete coverage or closure, surplus birds, and detection rates <1 all result in the survey being an index rather than yielding an unbiased estimate of density. Long-term trends in any of these quantities

cause bias in the trend estimate unless the effect on numbers recorded is just balanced by long-term changes in one of the other sources of bias.

### *Reducing bias due to incomplete coverage*

In virtually every landscape, some places are inaccessible. Thus, differences between the sampled population and the population of interest are the rule, not the exception, even in the most carefully designed studies. Intensive capture–recapture studies often are conducted near roads in protected areas to provide access for multiple observations and to assure continuity of the data. Extensive surveys often are conducted along roads to permit observations to be spread over large areas and to avoid issues of access to private property. In both situations bias equals the difference between the trend in the area sampled and the regionwide trend.

The best approach for reducing bias due to incomplete coverage is probably to develop habitat-based models to extrapolate from the surveyed to the nonsurveyed areas. If a small probability sample from the nonsurveyed area can be obtained, the effect of restricting the sample to part of the population of interest can be assessed.

### *Reducing bias due to closure, surplus birds, and detection rates*

Double-sampling (Cochran 1977, Anderson 2001, Bart and Earnst 2002) provides a general approach for reducing sources of bias other than incomplete coverage. In double-sampling a large sample is surveyed with a rapid method and a subsample is surveyed intensively to obtain

correction factors for the rapid survey. Several methods might be used to determine the number of birds resident on the intensively surveyed plots. For example, if most nests on the subsample of plots can be found, nests can be used to assign birds to plots, and double-observer or removal methods can be used to estimate the number of nests that are not found.

Double-sampling yields unbiased estimates if the rapid and intensive plots

Table 1. Effects on sources of bias of landbird survey methods. XXX indicates that the method eliminates the indicated source of bias if the assumptions are met.

Method	Source of bias: change in			
	coverage <sup>a</sup>	closure <sup>b</sup>	surplus birds <sup>c</sup>	detection rates <sup>d</sup>
A. Design and analysis				
Sampled population	XXX			
Habitat-based models	XXX			
Double sampling		XXX	XXX	XXX
B. Field method				
Unadjusted point counts				
Distance methods				XXX
Double observer methods				XXX
Removal methods				XXX

<sup>a</sup> Proportion of the population of interest covered by the sampled population

<sup>b</sup> Proportion of the target birds present in the study area throughout the study period

<sup>c</sup> Birds not part of the target population (e.g., because they breed north of the study area) that are in the study area for some of the study period

<sup>d</sup> Proportion of the target birds, present on the plots when they are surveyed, that are recorded on the survey

are selected using well-defined random sampling plans and if the surveys on intensive plots yield unbiased estimates of density. No assumption is needed concerning the consistency of detection rates or that intensive surveys yield exact counts (they just have to be unbiased). Double-sampling has several other advantages: 1) the rapid method can change as new methods become available; 2) domains can be compared even if detection rates differ (although separate estimates have to be made of detection rates in each domain); and 3) valuable ancillary information (e.g., nest success) can be obtained on intensive plots with little additional effort.

Double-sampling has been used successfully in many different environments and on many different species (waterfowl in the prairie pothole region, Smith 1995; shorebirds in the arctic, Bart and Earnst 2004; landbirds in riparian areas, Earnst and Heltzel 2004). The applicability of double-sampling needs more investigation, however. For example, obtaining unbiased estimates may be impossible in structurally diverse or dense habitats and may be difficult for wide-ranging species because large plots would be required.

#### *Distance, double-observer, and removal methods*

Several methods have been suggested to estimate detection rates, and their proponents argue that they are easy and reliable (Nichols et al. 2000, Farnsworth et al. 2002, Rosenstock et al. 2002). These methods, however, do not address bias due to coverage, closure, or surplus birds. Asserting that these methods yield unbiased estimates of density thus amounts to asserting that the sampled population and population of interest are congruent, that all resident birds are present during all surveys, and that no surplus birds are recorded. We know of no cases in which these assumptions are necessarily true, and urge that the assumptions be tested through double-sampling or other intensive methods.

Even if coverage, closure, and surplus birds are not problematic, distance, double-observer, and removal methods require assumptions that we believe are seldom realistic in bird surveys. For distance methods (Buckland et al. 2001), the key assumptions are that survey locations are randomly selected, that all birds at zero distance are detected, that birds do not move in response to the surveyor prior to being detected, and that the distances and bearings to the birds are measured accurately. All of

these assumptions are violated to some degree in most bird surveys using this method. Many surveys are conducted along roads, dikes, trails, or at other nonrandom locations. Habitat close to these locations is often not representative of the study region. When this is true, use of distance methods may produce seriously biased estimates of density. In most habitats birds initially at distance zero may move away from the observer before they are detected, while in closed habitats some birds are not detected because they do not sing and remain hidden in the dense vegetation. While bird species respond differently to the presence of humans within their habitats (see summary in Verner 1985), the few examples of birds not responding to people (e.g. certain seabirds nesting on remote islands) are the exceptions. Accurate distance estimation is difficult when neither the bird nor its location can be seen, which is common in many surveys. Training can help, but the volume of sound produced by a singing bird and reaching a surveyor, depends on site-specific characteristics including vegetation density and terrain, and these characteristics can vary substantially across most surveys. Thus, training in one or a few locations may lead to fairly accurate distance estimation at those sites, but may not lead to accurate distance estimation at other sites. Estimates of angles to unseen birds from a single location are usually accompanied by significant error (Lefebvre and Poulin 2003), which also can cause bias in distance estimates to individual birds and the resultant density estimates. Another difficulty with distance methods is that 70–100 or more observations are needed for accurate density estimation (Buckland et al. 2001; Ellingson and Lukacs 2003; and Hutto and Young 2002, 2003), but many species will not meet these sample-size requirements, especially the rare species that may be of greatest conservation concern.

Double-observer methods (Nichols et al. 2000) use counts from 2 surveyors to estimate the number of birds that each observer failed to detect. Even if the method's assumptions are met, it only estimates the number of "detectable" birds. In most studies many birds (e.g., birds on nests) are neither visible nor vocalize during a survey and are thus undetectable as if they were not present on the plot. Furthermore, the method requires the assumption that birds are equally detectable whereas in fact some (e.g., distant) birds are much harder to detect. Thus, in practice the method does not usually provide unbiased estimates of the number of detectable

birds. The method also reduces the sample size by 50% compared to each observer surveying alone with an attendant increase in sampling error.

The removal method (Farnsworth et al. 2002) requires that the detection rates for a species are constant within the survey period. This assumption is seriously violated if most detections are made using auditory cues. Many biotic and abiotic factors influence singing rates (Verner 1985). Most birds tend to sing in bouts, frequently in response to similar behavior by their neighbors, with intervening periods during which there is little if any song. Detection rates are thus much higher during bouts than at other times, rather than being constant as required by the removal method. Hence, this method will rarely yield unbiased estimates of how many birds are present unless birds do not sing in bouts.

In summary, the distance, double-observer, and removal methods do not reduce bias due to incomplete coverage, closure, or surplus birds, problems that are potentially serious in many surveys. Furthermore, they require assumptions that are seriously violated in most bird surveys; thus, they do not necessarily yield unbiased estimates of how many birds were on the plots during the surveys. It sometimes has been argued, in response to the concerns above, that even if the estimates produced by these methods are biased, they probably yield a better index than uncorrected counts. This claim is debatable, but does not address Anderson's original contention.

### *Resolution*

As indicated above, we believe that single-visit surveys seldom provide essentially unbiased estimates of resident bird density. Despite this view, however, we believe that the survey methods discussed above can be useful as the rapid method in a double-sampling context to provide accurate estimates of wildlife populations. For example, detection rates may vary between habitats or be affected by long-term changes in habitat. These differences do not cause bias in double-sampling estimates but may increase sampling error. Distance, double-observer, or removal methods could reduce this sampling error.

We also believe that debates about landbird survey methods have continued long enough without empirical investigations. Resolution to these debates will occur only by conducting a series of studies in which very intensive methods (e.g., employing banding and nest-finding) are used to determine numbers actually present and then candidate methods are used by independent surveyors to estimate the num-

ber present. Such studies will reveal the magnitude of bias due to closure, surplus birds, and detection rates and the need for a double-sampling approach. They also will reveal how best to carry out the intensive surveys in a double-sampling approach.

### **Habitat and distribution studies**

This commentary pertains to estimating long-term trends in population size. We should point out that none of the methods we discuss, including double-sampling, provides a very useful approach for habitat or distribution studies. The reason is that such studies generally make inferences about many different habitats or locations. For example, consider the regression equation,  $\text{bird density} = b_0 + b_1X_1 + b_2X_2 + \dots$ , where the  $b$ s are regression coefficients and the  $X$ s are habitat measures such as canopy cover and height or location measures such as elevation or aspect. Estimating detection rates separately for all combinations of the independent variables is impossible, and estimating an overall detection rate has no effect on the predicted relative densities in different habitats or areas. Investigators should design habitat studies to reduce variation in detection rates by training and choice of survey methods. More importantly, they should recognize that variation in detection rates might confound their results and follow up the most interesting conclusions with intensive studies.

### **Conclusion**

We emphasize that sampled populations should include as much of the population of interest as is practical, that well-defined sampling plans should be used, and that if index methods are used, they should be corrected for bias. More generally, potential bias should be carefully evaluated during survey design by using an expression for power that incorporates potential bias (Bart et al. 2004). Improving the accuracy of the estimates, not just eliminating bias, should be the objective. We suggest that index methods are often a cost-effective component of valid wildlife monitoring, but that double-sampling or another procedure that corrects bias or establishes bounds on bias is essential. Evaluation of this issue usually will show that surveys will be inconclusive unless it can be argued convincingly that the index ratio (survey result/population size) has not changed by more than 15–20% during the survey period. We disagree with the claim that relatively easy methods exist to obtain essentially unbiased estimates of bird density, especially when density is

defined carefully and in a manner appropriate for managers. Double-sampling probably has the best chance of yielding essentially unbiased estimates of density for many species, though it will probably not be suitable in all cases. In general, much more attention should be given to scrutinizing assumptions required at all stages of the estimation process.

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*Associate editor:* Krausman