The Auk 119(1):36–45, 2002

DOUBLE SAMPLING TO ESTIMATE DENSITY AND POPULATION TRENDS IN BIRDS

JONATHAN BART[1] AND SUSAN EARNST
U.S. Geological Survey Forest and Rangeland Ecosystem Science Center, Snake River Field Station, 970 Lusk Street, Boise, Idaho 83706, USA

ABSTRACT.—We present a method for estimating density of nesting birds based on double sampling. The approach involves surveying a large sample of plots using a rapid method such as uncorrected point counts, variable circular plot counts, or the recently suggested double-observer method. A subsample of those plots is also surveyed using intensive methods to determine actual density. The ratio of the mean count on those plots (using the rapid method) to the mean actual density (as determined by the intensive searches) is used to adjust results from the rapid method. The approach works well when results from the rapid method are highly correlated with actual density. We illustrate the method with three years of shorebird surveys from the tundra in northern Alaska. In the rapid method, surveyors covered ~10 ha h^{-1} and surveyed each plot a single time. The intensive surveys involved three thorough searches, required ~3 h ha^{-1}, and took 20% of the study effort. Surveyors using the rapid method detected an average of 79% of birds present. That detection ratio was used to convert the index obtained in the rapid method into an essentially unbiased estimate of density. Trends estimated from several years of data would also be essentially unbiased. Other advantages of double sampling are that (1) the rapid method can be changed as new methods become available, (2) domains can be compared even if detection rates differ, (3) total population size can be estimated, and (4) valuable ancillary information (e.g. nest success) can be obtained on intensive plots with little additional effort. We suggest that double sampling be used to test the assumption that rapid methods, such as variable circular plot and double-observer methods, yield density estimates that are essentially unbiased. The feasibility of implementing double sampling in a range of habitats needs to be evaluated.
Received 31 January 2001, accepted 21 September 2001.

RESUMEN.—Presentamos un método para estimar la densidad de aves nidificantes con base en un muestreo doble. La metodología incluye censos de una muestra grande de parcelas usando un método rápido como conteos de punto no corregidos, conteos en parcelas circulares variables (‘‘variable circular plot counts,’’ VCP) o el método de doble observador sugerido recientemente. Para determinar las densidades reales, una submuestra de estas parcelas también es censada usando métodos intensivos. Para ajustar los resultados de los censos rápidos se utiliza la razón entre el conteo promedio obtenido con el método rápido y la densidad media real (determinada a través de búsquedas intensivas). Esta metodología funciona bien cuando los resultados del método rápido están altamente correlacionados con la densidad real. Aquí ilustramos el uso del método basándonos en datos de tres años de censos de aves playeras en la tundra del Norte de Alaska. Utilizando el método rápido, censamos cada parcela sólo una vez, cubriendo ~10 ha h^{-1}. Los censos intensivos incluyeron tres búsquedas exhaustivas que llevaron ~3 h ha^{-1} y comprendieron el 20% del esfuerzo del estudio. Los censos realizados con el método rápido detectaron en promedio el 79% de las aves presentes. Esta tasa de detección fue utilizada para convertir el índice obtenido con el método rápido en un estimador no sesgado de la densidad. Del mismo modo, las tendencias estimadas con base en varios años de datos también estarían esencialmente libres de sesgos. Otras ventajas del muestreo doble son: (1) el método rápido puede modificarse conforme otros métodos se hagan disponibles, (2) las áreas de muestreo pueden ser comparadas aún si las tasas de detección difieren, (3) permite estimar el tamaño poblacional total y (4) se puede obtener información adicional de interés (e.g. éxito de anidación) en las parcelas intensivas con poco esfuerzo adicional. Sugerimos que el muestreo doble se utilice para poner a prueba el supuesto de que los métodos rápidos como el de VCP y el de doble observador

[1] E-mail: jbart@eagle.boisestate.edu

estiman la densidad esencialmente sin sesgos. La factibilidad de implementar el muestreo doble en una variedad de hábitats necesita ser evaluada.

THE NEED FOR accurate estimates of trends in avian abundance, and in some cases for estimates of absolute population size, is well acknowledged (Ralph et al. 1995, Carter et al. 2000, Beisinger et al. 2000, O'Connor et al. 2000). In statistical literature (e.g. Cochran 1977), accuracy is usually measured using the mean square error, defined as variance plus bias squared. ''Variance'' is a measure of precision, the degree to which estimates, drawn in the same manner from the same population, vary from sample to sample. ''Bias'' is the difference between the ''expected'' value of the estimate, its mean value based on a large number of samples, and the quantity being estimated. Precision is estimated by standard statistical methods whereas bias is not. It is thus imperative that methods be used that are unbiased, or in which the bias is small relative to precision.

Most avian survey methods are indices—surveys in which ratio of the count to actual population size is unknown. Indices cannot be used to estimate population size. In using them to estimate trend, we must assume that there is no substantial long-term trend in the ''index ratio'' (Bart et al. 1998), defined as index result divided by parameter, actual population size in this study. In recent years, there has been increasing concern over assuming that no temporal trend exists in the index ratio (e.g. Nichols et al. 2000). As a result, more emphasis is being placed on estimating index ratios so that density estimators may be used rather than indices.

We describe a method that yields essentially unbiased estimates of population size and thus of trend in population size. We use the qualifier ''essentially'' because few field methods, if any, are completely unbiased, but we believe that any bias in the method we describe is small enough to be ignored. The method is based on double sampling, a standard statistical method from the survey sampling literature (Cochran 1977, Thompson 1992). Double sampling has been widely used to survey waterfowl and has been used in at least two other avian studies (Handel and Gill 1992, Anthony et al. 1999), but it has not been widely used to study other avian taxa. The method involves an initial survey using a rapid method such as area searches, point counts, or variable circular plot counts, and a subsample of those plots on which actual density is determined through intensive methods. The ratio of the rapid-method result to actual density is then used to adjust results from the initial large sample of plots. The method yields unbiased estimates of density—and thus of trend in density—if the intensive methods provide accurate counts. No assumptions are required about how the index ratio in the initial surveys varies with observer, time of day, habitat, or other factors. We illustrate the method with several years of data from a study of shorebirds on the North Slope of Alaska.

METHODS

Estimating means and standard errors.—The approach below is from Thompson (1992) except that our r is his $1/r$. Let

n' = number of plots in the large sample surveyed with the rapid method
n = number of plots in the subsample on which intensive methods are used
$\bar{x}' = \sum x_i'/n'$
= mean number of birds recorded per plot in the large sample using the rapid method
$\bar{x} = \sum x_i/n$
= mean number of birds recorded per plot in the subsample using the rapid method
$\bar{y} = \sum y_i/n$
= mean number of birds actually present per plot in the subsample

The estimate of actual density, d, is obtained by adjusting results from the rapid method using results from the subsample:

$$d = \frac{\bar{x}'}{(\bar{x}/\bar{y})} = \frac{\bar{y}}{\bar{x}}\bar{x}' \quad (1)$$

The standard error of d may be estimated as

$$\widehat{\mathrm{SE}}(d) = \left[\frac{s^2(y_i)}{n'} + \left(\frac{1}{n} - \frac{1}{n'}\right)s^2(g_i)\right]^{0.5} \quad (2)$$

where g_i is calculated with the results from the subsample,

$$g_i = y_i - \frac{\bar{y}}{\bar{x}}x_i,$$

and

$$s^2(y_i) = \frac{\sum_i^n (y_i - \bar{y})^2}{n - 1}, \qquad s^2(g_i) = \frac{\sum_i^n (g_i - \bar{g})^2}{n - 1}$$

are sample variances of y_i and g_i. The first term on the right side of Equation (2) is the variance we would obtain if we carried out intensive surveys on all plots. The second term is an increment due to not surveying all plots with the intensive method (note that this term is 0 if $n = n'$). The second term depends on the correlation between true numbers present, y_i, and numbers obtained on the rapid survey divided by the detection ratio, $x_i/(\bar{x}/\bar{y})$. If these terms are equal—meaning that the rapid surveys are highly correlated with the true numbers—then $s^2(g_i) = 0$. See Thompson (1992) and Cochran (1977) for derivations and additional explanations.

The precision of the index ratio in the subsample, for example $r = \bar{x}/\bar{y}$, may also be of interest. The estimated variance of r may be expressed as

$$\hat{V}(r) = \frac{s^2(h_i)}{n\bar{y}^2} \tag{3}$$

where $h_i = x_i - ry_i$ is a standard method for simplifying calculation of standard errors for ratios (e.g. Cochran 1977) and $s^2(h_i)$ is variance of the h_i. Estimated standard error of the index ratio is

$$\widehat{\mathrm{SE}}(r) = \frac{s(h_i)}{\sqrt{n}\bar{y}} \tag{4}$$

where $s(h_i)$ is the standard deviation of the h_i (i.e. the square root of $s^2[h_i]$).

It may happen that few or no individuals of a species are recorded on the subsample of plots even though the species is recorded in the large sample often enough that density estimation is warranted. When that happens, the formulae above for density and its standard error cannot be used because $\bar{y} = 0$. If there is little variation in the index ratio for the species that were encountered commonly on the intensive plots, then density may be estimated using the combined index ratio for all species or a subset thought to have ratios similar to the species with missing data. In this situation, let

$\bar{x} = \frac{1}{n}\sum_1^n x_i$

x_i = number of individuals, of species used to estimate the index ratio, counted on plot i using the rapid method

$\bar{y} = \frac{1}{n}\sum_1^n y_i$

y_i = number of individuals, of species used to estimate the index ratio, actually present on plot i

$\bar{z} = \frac{1}{n}\sum_1^{n'} z_i$

z_i = number of individuals of the focal species counted on plot i using the rapid method

The estimated density, d_c (c for combined), is

$$d_c = \frac{\bar{z}}{(\bar{x}/\bar{y})} \tag{5}$$

Variance, which may be derived by expanding d in a Taylor series and consolidating terms, is

$$V(d_c) \cong \left(\frac{\bar{Y}\bar{Z}}{\bar{X}}\right)^2 \times \left\{\left(1 - \frac{n'}{N}\right)\frac{S^2(z_i)}{n'\bar{Z}^2} + \left(1 - \frac{n}{N}\right) \times \left[\frac{S^2(g_i)}{n\bar{Y}^2} + \frac{2}{n'}\left(\frac{\mathrm{Cov}(y_i, z_i)}{\bar{Y}\bar{Z}} - \frac{\mathrm{Cov}(x_i, z_i)}{\bar{X}\bar{Z}}\right)\right]\right\}$$

where $g_i = y_i - Rx_i$, $R = \bar{Y}/\bar{X}$. Covariances are about equal if correlation between x_i and y_i is high. They drop out if correlation between x_i and $y_i = 1$. Estimated covariances are 0 if no birds of the focal species are recorded on the intensive plots (all $z_i = 0$) and are unstable if a few birds are. Because their actual values are small, and difference between them divided by n′ is extremely small, we recommend ignoring covariances. If they are included, they are estimated using results from the subsample. For example,

$$\mathrm{cov}(y_i, z_i) = \frac{\sum_i^n (y_i - \bar{y})(z_i - \bar{z})}{n - 1}$$

Sample analogues are used for estimated standard error. If n'/N is small (the usual case), then standard error may be estimated as

$$\mathrm{se}(d_c) = d_c\left\{\frac{s^2(z_i)}{n'\bar{z}^2} + \frac{s^2(g_i)}{n\bar{y}^2}\right\}^{0.5} \tag{6}$$

The combined approach rests on the assumption that index ratio for the focal species is the same as for the species combined and may yield seriously biased estimates if the assumption is incorrect. This should be made clear when using the combined approach, and it should only be used for species that were absent or rare (e.g. <5 present) on the small sample of plots.

Allocation of effort.—An obvious question in double sampling is how to divide available resources between the first and second sample. Suppose that total resources (e.g. time, funding) are C, and costs of measuring a unit with rapid and with intensive methods are c' and c, respectively. The sample sizes, n' and n, must then be chosen to satisfy

$$C = c'\,n' + cn$$

It can be shown (Thompson 1992) that if this cost function adequately describes the study situation, then standard error of d is minimized when

$$n/n' = \alpha$$

with

$$\alpha = \sqrt{\frac{c'}{c}\left(\frac{s^2(g_i)}{s^2(y_i) - s^2(g_i)}\right)} \quad (7)$$

This leads to the following formulae for n' and n given C, c', and c:

$$n' = \frac{C}{c' + c\alpha} \quad (8)$$

and

$$n = \frac{C - c'n'}{c} \quad (9)$$

If advance estimates of costs, and of $s^2(y_i)$ and $s^2(g_i)$, are available, for example from a pilot study, then the equations above may be used to decide how to allocate effort between rapid and intensive surveys.

The shorebird study.—The study was carried out during 1994–2000 to prepare abundance maps and estimate total population size of shorebirds on the North Slope of Alaska. We defined abundance, for a given plot, as number of territorial males whose first nest of the season, or territory centroid for non-nesters, was within the plot. That approach provided an unambiguous definition of the parameter being estimated. We preferred not to define the parameter in terms of pairs because some males were presumably unpaired and because some species were polygynous. As a practical matter, however, we assumed that each male represented a pair and therefore doubled our estimate of male abundance when discussing shorebird abundance.

Plots were selected within broad habitat types (uplands, wetlands). Their borders followed natural boundaries, thus plots were of unequal size and were irregularly shaped. Stratification and systematic sampling were used to distribute plots evenly across the landscape. The full study, which also used GIS methods and habitat models, will be described elsewhere. To illustrate use of double sampling in its simplest context, we ignore stratification and variation in plot size. The data set is thus similar to those collected in standard point-count programs using uncorrected counts, distance methods, or the double-observer method (Nichols et al. 2000).

The rapid survey methods were developed during 1994–1997. We experimented with different methods and eventually chose a form of area search. Surveyors covered each plot by systematically recording all sightings and behavioral cues on a map of the plot, which would help them estimate actual abundance. They covered an average of ~10 ha h^{-1}. Immediately after each survey, the observer prepared a table with species as rows and types of evidence (nest, probable nest, pair, male, female, and unknown sex) as columns. The sum of observations of each type was calculated for each species, and then final estimates of abundance were made. Final estimate could be either higher or lower than the row total. For example, the surveyor might have recorded a nest in one area and a single male in another, but might conclude, after review of the entire survey, that the nest and male were probably from the same territory. Final estimate of abundance would thus be 1.0 less than the row total. Densities for each plot were then calculated, with plot area as determined using GIS methods, and were used as x_i in equations above.

We also experimented with different methods for conducting intensive searches. The final method was based on nest searches though we also included territorial pairs that apparently did not nest or had nests that failed before we found them. Each year, two surveyors spent the entire field season (about three weeks) surveying four plots of 10–14 ha each. Each surveyor worked primarily on two plots and was on those plots for several hours each day. Most of the time was spent searching for nests, but information such as pairing status, territory boundaries, nest locations, and nest fates was also collected to help determine number of territorial males on each plot. During 2000, surveyors recorded their time on each plot and estimated number of territorial males present (i.e. whose first nest of the season, or territory centroid for non-nesters, was within the plot) three times during the season. The final estimate was used as number of males present on each plot. We used new locations for the intensive plots each year to avoid pseudoreplication.

Each surveyor conducting rapid surveys also surveyed each intensive plot, usually twice during the field season. Surveyors conducting rapid surveys of the intensive plots had no prior experience with the plot (i.e. had not conducted nest searches there). We regarded the plot as the primary sampling unit and therefore calculated means per plot as the first step in statistical analysis. In the index ratio above, $r = \bar{x}/\bar{y}$,

$$\bar{x} = \sum_i^n x_i/n$$

and

$$\bar{y} = \sum_i^n y_i/n$$

where x_i = mean number of birds recorded on rapid surveys of plot i, and y_i = the actual number present on plot i as determined by intensive surveys.

Results

Rapid surveys were conducted by three to five observers each year during 1998–2000. Observers surveyed a total of 201 plots covering 77 km^2, and recorded 4,179 individual shorebirds of 15 species (Table 1). Ten species were

TABLE 1. Number of plots on which species were present and number of individuals recorded on extensive surveys.

Species	No. plots	Individuals recorded: Total	Mean/plot	SE	Coefficient of variation[a]
All species	188	4,179	54.3	3.45	0.06
Black-bellied Plover (*Pluvialis squatarola*)	71	124	1.6	0.21	0.13
America Golden-Plover (*Pluvialis dominica*)	45	75	1.0	0.19	0.19
Whimbrel (*Numenius phaeopus*)	8	4	0.1	0.02	0.39
Bar-tailed Godwit (*Limosa lapponica*)	36	55	0.7	0.18	0.24
Ruddy Turnstone (*Arenaria interpres*)	8	19	0.2	0.10	0.41
Semipalmated Sandpiper (*Calidris pusilla*)	152	1,242	16.2	1.38	0.09
Pectoral Sandpiper (*Calidris melanotos*)	160	955	12.4	0.99	0.08
Dunlin (*Calidris alpina*)	77	235	3.1	0.39	0.13
Stilt Sandpiper (*Calidris himantopus*)	54	95	1.2	0.20	0.16
Long-billed Dowitcher (*Limnodromus scolopaceus*)	98	297	3.9	0.51	0.13
Red-necked Phalarope (*Phalaropus lobatus*)	119	537	7.0	0.84	0.12
Red Phalarope (*Phalaropus fulicaria*)	98	591	7.7	1.21	0.16

[a] Coefficient of variation = Mean per plot/SE of the mean per plot.

fairly common (≥75 individuals recorded) whereas the other five were uncommon to rare. The common species were fairly widely distributed, five were recorded on ≥98 plots and all 10 were recorded on ≥36 plots. As with most territorial species, individuals were not highly clumped, and standard errors and coefficients of variation (CV) were fairly low. Three species had CV < 0.10 and 8 of the 10 common species had CV ≤ 0.16. CV for uncommon species were higher (mean CV = 0.31) because the denominator (estimated density) was very small. Standard errors, and thus confidence intervals, for those species were still small enough to indicate that their populations were small.

Intensive searches were conducted on four plots during each of the three years. In 2000, three complete searches, each requiring ~1 h ha^{-1}, were made of each plot (Table 2). Number of new nests found per search hour declined from 0.71 on the first search to 0.06 on the third search, indicating that nearly all nests were found. Similarly, our best estimates of actual number of nests on each plot changed little between second and third search. Thus, in this study, three searches, each involving ~1 person-h ha^{-1}, were sufficient to obtain an accurate estimate of actual densities.

TABLE 2. Search effort and results obtained during each of three complete nest searches on intensive plots during 2000.

	1st search (15–20 June)	2nd search (21–25 June)	3rd search (26 June–1 July)
Search h	62	65	72
Search h/ha	1.2	1.2	1.4
New nests	44	31	4
New nests/h	0.71	0.48	0.06
Estimated total	89	81	79

Rapid surveys of intensive plots were made twice during 1998 and 1999 and once during 2000. A total of 60 rapid surveys was made of the 12 intensive plots.

A total of 247 shorebirds occurred on intensive plots, and average number detected was 196 for an index ratio of 0.79 (Table 3). Estimated species-specific rates, for all species with at least five individuals present, varied from 0.49 to 0.93. To judge whether results indicated real variation between species or might have been due largely to sampling error, we calculated 85% confidence intervals for each ratio and determined whether they included the grand mean, 0.79. We used an 85% confidence interval to be conservative (i.e. a 95% interval would have been more likely to include 0.79). Seven of the nine confidence intervals included 0.79, whereas two did not. For one of those species, the Red Phalarope (*Phalaropus fulicaria*), we believe the index ratio had substantial negative bias. That bias resulted from logistic constraints that forced us to conduct rapid surveys of intensive plots late in the survey period in two of three years. By this time, female Red Phalaropes, which are much more conspicuous

TABLE 3. Individuals recorded during rapid surveys of intensive plots, actual numbers present based on intensive nest searches, and resulting index ratios.

	All	American Golden-Plover	Ruddy Turn-stone	Semi-palmated Sandpiper	Pectoral Sand-piper	Dunlin	Red-necked Phalarope	Red Phalarope	Other
Average estimate	196	5	7	72	46	15	29	13	10
Number present	247	8	7	101	45	14	36	27	11
Index ratio	0.79	0.63	0.93	0.71	1.02	1.05	0.80	0.49	0.89
SE	0.09	0.10	0.08	0.10	0.18	0.28	0.13	0.09	0.13
Lower 85% CI	0.66	0.48	0.82	0.56	0.76	0.64	0.62	0.37	0.71
Upper 85% CI	0.92	0.77	1.04	0.86	1.29	1.46	0.99	0.62	1.08

than males (who incubate the eggs), had left the study area. Most extensive surveys, however, were done while female Red Phalaropes were still present, so we assume the overall index ratio for Red Phalaropes was higher than the rate during rapid surveys of intensive plots. In addition, we could see no reason why detection ratio for Red Phalaropes would be markedly lower than the rate for Red-necked Phalaropes (*Phalaropus lobatus*), except that female Red-necked Phalaropes remained on the study area throughout rapid surveys of intensive plots. For those reasons, we discounted the low rate for Red Phalaropes. That left only one rate significantly lower than the mean for all species, but with an 85% confidence interval one would expect about one of eight confidence intervals to fall entirely outside the true value. This rationale indicated that results for all species except Red Phalaropes provided an appropriate data set for species recorded too rarely to use the combined approach. We therefore used the separate approach (Eqs. 1 and 2) for the ''all species'' estimates and for the common species in Table 3 but used the combined approach (Eqs. 5 and 6) for Red Phalaropes and species that were absent or rare on intensive plots but abundant enough on extensive plots to warrant analysis.

Density of all shorebird species combined was ~69 pairs / km² (Table 4). The CV of the estimated density was only 3%, indicating that estimate was quite accurate. The most common species, in order of abundance, were Semipalmated Sandpiper (*Calidris pusilla*), Pectoral Sandpiper (*Calidris melanotos*), Red-necked Phalarope, and Red Phalarope. Other species were less than half as abundant as the phalaropes. Four species not mentioned in Table 4 were also recorded but only very rarely. CV were ≤12% for all but one species that was rare. The sampled population (area from which plots were randomly selected) covered 816 km². Estimated number of shorebirds within that area was 55,951. An approximate 95% confidence interval may be constructed as point estimate ± twice the CV × point estimate. The CV for the estimated total is the same as for the

TABLE 4. Estimated densities and population totals for the sampled population and population of interest.

Species	Method	Density	SE	Coefficient of variation	Estimated total: Sampled area	Estimated total: Study area
All	Separate	68.57	2.23	0.03	55,951	239,917
Black-bellied Plover	Combined	2.03	0.22	0.11	1,660	7,119
American Golden-Plover	Separate	1.56	0.13	0.08	1,275	5,466
Bar-tailed Godwit	Combined	0.91	0.11	0.12	745	3,195
Ruddy Turnstone	Combined	0.31	0.16	0.51	253	1,084
Semipalmated Sandpiper	Separate	22.80	1.16	0.05	18,607	79,785
Pectoral Sandpiper	Separate	12.17	0.65	0.05	9,931	42,583
Dunlin	Separate	2.91	0.31	0.11	2,373	10,174
Stilt Sandpiper	Combined	1.56	0.17	0.11	1,272	5,456
Long-billed Dowitcher	Combined	4.89	0.53	0.11	3,990	17,109
Red-necked Phalarope	Separate	8.68	0.48	0.06	7,086	30,383
Red Phalarope	Combined	9.73	1.07	0.11	7,936	34,032

density. Thus, the 95% CI for the estimated population total is 55,951 ± (0.06)(55,951), which equals approximately 52,600 to 59,300 pairs. The entire study area covered 3,499 km^2. Extrapolation to that larger area suggests a total population of ~240,000 (±14,000) pairs or ~0.5 million individual shorebirds of all species. Inferences apply rigorously to the sampled population, assuming only that statistical assumptions are valid. Inferences to the larger population of interest must be supported by additional evidence indicating that the population of interest is unlikely to differ in overall density from the sampled population (evidence for that assumption in our study will be presented elsewhere).

DISCUSSION

Double sampling in this study provided a cost-effective method for obtaining essentially unbiased estimates of shorebird density in a large, remote area in which travel is difficult. In contrast, a survey using only the rapid method would not have yielded a useful estimate of population size, and estimates of trend based on repeated surveys would have been compromised by possible existence of substantial bias due to differences in observer methods, phenology, habitat or other factors affecting detection rate.

Approximately 20% of resources in the study were expended on obtaining the index ratio that allowed us to convert results from the rapid area-searches into density estimates. To put that expenditure in perspective, we would have obtained a sample of rapid surveys ~25% larger had all the effort been devoted to the rapid method. Let $\bar{x}_i'$ be the estimate actually obtained and $\bar{x}_2'$ is the estimate we would have obtained with a 25% larger sample size. Because $\widehat{SE}(\bar{x}') = \widehat{SD}(x_i')/\sqrt{n}$, we may write

$$\frac{\widehat{\mathrm{SE}}(\bar{x}_2')}{\widehat{\mathrm{SE}}(\bar{x}_1')} = \sqrt{\frac{n_1}{n_2}} = 0.894$$

so estimated standard errors and CVs would have been ~11% smaller. For example, the CV for the uncorrected mean density for all species, obtained using the rapid method, would have been 0.054 rather than 0.06 (Table 1). The proportional effort required to estimate the index ratio declines as number of surveyors increases because only four intensive plots are needed (in our design) regardless of how many surveyors conduct rapid surveys. For example, with 20 surveyors ~10% of the effort (compared to 20% in our study) would have been needed to have four intensive plots. On the other hand, with only four surveyors, four intensive plots would require half the total time spent in the study.

After a year or two of data have been collected, formulae for optimal allocation of effort or for standard error of the density estimate may be used to explore other ways of dividing effort between rapid and intensive surveys. If estimating population size is the only objective, then Equation (9) provides an appropriate solution. In many studies, including ours, obtaining wide coverage of the study area will be a separate objective. Thus, we wanted to survey shorebirds in a large number of locations to learn more about habitat relationships and identify areas of especially high abundance, and we were willing to incur some loss in precision of the population size estimate to obtain the goal of thorough coverage. In such cases, it may be useful to investigate how different allocations of effort, between the rapid and intensive surveys, would affect standard error of the density estimate. Results tend to vary, sometimes substantially, between species. Data from the Dunlin (*Calidris alpina*) are used here as an example. Suppose we had surveyed only 6 plots intensively, rather than 12. We could then have covered ~250 plots (rather than 201). The variances for Dunlin were $V(y_i) = 4.20$ and $V(g_i) = 1.73$. Substitution of these values in Equation (2) yields $\mathrm{SE}(d) = 0.55$. The value we obtained with 12 intensive plots (Table 3) was 0.28. Thus, reducing number of intensive plots to 6 would have doubled the standard error of density (and thus population size estimate).

Several benefits result from using the double-sampling approach. First and foremost, the approach provides estimates of density that are unbiased as long as (1) intensive plots are a random sample from the population (no assumption is needed that the index ratio is constant across observers or areas); (2) the rapid method is carried out on those plots in the same manner as on other plots; and (3) number of birds present is measured without error (or at least the average number counted on all intensive plots equals average number actually present). Several authors have noted that if bird surveys are worth doing at all, they are probably worth doing in a manner that permits estimation of index ratios (Burnham 1981, Nichols et al. 2000). Double sampling does permit estimation of index ratios. Below we consider whether other methods such as distance estimation and double-observer methods permit estimation of index ratios.

Second, double sampling offers the possibility of trends estimated without bias. That is a major benefit because index methods generally suffer from numerous potential biases (Lancia et al. 1994). Observer skill may change in ways not acknowledged by the estimation method. Extraneous factors such as traffic noise may change through time. Singing rates may change, for example due to change in survey times or to change in habitat quality. With distance methods, observer skill in estimating distances, or in detecting birds before they move, may change through time. All of these problems cause bias in estimating temporal trends. Spatial trends are even harder to estimate with index methods because detection rates may vary across space in ways not acknowledged by the index method. If trend estimates are used to affect resource allocation, then they are likely to be challenged in adversarial contexts such as the courts. Even if biologists running the index program have confidence in their method, they may have trouble defending trend estimates due to possibility of biases mentioned above.

Even if some bias exists in the estimate of density obtained with double sampling, that approach will generally yield trend estimates with far smaller potential bias than index methods. That is true because bias in the index method comes from temporal trend in the index ratio, whereas bias in the double-sampling method comes only from temporal trend in ratio of detailed counts on assessment plots to actual numbers present there. Much less opportunity for trend in that ratio exists simply because much more time is spent on those plots than in the rapid method.

A third advantage of double sampling is that the rapid method can be changed as different methods become available or investigator preferences change, and results from different studies, using different rapid methods, can be combined because in all cases actual density is estimated. For example, the rapid method might be unrestricted point counts, restricted point counts, distance methods, or the double-observer method. Survey times might also vary. As long as an index ratio is estimated with each method, estimates of actual density are obtained and thus results can be combined. In sharp contrast, index methods are difficult or impossible to combine in a rigorous manner. A related advantage of double sampling is that weighting of results from different areas is simple and objective because it is based solely on size of each area. In contrast, combining results from areas surveyed using index methods requires a complex weighting system that has been difficult for investigators to understand and controversial among the few that do understand it (James et al. 1996, Thomas 1996). Ignoring the weighting problem has the virtue of simplicity but may give seriously biased results.

A fourth advantage of double sampling is that domains of interest (e.g. different habitats or regions) can be compared even if index ratios differ between domains. If index ratios do—or may—differ, then separate estimates of them must be made, and that increases the effort devoted to that part of the study. Index methods, however, do not permit any comparison (without bias) when index ratios differ.

Another advantage of double sampling is that estimates of total population size may be valuable beyond their use in obtaining trend estimates. For example, the recently completed Shorebird Conservation Plan (Brown et al. 2000) establishes estimating population size for each shorebird species as one of four goals in its monitoring plan. Emphasis on estimating population size is also evident in many Partners in Flight documents (e.g. Carter et al. 2000, Downes et al. 2000, Pashley et al. 2000).

A final advantage of double sampling is that much valuable ancillary information may be obtained from intensive plots. For example, if densities are determined by finding nests, then nest success can be estimated easily and may help distinguish source from sink habitats. Finding nests, and intensive observations made in the process of finding them, may also help determine whether the species nest and forage in the same habitats, which will help in interpretation of survey results and will usually reveal breeding-season phenology, which may help decide on survey timing. In our study, we gained more insights about habitat associations from the few intensive plots than from all of the rapid surveys.

Additional emphasis has been placed recently on methods that provide some measure of index ratios. Those include distance methods, the double-observer method, and other methods under development (Buckland et al. 1993, Nichols et al. 2000). Whether those methods permit unbiased estimation of density is often unclear. Distance methods, for example, require that birds at the surveyors' locations always be detected. But some birds at the surveyors' locations may not be visible (e.g. in multistoried habitats) or may move away undetected (e.g. in more open habitats). Field trials have indicated that the variable circular plot method underestimates actual populations in most cases (DeSante 1981, 1986; Jones et al. 2000), though not in all cases (Fancy 1997). If many of the birds close to the observer are not detected, then the distance method cannot be viewed as providing an estimate of density and should be considered an index method, though quite possibly a better index than simple point counts. The double-observer method assumes that all birds have the same probability of being detected by a given observer. But distant birds or ones that sing less often have lower detection probabilities than birds that are close or that sing frequently, and it may be shown that the method tends to underestimate density when variation in detection rates occurs. Thus, this method too may often be an index rather than a density estimator, though it (like the distance methods) may produce an index with less potential for bias than uncorrected counts. We believe that, when practical, these methods should be used in a double-sampling context. It may turn out that the index ratio is very close to 1.0, and if so, the intensive plots can subsequently be omitted. On the other hand, if initial trials show that the rapid method does not provide essentially unbiased estimates of density, then double sampling can be continued and provides the valuable function of converting index results into unbiased density estimates.

For all of the reasons above, we believe that the double-sampling method warrants consideration in many avian surveys. Other definitions and field methods than the ones used in this study, however, may be more practical in many cases. ''Number present'' does not need to mean number of birds whose first nest of the season is within the plot. Any definition of ''present'' may be used so long as each bird in the population of interest is assigned a single place by the definition. If this is true, then population size equals density times size of the study area, and an unbiased estimate of density may be used to obtain an unbiased estimate of population size. ''Present on a plot'' might thus be defined as meaning the territory centroid is within the plot or that the most commonly used song perch is within the plot. Different definitions of ''present'' may be used to cope with different practical constraints. This in turn means that methods other than nest searching may be used on intensive plots. For example, if ''present'' is defined using territory centroids, then territories might be defined using singing perches and repeated, intensive spot-mapping might be used to delineate territories. Accurate maps of birds with territories near plot borders would be needed. For birds within the plot, it would only be necessary to distinguish individuals from each other; their territory boundaries would not have to be determined precisely because it would be clear that they were within the plot. Thus, a territory-mapping rather than nest-finding approach might be preferred in habitats where finding all nests is not practical. More generally, investigators interested in using double sampling should tailor their definition of ''present'' and field methods used in both rapid and intensive surveys to their particular situations.

ACKNOWLEDGMENTS

We thank our field technicians and others who helped collect data: B. Arquilla, D. Battaglia, W. Boyd, D. Braun, B. Clock, P. Cotter, M. Coupe, P. Dougherty, C. Eldermire, H. Johnson-Schultz, P. Lemons, M. Lott, S. Malone, P. Martin, K. Moiteret, S. O'Connor, R. Pagen, N. Parker, D. Poinsette, E. Rasmussen, A. Schmidt, S. Schulte, N. Senner, J. Stephens, E. Urban, C. Warren, and K. Woodling. The project was funded by U.S. Department of the Interior, Fish and Wildlife Service Migratory Birds, Region 7, Nongame Bird Program and the U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center. We also thank K. Wohl, B. Andres, H. Johnson-Schultz, P. Cotter, and the J. Helmericks family for logistic support.

LITERATURE CITED

ANTHONY, R. G., M. G. GARRETT, AND F. B. ISAACS. 1999. Double-survey estimates of Bald Eagle populations in Oregon. Journal of Wildlife Management 63:794–802.

BART, J., M. A. FLIGNER, AND W. I. NOTZ. 1998. Sampling and Statistical Methods for Behavioral Ecologists. Cambridge University Press, Cambridge, United Kingdom.

BEISSINGER, S. R., J. M. REED, J. M. WUNDERLE, JR., S. K. ROBINSON, AND D. M. FINCH. 2000. Report of the AOU Conservation Committee on the Partners in Flight species prioritization plan. Auk 117:549–561.

BROWN, S., C. HICKEY, AND B. HARRINGTON, EDS. 2000. United States Shorebird Conservation Plan. Manomet Center for Conservation Sciences, Manomet, Massachusetts.

BUCKLAND, S. T., D. R. ANDERSON, K. P. BURNHAM, AND J. I. LAAKE. 1993. Distance Sampling: Estimating Abundance of Biological Populations. Chapman and Hall, London.

BURNHAM, K. P. 1981. Summarizing remarks: Environmental influences. Studies in Avian Biology 6:324–325.

CARTER, M. F., W. C. HUNTER, D. N. PASHLEY, AND K. V. ROSENBERG. 2000. Setting conservation priorities for landbirds in the United States: The Partners in Flight approach. Auk 117:541–548.

COCHRAN, W. G. 1977. Sampling Techniques, 3rd ed. John Wiley and Sons, New York.

DESANTE, D. F. 1981. A field test of variable circular-plot censusing technique in a California coastal scrub breeding bird community. Studies in Avian Biology 6:177–185.

DESANTE, D. 1986. A field test of the variable circular-plot censusing method in a Sierran subalpine forest habitat. Condor 88:129–142.

DOWNES, C. M., E. H. DUNN, AND C. M. FRANCIS. 2000. Canadian Landbird Monitoring Strategy: Monitoring Needs and Priorities into the New Millennium. Partners In Flight–Canada. Ottawa, Ontario.

FANCY, S. G. 1997. A new approach for analyzing bird densities from variable circular-plot counts. Pacific Science 51:107–114.

HANDEL, C. M., AND R. E. GILL, JR. 1992. Breeding distribution of the Black Turnstone. Wilson Bulletin 104:122–135.

JAMES, F. C., C. E. MCCULLOCH, AND D. A. WIEDENFELD. 1996. New approaches to the analysis of population trends in land birds. Ecology 77:13–27.

JONES, J., W. J. MCLEISH, AND R. J. ROBERTSON. 2000. Density influences census technique accuracy for Cerulean Warblers in eastern Ontario. Journal of Field Ornithology 71:46–56.

LANCIA, R. A., J. D. NICHOLS, AND K. H. POLLOCK. 1994. Estimating the number of animals in wildlife populations. Pages 215–253 *in* Research and Management Techniques for Wildlife and Habitats, 5th ed. (T. A. Bookhout, Ed.). The Wildlife Society, Bethesda, Maryland.

NICHOLS, J. D., J. E. HINES, J. R. SAUER, F. W. FALLON, J. E. FALLON, AND P. J. HEGLUND. 2000. A double-observer approach for estimating detection probability and abundance from point counts. Auk 117:393–408.

O'CONNOR, R. J., E. DUNN, D. H. JOHNSON, S. L. JONES, D. PETIT, K. POLLOCK, C. R. SMITH, J. L. TRAPP, AND E. WELLING. 2000. A Programmatic Review of the North American Breeding Bird Survey. Patuxent Wildlife Research Center, Laurel, Maryland.

PASHLEY, D. N., C. J. BEARDMORE, J. A. FITZGERALD, R. P. FORD, W. C. HUNTER, M. S. MORRISON, AND K. V. ROSENBERG. 2000. Partners in Flight: Conservation of Land Birds of the United States. American Bird Conservancy, The Plains, Virginia.

RALPH, C. J., J. R. SAUER, AND S. DROEGE, EDS. 1995. Monitoring bird populations by point counts. U.S. Department of Agriculture, Forest Service General Technical Report PSW-GTR-149.

THOMAS, L. 1996. Monitoring long-term population change: Why are there so many analysis methods? Ecology 77:49–58.

THOMPSON, S. K. 1992. Sampling. John Wiley and Sons, New York.

Associate Editor: M. Murphy