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Evaluation of aerial sampling methods for detecting waterbird colonies

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ABSTRACT. Estimating the number of waterbird colonies in a given area can have important conservation implications, including assessment of the regional or global importance of an area and the impacts of conservation efforts (e.g., habitat restoration) and human disturbance (e.g., oil spills). Our objective was to examine differences in estimates of the number of waterbird colonies determined using strip-transect (ST) surveys, distance sampling, and adaptive cluster sampling (ACS), and to compare these estimates to the minimum number of known colonies (MNKC) obtained using point-to-point surveys. We conducted aerial surveys in May 2004 and May and June 2005 at two sites in southern Louisiana: the Atchafalaya Basin (AB), a large forested wetland, and the Barataria-Terrebonne estuary (BTE), a large coastal marsh with isolated clumps of woody vegetation suitable for nesting. In AB, we detected nine and eight colonies using the ACS and ST/distance sampling methods, respectively. Neither ACS estimator of number of colonies (Horvitz–Thompson and Hansen–Hurwitz) was within the 95% confidence interval of the estimate determined from ST; ST estimated—two to three times more colonies than either ACS estimator. The MNKC for the AB was 33, well within the 95% confidence interval of $\hat{Y}$ by ST sampling. For the BTE, ACS estimators ($\hat{Y}_{\mathrm{HT}} = 20.49$, CI = 9.3–31.7; $\hat{Y}_{HH} = 14.15$, CI = 2.3–26.0) were similar to the MNKC (20), whereas the ST ($\hat{Y} = 87.94$, CI = 82.9–92.9) and distance sampling ($\hat{Y} = 60$, CI = 31–113) methods produced much larger estimates. Our results suggest that the ACS method performed better when waterbird colonies were spatially clumped (BTE) and the ST method performed better in areas where colonies were more uniformly distributed (AB). Depending on management objectives, a complete, systematic survey of a study area may be required if the potential for missing large colonies is unacceptable. If surveying an area with no previous information about colony location or dispersion, we recommend a coarse-scale analysis of the availability and contiguity of habitat likely to contain waterbird colonies; this analysis will help determine the most appropriate survey method.

RESUMEN. **Una evaluación de métodos aéreos usados para detectar colonias de aves acuáticas**

La estimación del número de colonias de aves acuáticas en un área puede tener importantes implicaciones para la conservación, incluyendo la evaluación de la importancia regional o global de un área y los impactos de los esfuerzos para la conservación (ej., restauración de hábitat) y disturbio humano (ej., derrames de petróleo). Nuestro objetivo fue examinar las diferencias en las estimaciones del número de colonias de aves acuáticas determinadas usando muestreos de censos por transecta (CT), muestreos de distancia, y muestreo adaptativo por grupos (MAG) y comparar estas estimaciones al numero mínimo de colonias conocidas (NMCC) obtenidos usando muestreos de punto a punto. Realizamos muestreos aéreos en Mayo del 2004 y Mayo y Junio del 2005 en dos sitios en el sur de Louisiana: la Bahía de Atchafalaya (BA), cual es un pantano con bosque, y el estero de Barataria-Terrebonne (EBT), cual es un humedal costero grande con manchas de vegetación aisladas que son adecuadas para nidificación. En BA, detectamos nueve y ocho colonias usando los métodos MAG y CT/muestreos de distancia, respectivamente. Ninguno de los dos estimadores de MAG del numero de colonias (Horvitz-Thompson y Hansen-Hurwitz) estuvo dentro del intervalo de confianza de 95% de la estimación determinada con CT; el CT estimó 2–3 veces mas colonias que cualquiera de los dos estimadores de MAG. El NMCC para BA fue de 33, cual es dentro del intervalo de confianza de 95% de $\hat{Y}$ mediante el muestreo de CT. Para el EBT, los estimadores de MAG ($\hat{Y}_{\mathrm{HT}} = 20.49$, IC = 9.3–31.7; $\hat{Y}_{HH} = 14.15$, IC = 2.3–26.0) fueron similares al NMCC (20), mientras que los métodos de CT ($\hat{Y} = 87.94$, CI = 82.9–92.9) y muestreo de distancia ($\hat{Y} = 60$, CI = 31–113) produjeron estimaciones mucho mas grandes. Nuestros resultados sugieren que el método de MAG funcionó mejor cuando las colonias de aves acuáticas estuvieron espacialmente mas agrupados (EBT) y el método de CT tuvo más éxito en áreas donde las colonias estuvieron más uniformemente distribuidas (BA). Dependiendo de los objetivos de manejo, un muestreo completo y sistemático de un área de estudio podría ser requerido si la posibilidad de no detectar colonias grandes

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no es aceptable. Si se va a muestrear un área para la cual no existe información previa sobre la ubicación o dispersión de las colonias, recomendamos un análisis a escala gruesa sobre la disponibilidad y contigüidad de hábitat que probablemente tenga colonias de aves acuáticas; este análisis ayudara en determinar el método de muestreo mas apropiado.

Key words: adaptive cluster, colony, distance sampling, strip transect

Surveys for detecting waterbird colonies present many sampling challenges due to habitat differences, mixed-species composition, and ephemeral changes in the location of colonies. Although aerial surveys are frequently used to estimate the size (i.e., nesting pairs) of waterbird colonies, these estimates are often biased, inaccurate, and imprecise (Frederick et al. 2003, Rodgers et al. 2005, Green et al. 2008). Considerable research has been devoted to methods of estimating the number of birds in a colony, whereas little attention has been paid to methods of detecting unknown waterbird colonies (Buckley and Buckley 1976, Kushlan 1979, Erwin 1982, Frederick et al. 1996, 2003, Green et al. 2008). For detection of waterbird colonies (presence/absence) over large areas, aerial surveys are typically used because large areas can be covered in less time. Additionally, many waterbird colonies are located in large tracts of undeveloped land, often only accessible via watercraft or aircraft (Green et al. 2008). Although some waterbird colonies may be active over successive years, colony turnover is common in large tracts of land with suitable breeding habitat. Colonies may be active for several years and then be abandoned for various reasons, including site degradation (Oliver and Legovic 1998) and droughts and hurricanes (Leberg et al. 2007).

Aerial search efforts for active colonies, both old and new, are often conducted by following a flight track that revisits all known colonies while searching for new colonies between known locations, that is, the point-to-point method (Green et al. 2006). This method relies on an existing database of known active or inactive colony locations to determine flight tracks. Although relatively straightforward, use of this method means that previously unknown colonies located away from the flight track will not be discovered. Of course, if a previously unsearched area is being surveyed for waterbird colonies, the point-to-point method will obviously not be applicable.

The strip-transect (ST) method is traditionally used for conducting aerial surveys of waterbird colonies (Rodgers et al. 2005). STs are flown in straight lines and fixed-width distances perpendicular to the flight path represent the area surveyed (Burnham et al. 1980). This method assumes that colonies are randomly distributed across the landscape and all are equally detectable if STs are randomly determined (Barry and Welsh 2002, Welsh 2002). ST surveys are relatively straightforward and logistically simple, but can be cost-prohibitive if adequate coverage of large areas of potentially suitable habitat is required.

Distance-based sampling is a commonly used method for estimating abundance and is often used for aerial surveys (see multiple examples in *Wildlife Research* 35[4]). Distance sampling, using methods similar to the ST method, allows for calculation of a distance distribution function that is used to estimate density. Distance data provide the opportunity to estimate the probability of detection that is used to adjust the incomplete counts. The probability of detecting a colony decreases with increasing distance from the transect line. There are several assumptions associated with distance and ST sampling: (1) transect lines are randomly distributed with respect to distribution of the object, (2) objects directly on the transect line have a probability of detection of one, and (3) objects do not move in response to disturbance from sampling (Buckland et al. 2001).

New sampling methods have been proposed for conducting surveys that could potentially increase the efficiency of survey efforts, increase the precision of the estimate, and reduce the bias associated with the population (i.e., colony) estimate. Adaptive cluster sampling (ACS) uses information gathered during initial sampling to guide further sampling and determine when to cease sampling the area (Thompson 1990, Seber and Thompson 1994). After initial sampling, the neighborhood (adjacent sample units) of any initial sample unit that satisfies the condition (e.g., ≥ 1 colony) is also surveyed. Sampling continues until no more sampling units are found within the neighborhood that satisfy the condition. Initial sampling units and neighborhood units form a cluster and are used in the final analysis. This method, considered most appropriate when targets of interest may be aggregated, has been used for a variety of taxa and habitats, including rockfish (*Sebastes* spp.; Hanselman et al. 2003), wintering waterfowl (Smith et al. 1995), amphibians and reptiles (Noon et al. 2006), and vernal pools (Van Meter et al. 2008). Based on coarse-scale analysis of previous waterbird colony surveys in Louisiana (e.g., Michot et al. 2003), we hypothesized that waterbird colonies were spatially aggregated and, therefore, that ACS may be an appropriate survey method for estimating the number of colonies.

Our objectives were to (1) examine differences in estimates of the number of waterbird colonies determined using ST surveys, distance sampling, and ACS, and (2) compare these estimates to the minimum number of known colonies (MNKC) obtained using point-to-point surveys. Point-to-point surveys were conducted, independently of other sampling, by surveying all known colonies, active and inactive, and searching for unknown colonies along flight tracks between known colonies. We also examined how these estimates may be affected by habitat, evaluating the approaches in both forested wetlands and coastal marsh. We predicted that colony sites would be more clumped in heterogeneous coastal marshes than in the more homogeneous forested wetlands, and thus ACS approaches would have greater utility in the former.

METHODS

We selected two study areas in Louisiana, the Atchafalaya River Basin (AB) and Barataria-Terrebonne Estuarine (BTE) complex, to evaluate these survey methods for estimating the number of waterbird colonies. These two study sites, long recognized to be important for nesting colonial waterbirds (Portnoy 1977, Martin and Lester 1990, Michot et al. 2003, Green et al. 2006), were selected because of structural and spatial differences in nesting habitat. The AB (2400 km^2) is a tributary of the Mississippi River and contains the largest contiguous bottomland hardwood forest and cypress-tupelo swamp in North America. The basin is about 70% forested wetland, with the remainder a mixture of marshland and open water (Keeland and Gorham 2009); our surveys were conducted in the forested portion of the basin. The BTE (6304 km^2) consists of two basins (Barataria and Terrebonne) located between the Mississippi and Atchafalaya rivers, and consists of a mixture of fresh (i.e., *Panicum*), brackish and salt (*Spartina* spp.) marsh with interspersed mangrove hammocks and forested wetlands (i.e., *Cephalanthus* spp.; Visser et al. 1996). These scattered areas of woody vegetation were used as colony sites by waterbirds, creating the potential for colonies to be clumped.

Aerial survey techniques. Fixed-wing aircraft surveys were conducted in May 2004 in the Atchafalaya Basin (AB) and May and June 2005 in the BTE complex using a single-engine aircraft (Cessna 185). All aerial surveys were conducted at ~150 m above ground level and 157 km/h fixed-wing aircraft speed; relatively constant altitude and flight speed were maintained to minimize variation in detection probability (Laake et al. 2008). Two observers (MCG and MCL) conducted the surveys, each looking out different sides of the aircraft during ST and ACS flights.

Strip-transect sampling. We used aerial line, or ST sampling, as our simple random sampling method for comparison with ACS. To determine starting points for STs, we again used the Random Sampling Tools extension of ArcView 3.2 to randomly select points within the study-site boundary; all transects were oriented in an eastwest direction. For both study sites, we used STs 10 km in length and 750 m half-width. Rodgers et al. (2005) reported a colony detection rate of 56–84% for 5-km width (2.5 km half-width) transects, making it likely that we would observe most, if not all, colonies within 750 m half-width strips. All transects were >2 km apart to avoid overlap of transects and double counting of colonies.

Distance sampling. Distance sampling, in contrast to ST sampling, allows differences in detectability with respect to distance from observers and makes use of all colonies observed in the estimation procedures, not only those located within the ST (Burnham and Anderson 1984). However, a disadvantage of distance sampling is that it requires a large number of observations to obtain a reasonable estimate of how detectability changes with distance and assumes distance from transects to each colony can be measured without error.

We used the same transects for both ST surveys and distance sampling. Once a colony was located, its position was determined by global positioning system (GPS) so that its distance, perpendicular to the transect line, could be determined. We used the program DISTANCE (Thomas et al. 2006) to estimate the detection function, number of colonies, and colony density. Because of large error in colony size estimates from fixed-winged aircraft (Green et al. 2008), we did not include colony size as a covariate in the estimation procedures.

Adaptive cluster sampling. For each study site, we used a geographic information system (GIS; ArcView 3.2, Environmental Systems Research Institute, Redlands, CA) to create a grid cell, with individual cell dimensions of 4 km × 4 km. We then used the Random Sampling Tools extension for ArcView 3.2 to randomly select a set of cells (center point of each cell) from each study-site grid for determining our initial sampling cells, or initial sampling clusters, for ACS. If the initial sampling cluster satisfied the condition (≥1 active colony), then all clusters sharing a common side with the initial sampling cluster, or primary unit, were also sampled; these secondary sampling clusters are referred to as a neighborhood. This process continued until the network (consists of primary and secondary units) was surrounded by clusters that failed to satisfy the condition (≥1 active colony); these clusters are called "edge units." The network plus the edge units represents the ACS cluster. All clusters were surveyed by flying to the center point of the 4 km × 4 km cluster, then proceeding past the center point for approximately 1 km before initiating the turn and flying a square at approximately 1 km from the center point and looking out both sides of the aircraft. Flying a square route (rather than a circle) enabled us to keep the aircraft level for most of the survey to minimize the difficulty of seeing out both sides of the aircraft while turning. We flew this route twice for each cluster.

We calculated estimated mean densities and variances using Hansen–Hurwitz (HH) and Horvitz–Thompson (HT) estimators (Thompson and Seber 1996). The HT estimator is based on initial intersection probabilities between sampling units and networks whereas the HH estimator is based on the initial number of actual intersections. Estimators were calculated using the SAS macro published in Philippi (2005). We also calculated the ratio of standard errors of estimates from ST and ACS to evaluate the efficiency of each sampling method (Noon et al. 2006).

Spatial dispersion. The precision and accuracy of survey sampling methods may be influenced by the spatial dispersion of the targets. ACS is more effective when targets of interest are aggregated, whereas distance sampling is considerably more efficient when individuals are uniformly scattered or randomly dispersed (Thompson 1990, Thompson and Seber 1996). Using the known locations of all known active colonies found during our study, we calculated an index of dispersion (ID) and a test statistic to determine if the spatial pattern (colony locations) departed significantly from a random pattern (Ludwig and Reynolds 1988). If a Poisson distribution is rejected, computing the Green's Index (Ludwig and Reynolds 1988) provides an estimate of the degree of clumping, with 1.0 signifying complete clumping (e.g., all colonies located in a single sampling cell).

RESULTS

For our initial sampling, ST surveys, distance sampling, and ACS were conducted on approximately 20% of the total area of each study site. In May 2004, we flew 27 STs (540 km^2) and 42 initial adaptive clusters (672 km^2) over AB (Fig. 1, Table 1). Because we located colonies in our initial clusters, we sampled the neighborhoods of those clusters, resulting in a total of 58 clusters surveyed (928 km^2). In AB, we detected nine and eight colonies using the ACS and ST/distance sampling methods, respectively. Neither ACS estimator of number of colonies was within the 95% confidence interval of the estimate from ST; ST estimated 2–3 times more colonies than either ACS estimator (Table 1). The MNKC (Green et al. 2006) for the AB was 33, well within the 95% confidence interval of $\hat{Y}$ by ST sampling.

Distance sampling for the AB was based on only eight colonies, so estimates should be viewed with caution. The estimated half-strip width was 1114.7 m (L95% CI–U95% CI = 685.1–1813.7 m). The estimated number of colonies was 32 (CI = 16–66), close to the estimate for ST sampling.

During May–June 2005, we initially flew 58 STs (580 km^2) and 41 adaptive clusters

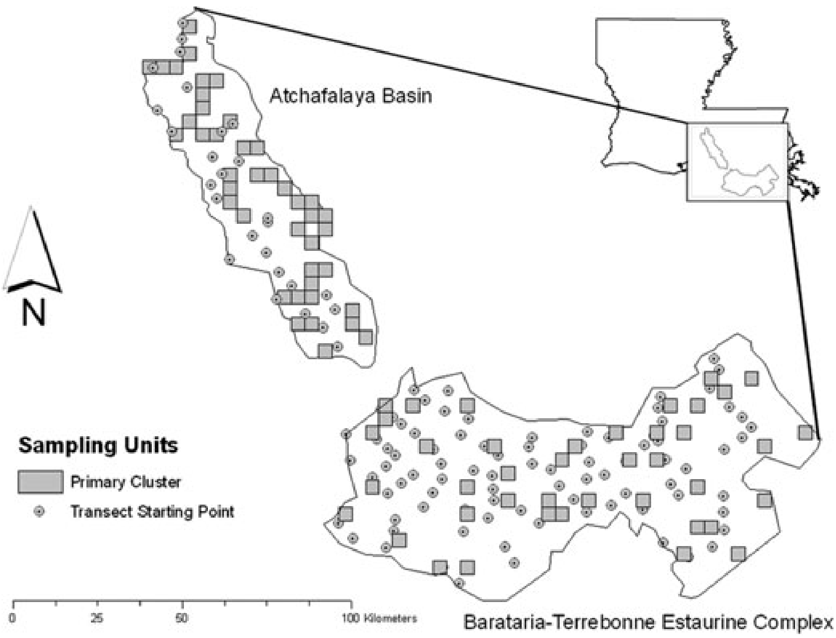

Fig. 1. Location of two study sites, Atchafalaya Basin and Barataria-Terrebonne Estuarine Complex, in southern Louisiana, USA.

(656 km^2) over BTE (Fig. 1). Because we detected colonies within our initial clusters, we surveyed the neighborhoods, resulting in a final sample size of 82 clusters (1312 km^2). Due to the much larger area surveyed by ACS, we increased our total number of STs surveyed to 86 transects (860 km^2). In the BTE, we detected 14 and 12 colonies using the ACS and ST methods, respectively. Similar to the results for the AB, neither ACS estimator was within the 95% confidence interval of the ST estimate; the ST estimate was 3–5 times larger. The known number of colonies (Green et al. 2006) within the BTE was 20, similar to estimates of $\hat{Y}$ by HT and HH estimators.

The estimated half-strip width for the BTE was 985.6 m (L95%CI–U95% CI = 663.7–1463.6 m). This value was similar to that obtained for the AB, indicating that detectability did not vary greatly between the two habitats. The estimated number of colonies using the distance sampling method was 60 (31–113), considerably higher than the known number of colonies.

The ST and distance sampling methods consistently estimated higher densities of colonies/km^{-2} than the ACS method (Table 2). The two survey methods varied in their efficiency of sampling, with ST more efficient in the AB and ACS more efficient in BTE. For both study sites, the distributions of waterbird colonies were significantly different from random patterns and were spatially clumped (AB: GI = 0.064, ID = 1.96, $P = 0.004$; BTE: GI = 0.120, ID = 2.79, $P < 0.001$). Based on Green's Index of clumping, the deviation from randomness was twice as high for BTE than for AB.

DISCUSSION

Our comparisons of ACS, ST, and distance sampling methods for estimating the number of colonies in an area revealed different results for each method for our two study sites. In the AB, the estimated mean number of colonies using ST and distance sampling methods was close to the MNKC, whereas the ACS method resulted in underestimates. Although it may not represent the true count of all colonies within the study area, the MNKC does illustrate that at least 33 active colonies were located in the study area at the time of our surveys and that ACS estimates were grossly underestimated. Furthermore, both

Table 1. Estimates of the number of waterbird colonies ($\hat{Y}$) and 95% confidence intervals (CI) for the Atchafalaya Basin (AB) and the Barataria-Terrebonne (BTE) study areas using adaptive cluster sampling (ACS) Estimators (Horvitz–Thompson [HT] and Hansen–Hurwitz [HH]), Strip-transect (ST) surveys, and distance sampling. Also reported are the total number of sampling units for ACS, initial ACS sample size, final ACS sample size, total number of units with colonies (ACS, ST, and distance sampling), and the range of ACS network size. The total number of transects (N) and transects with colonies (N with colonies) was the same for both ST and distance sampling.

	Sampling method										
	ACS							Transects (ST and distance sampling)			
Study area	N_{TOT}	N_{ACS} initial	N_{ACS} final	N_{ACS} with colonies	Network total (range)	$\hat{Y}_{HT}$ (CI)	$\hat{Y}_{HH}$ (CI)	N	N with colonies	$\hat{Y}_{ST}$ (CI)	$\hat{Y}_{DIST}$ (CI)
AB	150	42	58	5	17 (1–22)	10.6 (5.6–16.7)	5.01 (0.0–11.4)	27	8	35.56 (32.9–38.3)	32[a] (15–66)
BTE	394	41	82	12	30 (1–21)	20.49 (9.3–31.7)	14.15 (2.3–26.0)	86	12	87.94 (82.9–92.9)	60[b] (31–113)

[a]Estimated half-width = 1114.7 m (CI = 685.1–1813.7 m).
[b]Estimated half-width = 985.6 m (CI = 663.7–1463.6 m).

transect-based approaches were more efficient, in terms of increasing the precision of estimates, than the ACS approaches.

In the BTE complex, ST and distance estimates of >60 colonies seem biologically unrealistic because only 17 active colonies were known in the area from MNKC; this estimate from MNKC is similar to that determined using the ACS_{HT} method. Although there were over 49 known colony locations (active and inactive) in the BTE complex, colony activity is ephemeral and many colonies have not been active for ≥10 yr (Green et al. 2006). Assuming that the point-to-point method detects all colonies within 986 m (the half-strip detection distance estimated for BTE), we probably surveyed 20% of the total study area. During the ST and ACS flights, we surveyed an additional 25% of the study area (45% total) and only detected two new active colonies. Thus, it seems likely that the estimates of large numbers of currently undetected colonies in the BTE, based on transect approaches, are not realistic. In addition to being more biologically realistic for the BTE study area, ACS estimators were slightly more precise than the ST estimator, although efficiency was still low compared to the distance estimator. However, the gain in efficiency over ACS would not be enough to favor use of the distance estimator for future surveys in habitats like the BTE, given that its estimates were apparently biased upward and biologically unrealistic.

The difference in estimates and in which estimator performed better may be due to more heterogeneous habitat in the BTE site than the mostly contiguous AB. The ACS method assumes that targets of interest (e.g., colonies) are spatially clumped and not uniformly distributed across the landscape, whereas ST surveys assume uniform distribution (Barry and Welsh 2001, Welsh 2002). Our estimates of spatial patterning revealed that waterbird colonies in both study sites were clumped, even though the habitats vary in heterogeneity. Of 14 colonies detected during ACS sampling in BTE, 11 were within two networks (out of 30 total networks); this is in agreement with the dispersion index that estimated colonies in BTE to be twice as clumped as colonies in AB. It is not clear whether waterbird colonies will also be more clumped in coastal marshes than forested wetlands in other locations. However, if this pattern is applicable to other study sites, ACS approaches

Table 2. Estimated colony density (colonies km^{-2}) and relative sampling efficiency from Atchafalaya Basin (AB) and Barataria-Terrebonne Estuary (BTE), Louisiana, USA (2004–2005) based on three different sampling methods: strip transect (ST), distance sampling, and adaptive cluster sampling using the Horvitz–Thompson estimator (ACS_{HT}). Relative sampling efficiency was calculated for ST and distance sampling relative to ACS_{HT}. A ratio larger than 1 indicated greater efficiency for ACS_{HT}.

	Sampling method							
	ST		Distance sampling		ACS_{HT}		Relative efficiency	
Study area	Density	SE	Density	SE	Density	SE	Ratio[a]	Ratio[b]
AB	0.015	0.0118	0.013	0.0049	0.071	0.0173	0.681	0.283
BTE	0.014	0.0148	0.009	0.0031	0.052	0.0144	1.030	0.215

[a]Ratio = $SE[\mu]_{ST}/SE[\mu]_{ACS}$.
[b]Ratio = $SE[\mu]_{DIST}/SE[\mu]_{ACS}$.

would be preferred in the former and transect-based approaches in the latter. Of the two ACS estimators, HT estimated a greater number of colonies for both sites and produced an estimate similar to the known number of colonies in the BTE complex, providing additional support for use of HT estimators in ecological studies (Salehi 2003).

ACS and ST methods do not account for variation in detection probability. Although we were confident, we sampled each transect/cluster extensively enough to be sure we did not miss any large colonies (>50 breeding pairs) and no known colony in an ACS plot went undetected, the inability to account for the possibility of undetected colonies is a universal problem associated with aerial surveys (Frederick et al. 1996).

The ST and distance methods produced similar estimates of colony numbers. This might not be surprising given that the half-strip widths we used for ST estimates were conservative based on the half-strip estimates of detectability obtained from distance sampling. Given that little additional time is required to conduct distance sampling, we suggest that distances of colonies from transects be obtained because doing so permits determining an estimate of detectability. This could be important when comparing estimates from different habitats. Furthermore, our results suggest that the 2.5-km half-width strips used by Rodgers et al. (2005) may result in many undetected colonies in the habitats we surveyed.

An assumption of distance sampling is that distances from transect to surveyed objects are measured accurately (Buckland et al. 2001). This has been historically difficult to achieve for aerial surveys, but is more feasible with the use of GPS. However, in addition to the inherent error associated with GPS, errors in accuracy can occur when making a GPS fix on the transect and when located over a colony. Reaction time and decisions about what actually represents the center of a waterbird colony can produce inaccuracies in distance measurements, potentially violating a major assumption of distance sampling. However, given that our distance estimates were similar to those based on a fixed width, errors associated with distances from the transect line were likely not a significant source of bias in our study.

An assumption of both transect methods is that all colonies have equal detectability. We did not have sufficient data to test the effects of violating this assumption, but suspect that both the number of nesting pairs and species composition (Green et al. 2008) affected detectability of colonies. The use of these variables as covariates in estimation procedures would be possible if numbers could be estimated accurately. For this reason, and to improve estimates of distances between transects and colonies, we suggest that helicopters, rather than fixed-wing aircraft, be used whenever possible (Green et al. 2008).

For the AB, we detected no new colonies using either ACS or ST surveys, and both methods resulted in locating fewer colonies than known to be present. Use of the ACS method was ineffective and inefficient and the transect methods produced estimates of colony number similar to those of the point-to-point survey. In the AB, the point-to-point survey method appeared to be suitable for monitoring existing colonies. However, the point-to-point survey method does not provide an estimate of colonies that would be missed or a measure of error in estimates of colony number. In the BTE, the point-to-point method appears inadequate because of the limited search area and because new colonies were detected using the other methods. The point-to-point method appears to be useful only for continued monitoring of known colonies and is not a viable option for locating and estimating the number of colonies in a given area. We recommend that, in addition to monitoring known colony locations with point-to-point flights, the ACS or ST methods, depending on habitat, be used regularly, both to estimate colony number and detect new colonies. Because none of the survey methods we used assure 100% detection probability, missing an entire cluster of colonies could have significant conservation and management implications. If the chance of missing colonies in a survey area is unacceptable for a given management plan, then a systematic survey covering 100% of the study area would be the only alternative.

When conducting colony surveys, investigators must decide whether to adopt one method for estimating the number of colonies, regardless of habitat, or to use several methods, with the choice of method depending on habitat, known information, and the species in question (Goldberg et al. 2007). Our results suggest there is no single best method for surveying waterbird colonies and prior knowledge of colony locations and habitat composition may provide sufficient information to select one method over another. In heterogeneous habitats where colonies are potentially clumped, the ACS method is preferable to the transect approaches. In more homogenous habitat, we recommend distance sampling from transects if distances to colonies from transects can be estimated accurately. Depending on management objectives, a complete, systematic survey of a study area may be warranted if the possibility of potentially missing large colonies is too high. If surveying an area with no historical information about colony location or the spatial aggregation of colonies, we recommend a coarse-scale analysis of the available habitat likely to contain waterbird colonies and the habitat's contiguity; this analysis will help determine the survey method that is most appropriate.

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LITERATURE CITED

Barry, S. C., and A. H. Welsh. 2001. Distance sampling methodology. Journal of the Royal Statistical Society B: Statistical Methodology 63: 31–53.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers, and L. Thomas. 2001. Introduction to distance sampling: estimating abundance of biological populations. Oxford University Press, Oxford, UK.

Buckley, P. A., and F. G. Buckley. 1976. Guidelines for the protection and management of colonial nesting waterbirds. U.S. National Park Service, Boston, MA, USA.

Burnham, K. P., D. R. Anderson, and J. L. Laake. 1980. Estimation of density from line transect sampling of biological populations. Wildlife Monographs 72: 7–202.

———, and ———. 1984. The need for distance data in transect counts. Journal of Wildlife Management 48: 1248–1254.

Erwin, R. M. 1982. Observer variability in estimating numbers: an experiment. Journal of Field Ornithology 53: 159–167.

Frederick, P. C., T. Towles, R. J. Sawicki, and G. T. Bancroft. 1996. Comparison of aerial and ground techniques for discovery and census of wading bird (Ciconiiformes) nesting colonies. Condor 98: 837–841.

———, B. Hylton, M. Ruane, and J. A. Heath. 2003. Accuracy and variation in estimates of large numbers of birds by individual observers using an aerial survey simulator. Journal of Field Ornithology 74: 281–287.

Goldberg, N. A., J. N. Heine, and J. A. Brown. 2007. The application of adaptive cluster sampling for rare subtidal macroalgae. Marine Biology (Berlin) 151: 1343–1348.

Green, M. C., M. C. Luent, T. C. Michot, C. W. Jeske, and P. L. Leberg. 2006. Statewide wading bird and seabird nesting colony inventory, 2004–2005. Louisiana Department of Wildlife and Fisheries, Louisiana Natural Heritage Program, Baton Rouge, Louisiana.

———, ———, ———, ———, and ———. 2008. Comparison and assessment of aerial and ground estimates of waterbird colonies. Journal of Wildlife Management 72: 697–706.

Hanselman, D. H., T. J. Quinn II, C. Lunsford, J. Heifetz, and D. Clausen. 2003. Applications in adaptive cluster sampling of Gulf of Alaska rockfish. Fisheries Bulletin 101: 501–513.

Keeland, B. D., and L. E. Gorham. 2009. Delayed tree mortality in the Atchafalaya Basin of southern Louisiana following Hurricane Andrew. Wetlands 29: 101–111.

KUSHLAN, J. A. 1979. Effects of helicopter censuses on wading bird colonies. Journal of Wildlife Management 43: 756–760.

LAAKE, J., R. J. GUENZEL, J. L. BENGTSON, P. BOVENG, M. CAMERON, AND M. B. HANSON. 2008. Coping with variation in aerial survey protocol for line-transect sampling. Wildlife Research 35: 289–298.

LEBERG, P. L., M. C. GREEN, B. A. ADAMS, K. M. PURCELL, AND M. C. LUENT. 2007. Response of waterbird colonies to hurricanes: loss of individual rookeries has little effect on regional breeding populations. Animal Conservation 10: 502–508.

LUDWIG, J. A., AND J. F. REYNOLDS. 1988. Statistical ecology: a primer on methods and computing. John Wiley and Sons, Hoboken, NJ.

MARTIN, R. P., AND G. D. LESTER. 1990. Atlas and census of wading bird and seabird nesting colonies in Louisiana: 1990. Louisiana Department of Wildlife and Fisheries Louisiana Natural Heritage Program. Special Publication No. 3, Baton Rouge, LA.

MICHOT, T. C., C. W. JESKE, J. C. MAZOUREK, W. G. VERMILLION, AND R. S. KEMMERER. 2003. Atlas and census of wading bird and seabird nesting colonies in south Louisiana 2001. Barataria-Terrebonne National Estuary Program Report No. 32, Thibodeaux, Louisiana.

NOON, B. R., N. M. ISHWAR, AND K. VASUDEVAN. 2006. Efficiency of adaptive cluster and random sampling in detecting terrestrial herpetofauna in a tropical rainforest. Wildlife Society Bulletin 34: 59–68.

OLIVER, J. D., AND T. LEGOVIC. 1988. Okefenokee marshland before, during and after nutrient enrichment by a bird rookery. Ecological Modelling 43: 195–223.

PHILIPPI, T. 2005. Adaptive cluster sampling for estimation of abundances within local populations of low-abundance plants. Ecology 86: 1091–1100.

PORTNOY, J. W. 1977. Nesting colonies of seabirds and wading birds – coastal Louisiana, Mississippi, and Alabama. U.S. Fish and Wildlife Service FWS/OBS-77/07, Washington, D.C.

RODGERS, J. A., P. S. KUBILIS, AND S. A. NESBITT. 2005. Accuracy of aerial surveys of waterbird colonies. Waterbirds 28: 230–237.

SALEHI, M. M. 2003. Comparison between Hansen-Hurwitz and Horvitz-Thompson estimators for adaptive cluster sampling. Environmental and Ecological Statistics 10: 115–127.

SEBER, G. A. F., AND S. K. THOMPSON. 1994. Environmental adaptive sampling. In: Handbook of statistics, volume 12 (G. P. Patel and C. R. Rao, eds.), pp. 201–220. Elsevier, New York, NY.

SMITH, D. R., M. J. CONROY, AND D. H. BRAKGAE. 1995. Efficiency of adaptive cluster sampling for estimating density of wintering waterfowl. Biometrics 51: 777–788.

THOMAS, L., J. L. LAAKE, S. STRINDBERG, F. F. C. MARQUES, S. T. BUCKLAND, D. L. BORCHERS, D. R. ANDERSON, K. P. BURNHAM, S. L. HEDLEY, J. H. POLLARD, J. R. B. BISHOP, AND T. A. MARQUES. 2006. Distance 5.0. Release 2. Research Unit for Wildlife Population Assessment, University of St. Andrews, St. Andrews, UK.

THOMPSON, S. K. 1990. Adaptive cluster sampling. Journal of the American Statistical Association 85: 1050–1059.

———, AND G. A. F. SEBER. 1996. Adaptive sampling. John Wiley, New York, NY.

VAN METER, R., L. L. BAILEY, AND E. H. CAMPBELL GRANT. 2008. Methods for estimating the amount of vernal pool habitat in the northeastern United States. Wetlands 28: 585–593.

VISSER, J. M., C. E. SASSER, R. H. CHABRECK, AND R. G. LINSCOMBE. 1996. Marsh-vegetation types of Barataria and Terrebonne estuaries: 1968-present. Barataria Terrebonne National Estuaries Program. Publication 29, Thibodaux, LA.

WELSH, A. H. 2002. Incomplete detection in enumeration surveys: whither distance sampling? Australian and New Zealand Journal of Statistics 44: 901–910.