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Field evaluation of distance-estimation error during wetland-dependent bird surveys

Christopher P. Nadeau[A,C,D] *and Courtney J. Conway*[B]

[A]Arizona Cooperative Fish and Wildlife Research Unit, 325 Biological Sciences East, University of Arizona, Tucson, AZ 85721, USA.
[B]US Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, Department of Fish and Wildlife Sciences, University of Idaho, Moscow, ID 83844, USA.
[C]Present address: New York Cooperative Fish and Wildlife Research Unit, Department of Natural Resources, Cornell University, Ithaca, NY 14853, USA.
[D]Corresponding author. Email: cpn28@cornell.edu

Abstract

Context. The most common methods to estimate detection probability during avian point-count surveys involve recording a distance between the survey point and individual birds detected during the survey period. Accurately measuring or estimating distance is an important assumption of these methods; however, this assumption is rarely tested in the context of aural avian point-count surveys.

Aims. We expand on recent bird-simulation studies to document the error associated with estimating distance to calling birds in a wetland ecosystem.

Methods. We used two approaches to estimate the error associated with five surveyor's distance estimates between the survey point and calling birds, and to determine the factors that affect a surveyor's ability to estimate distance.

Key results. We observed biased and imprecise distance estimates when estimating distance to simulated birds in a point-count scenario ($\bar{x}_{\mathrm{error}} = -9$ m, s.d.$_{\mathrm{error}} = 47$ m) and when estimating distances to real birds during field trials ($\bar{x}_{\mathrm{error}} = 39$ m, s.d.$_{\mathrm{error}} = 79$ m). The amount of bias and precision in distance estimates differed among surveyors; surveyors with more training and experience were less biased and more precise when estimating distance to both real and simulated birds. Three environmental factors were important in explaining the error associated with distance estimates, including the measured distance from the bird to the surveyor, the volume of the call and the species of bird. Surveyors tended to make large overestimations to birds close to the survey point, which is an especially serious error in distance sampling.

Conclusions. Our results suggest that distance-estimation error is prevalent, but surveyor training may be the easiest way to reduce distance-estimation error.

Implications. The present study has demonstrated how relatively simple field trials can be used to estimate the error associated with distance estimates used to estimate detection probability during avian point-count surveys. Evaluating distance-estimation errors will allow investigators to better evaluate the accuracy of avian density and trend estimates. Moreover, investigators who evaluate distance-estimation errors could employ recently developed models to incorporate distance-estimation error into analyses. We encourage further development of such models, including the inclusion of such models into distance-analysis software.

Additional keywords: detection probability, distance error, distance sampling, marsh birds.

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Introduction

Monitoring temporal and spatial variation in wildlife populations is a foundation of wildlife management. Therefore, collecting reliable data on which to base population-trend estimates is crucial (Thompson 2002). Heterogeneous detection probability can hinder our ability to accurately estimate population density or trends from count data. For this reason, many authors have recommended incorporating methods to estimate detection probability during surveys (Nichols *et al*. 2000, 2008; Farnsworth *et al*. 2002; Rosenstock *et al*. 2002; Thompson 2002). However, there is much debate over the use of methods to estimate detection probability versus the use of indices that do not try to model variation in detection probability when using count data to estimate population density or trends (Anderson 2001, 2003; Engeman 2002; Hutto and Young 2002, 2003; Ellingson and Lukacs 2003; Johnson 2008). Proponents of indices often argue that the assumptions of methods used to estimate detection probability cannot be met in a field setting and, hence, the methods do little to address the biases caused by temporal and spatial variation in detection probability (Hutto and Young 2002, 2003; Johnson 2008). More efforts to evaluate the assumptions inherent in the methods commonly used to estimate detection probability in a field setting could help resolve this debate (Buckland *et al*. 2001; Nichols *et al*. 2008).

The most common methods to estimate detection probability during avian surveys involve recording a distance between the survey point and individual birds detected during the survey period (Rosenstock *et al*. 2002). Furthermore, recent developments in methods to estimate detection probability suggest a combination of distance estimates and other ancillary data to produce a more robust estimate of detection probability (Farnsworth *et al*. 2002; Buckland *et al*. 2004; Kissling and Garton 2006; Alldredge *et al*. 2007*a*, 2007*b*). Accurately estimating distance from the surveyor to birds detected during a survey is an important assumption of all these methods; however, this assumption is likely to be violated in many avian monitoring efforts (Scott *et al*. 1981; Alldredge *et al*. 2007*b*, 2008; Camp 2007). Indeed, proponents of indices have argued that this assumption is difficult or impossible to achieve during most avian surveys (Hutto and Young 2002, 2003; Johnson 2008). Estimating distances to birds is difficult in many survey situations because birds are often detected aurally without being seen by the surveyor (Scott *et al*. 1981; Rosenstock *et al*. 2002; Nadeau *et al*. 2008). Consequently, surveyors must localise the bird using only the bird's call. The error when estimating distance to a bird's call may be large and accuracy is potentially influenced by many environmental factors (Scott *et al*. 1981; Alldredge *et al*. 2007*b*). Furthermore, the accuracy of distance estimates may vary both within and among surveyors (Scott *et al*. 1981; Alldredge *et al*. 2007*b*). The influence of distance-estimation errors (both biased and unbiased) on estimates of detection probability are well documented (Buckland *et al*. 2001, 2004). For these reasons, investigators may reach inappropriate conclusions regarding how bird density varies across years, study sites, or treatments if distance-estimation errors are not quantified and incorporated into analyses.

Numerous authors who have used distance functions to estimate detection probability during avian surveys have acknowledged that their distance estimates may not have been accurate (DeSante 1981, 1986; Tarvin *et al*. 1998; Norvell *et al*. 2003). However, it is very unusual to see quantitative evaluations of distance-estimation error in published analyses that use distance to estimate detection probability (Borchers *et al*. 2010) and few studies have evaluated the extent of distance-estimation error in the context of point-transect sampling. We are aware of only four studies that quantified distance-estimation error in the context of avian point-count surveys (Scott *et al*. 1981; Ransom and Pinchak 2003; Alldredge *et al*. 2007*b*; Camp 2007), and only two of these studies quantified distance-estimation error associated with birds detected aurally (Scott *et al*. 1981; Alldredge *et al*. 2007*b*). Three of the four studies quantified distance-estimation error associated with bird surveys within forest-dominated plant communities. Hence, more work is needed to quantify the extent of distance-estimation error in other ecosystems.

Quantifying distance-estimation error is not only important to evaluate the assumption that surveyors accurately estimate distance to birds detected during a point-count survey, but can also provide critical information necessary to develop models that incorporate distance-estimation error into data analyses. Numerous methods have been proposed to incorporate distance-estimation error during analyses of survey data (see Marques 2004; Borchers *et al*. 2010, for reviews). However, biometricians have little data from realistically simulated surveys on which to base these models. Hence, more data are needed to quantify distance-estimation error during bird surveys so that biometricians can model error structure and develop better methods to incorporate distance-estimation error into analyses of avian point-count surveys.

The objectives of our study were to (1) evaluate the bias and precision of distance estimates during aural point-count surveys for wetland-dependent birds, (2) identify factors that cause distance-estimation errors during surveys for wetland-dependent birds, and (3) provide information on the structure of distance-estimation errors to inform the development of models used to correct for such errors. Our work builds on the two studies that have quantified distance-estimation error to aurally detected birds during bird surveys in forest ecosystems (Scott *et al*. 1981; Alldredge *et al*. 2007*b*), by extending those approaches to a wetland ecosystem. Moreover, our work extends recent novel approaches to simulate bird calls in a field setting so as to test the assumptions of point-count surveys (Alldredge *et al*. 2007*b*, 2008; Simons *et al*. 2007). The expansion of these methods was advocated by the participants of a recent workshop on the models used to estimate detection probability during avian point-count surveys (Nichols *et al*. 2008).

We focussed our study on six species of wetland-dependent birds, including pied-billed grebes (*Podilymbus podiceps*), least bitterns (*Ixobrychus exilis*), and four species of rail. These birds are ideal subjects for the present study because they are inconspicuous and rarely detected visually during point-count surveys (Tacha and Braun 1994; Conway *et al*. 2004; Nadeau *et al*. 2008). Moreover, distance sampling has been proposed as one approach for estimating components of detection probability during standardised surveys of wetland-dependent birds in Canada (Jobin *et al*. 2011) and throughout North America (Conway and Timmermans 2005; Conway and Droege 2006; Conway 2009, 2011). However, investigators need to evaluate the bias and precision of distance estimates to wetland-dependent birds during point-count surveys if future investigators intend to use distance sampling in analyses of survey data generated by these regional and continental monitoring programs.

Materials and methods

Study area

We tested surveyors' ability to estimate distance to wetland-dependent birds at the following five study sites in the southwestern United States: Sonny Bono-Salton Sea National Wildlife Refuge in California, north of the Imperial Dam in California, Imperial National Wildlife Refuge in Arizona (two study sites) and Mittry Lake Wildlife Area in Arizona. Marshes within each study site were either impoundments managed for rails, or seep marshes adjacent to irrigation canals. Dominant vegetation in each marsh was either southern cattail (*Typha domingensis*) or chairmaker's bulrush (*Schoenoplectus americanus*) and ranged in height from 1 to 3 m.

Estimating distance during simulated point-count surveys

We evaluated the bias and precision of distance estimates during 20 simulated point-count surveys in June 2006. We completed four simulated point-count surveys at each of the five different study sites. We used five to six CD players attached to portable speakers placed at water level within the emergent marsh vegetation to simulate vocalisations of wetland-dependent birds at each study site. We placed CD players 5–251 m ($\bar{x} = 102$ m, s.d. = 53 m) from survey points. The CD players remained in the same locations for each of the four simulated surveys at each study site, and the surveyors rotated among survey points for each simulated survey. We placed survey points on the interface of the upland and emergent marsh vegetation as per recommendations from standardised survey protocols in North America (Conway 2009, 2011). We used a Garmin eMap (Olathe, KS, USA) global positioning system (GPS) receiver to record the location of each CD player and survey point. We also recorded the azimuth for the direction in which the speakers pointed. We used a geographic information system (GIS) to (1) calculate the distance between each survey point and each CD player, and (2) determine whether the speakers pointed towards or away from the surveyor. Ideally, we would have measured the distance to each CD player with a tape measure; however, walking a straight line through the dense marsh vegetation with a tape measure in hand was impossible.

Each CD player broadcast one of 48 different combinations of vocalisations throughout the survey. We used the most common calls for five focal species during the simulated point-count surveys, as follows: pied-billed grebe (*owhoop* and *hyena*), least bittern (*coo* and *kak*), black rail (*Laterallus jamaicensis*, *kicky-doo* and *grr*), clapper rail (*Rallus longirostris*, *kek* and *clatter*) and Virginia rail (*Rallus limicola*, *grunt* and *ticket*). We did not broadcast the calls of the sixth species (common moorhen) included in our analysis. Detailed descriptions and digital examples of these calls are available at http://ag.arizona.edu/research/azfwru/NationalMarshBird (verified 7 April 2012). Each simulated point-count survey lasted 5 min and we broadcast 6–12 bird calls during the 5-min period (i.e. surveyors had the opportunity to estimate a distance to 6–12 bird calls during each 5-min simulated survey). The 6–12 bird calls broadcast during each 5-min survey were a mix of species (3 or 4 species from the list above) and a mix of call types (1 or 2 call types for each species). We broadcast some species and call types more than once during each survey, which reflects what a surveyor might encounter during an actual point-count survey for wetland-dependent birds. We broadcast each call at ~90 dB, measured 1 m from the speaker. We broadcast a subset of calls ($n = 32$) at ~70 dB, measured 1 m from the speaker during 15 of the surveys to evaluate whether volume of a bird's call influenced the accuracy of distance estimates. We also varied the length of time we played each call (0.5, 1 and 2 min) to determine whether the duration of the call influenced the accuracy of distance estimates.

Each simulated point-count survey involved three surveyors (standing at different survey points) who had prior experience surveying wetland-dependent birds, but differed in their training and experience estimating distance to birds; Surveyor 1 had 12 months of prior experience surveying wetland-dependent birds at our study sites and had training estimating distance to wetland-dependent birds at the locations where the field trials took place; Surveyor 2 had 3 months of prior experience surveying wetland-dependent birds at our study sites and prior experience and training estimating distance to forest birds, but had no training estimating distance to wetland-dependent birds; and Surveyor 3 had 3 months of prior experience surveying wetland-dependent birds at our study sites, but no training estimating distance to birds. Each surveyor recorded all wetland-dependent birds (simulated or real) heard during the survey period. Surveyors recorded the species, call type, minute during the survey when they detected each call, and estimated a distance to each call, as they would during a typical survey following the Standardised North American Marsh Bird Monitoring Protocol (Conway 2009, 2011). Surveyors also recorded the direction to each call and whether they thought they could see the location within the marsh where the call originated. We used this information during analysis to distinguish each surveyor's distance estimates to the real and simulated birds that they detected during the survey period. We compared the surveyor-estimated distance to each simulated bird with the GIS-measured distance to each simulated bird, to determine the error associated with each surveyor's distance estimates. The three surveyors did not discuss their distance estimates after each survey.

We tested the accuracy of the GIS-measured distances at each study site to ensure that the errors we observed in the surveyor-estimated distances (i.e. surveyor-estimated distance minus GIS-measured distance) were not caused by inaccuracies in the GIS-measured distances. We used a tape measure to measure a distance of 240–300 m (depending on the study site) along a road next to the edge of the marsh at each of the five study sites and flagged points at 30-m increments. The maximum distance varied among study sites because of the length of the road next to each study site. We then used four GPS receivers to determine the geographic coordinates at each 30-m increment, including the start point. We used four GPS receivers to estimate error during these trials because we used more than one GPS receiver during the simulated point-count surveys. We imported the geographic coordinates into a GIS and determined the distance from the start point to each 30-m increment, following the same procedures as we used for the simulated point-count surveys. We calculated the error in each GPS receiver as the GIS-measured distance from the start point minus the tape-measured distance from the start point. We measured the distance with the tape measure along a road next to the marsh, rather than in the marsh vegetation, because walking a straight line through the dense marsh vegetation with a tape measure in hand was impossible. However, we did take 4–10 GPS readings within the marsh vegetation at three of the study sites to compare the following measurements to the measurements taken along the road: (1) the number of satellites visible to the GPS receiver, and (2) the estimated accuracy as reported by the GPS.

Estimating distance to real wetland-dependent birds

We estimated the bias and precision of distance estimates to real wetland-dependent birds during 59 field trials. Each field trial involved 3–5 surveyors (five surveyors in total, including the three surveyors from the simulated point-count surveys). The two additional surveyors in these field trials had prior experience surveying wetland-dependent birds, but differed in their experience estimating distance to birds; Surveyor 4 had 12 months of prior experience surveying wetland-dependent birds at our study sites and had training estimating distance to wetland-dependent birds at the locations where the field trials took place; and Surveyor 5 had 3 months of prior experience surveying wetland-dependent birds at our study sites, but no training estimating distance to birds. The surveyors walked along a road parallel to the edge of the marsh during each field trial, stopped when they heard a bird calling, and took 15–30 s to estimate a distance to the bird. The surveyors made certain that they estimated the distance to the same bird using the direction to the bird, and the frequency and timing of the bird's call, but did not discuss their distance estimates or the location of the bird relative to any wetland features. Each surveyor also used a compass to estimate an angle to each calling bird relative to the road which paralleled the edge of the marsh. We repeated this process during each of the 59 field trials for 59 individual birds, including one pied-billed grebe, 15 least bitterns, five black rails, 34 clapper rails, three Virginia rails and one common moorhen (*Gallinula chloropus*).

We estimated the distance from the surveyors to each of the 59 birds using trigonometry so that we could estimate the error associated with the distance estimates to each bird. After each surveyor estimated the distance and angle to the focal bird, one surveyor walked down the road until he thought he was 90 degrees from the calling bird. This surveyor used a GPS receiver to record (1) the location where the surveyors stood when they estimated distance to the bird, and (2) the location along the road that was 90 degrees from the bird. This process occurred within ~1 min of when the surveyors estimated distance to the bird. We calculated the trigonometry-estimated distance to the bird as $x / COS\theta$, where x is the distance along the road between the location where the surveyors estimated distance and the location 90 degrees from the bird, and θ is the mean of the 3–5 angle measurements that the surveyors recorded. We estimated the error associated with each distance estimate as the surveyor-estimated distance to each bird minus the trigonometry-estimated distance to each bird. We did these calculations after we completed all the field trials so that the surveyors were unaware of how accurate they were during the field trials.

We used the trigonometry-estimated distance to each bird to help evaluate the accuracy of surveyor-estimated distances because it is impossible to enter the marsh vegetation to determine the true location of the calling bird without tremendous disruption to, and movement by, the focal bird. Furthermore, wetland-dependent birds on our study sites rarely flush when disturbed. Despite the possible error associated with this method, we were unable to think of a more accurate method for evaluating distance estimates to actual wetland-dependent birds calling within a dense emergent marsh. Hence, we present the results of these trials as a supplement to the results from the simulated point-count surveys. We encourage future studies to test the accuracy of this method because the method could provide a time-efficient means of evaluating the accuracy of distance estimates to wetland-dependent birds in future survey efforts.

Factors affecting the accuracy of distance estimation

We used variable weights (Burnham and Anderson 2001; Anderson 2008) based on Akaike's information criteria adjusted for small samples (AICc, Burnham and Anderson 2001) to evaluate the relative importance of a suite of explanatory variables at explaining the error in surveyor-estimated distance. Variable weights are a sum of the AICc model weights (Burnham and Anderson 2001; Anderson 2008) for all models where the variable is present, based on models for all possible combinations of fixed-effect explanatory variables of interest. Explanatory variables with higher weights are considered better at explaining variation in the response variable. Ranking the relative importance of variables on the basis of variable weights is an exploratory method used to narrow a large list of variables to those that are important when little *a priori* knowledge is available to determine which explanatory variables warrant further study (Anderson 2008). This method was ideal for our study because a large number of potential variables could affect distance-estimation error; however, few studies have evaluated which variables are most responsible for errors in surveyors' estimates of distance to birds during aural surveys. We used the model.avg function in the Multi-model Inference package (Barton 2010) in the statistical program R (R Development Core Team 2010) to determine the variable weights for each fixed-effect explanatory variable of interest. We ranked the importance of variables in explaining the distance-estimation errors observed during the simulated point-count surveys separate from distance-estimation errors when estimating distance to real birds.

We ranked the relative importance of the following eight fixed-effect explanatory variables at explaining the distance-estimation errors we observed during our simulated point-count surveys: the GIS-measured distance to the bird, whether the surveyor thought they could see the general area within the marsh where the bird call originated, the species of bird, the surveyor, the volume of the call-broadcast (70 or 90 dB), the direction the speakers were facing (towards or away from the surveyor), the duration of each simulated bird call that the surveyors detected, and the number of individual birds detected (both real and simulated) by the surveyor during the 5-min point-count survey. Previous studies have suggested that many of these variables could influence the accuracy of distance estimates (Scott *et al*. 1981; Alldredge *et al*. 2007*b*); however, few of these variables have been evaluated in a field setting. We included the following two random effects in each model used to calculate the fixed-effect variable weights (i.e. models with all combinations of the fixed-effect variables): (1) survey point, and (2) location of the CD player broadcasting the calls for each simulated bird. These random effects helped account for the within-point and within-CD player variance caused by (1) surveyors estimating distances to multiple birds from the same survey point, (2) broadcasting multiple calls from the same CD players during the same simulated point-count survey and (3) CD players remaining in the same location across all four simulated surveys at a study site.

Similar to our approach with simulated birds described above, we ranked the relative importance of the following four fixed-effect explanatory variables at explaining the distance-estimation errors we observed when estimating distance to real birds: the trigonometry-estimated distance to the bird, whether the surveyor thought they could see the general area within the marsh where the bird call originated, the species of bird and the surveyor. We included a random effect for trial number in each model used to calculate the variable weights to account for within-trail variance caused by distance estimates taken by the 3–5 surveyors to the same bird from the same location.

Results

Estimating distance during simulated point-count surveys

Surveyors estimated 291 distances to simulated birds at distances ranging from 5 to 239 m ($\bar{x}$ = 90 m, s.d. = 47 m). Errors in distance estimates (i.e. surveyor-estimated distance minus GIS-measured distance) to the simulated birds during a point-count survey ranged from –167 to 236 m ($\bar{x}$ = –9 m, s.d. = 47 m; Figs 1*a*, 2*a*). We observed errors between 0 and 29.88 times the GIS-measured distance ($\bar{x}$ = 0.61, s.d. = 2.08). The GIS-measured distance to the simulated bird, species, call volume and surveyor were the highest-ranked variables in explaining variation in the distance-estimation error among the eight variables we examined (Tables 1–3). All surveyors were more likely to overestimate distance to simulated birds close to them (<72 m) and underestimate distance to birds farther away (>72 m; the *x*-intercept in Fig. 1*a* for all observers pooled). The slope of this relationship was steepest for Surveyor 3, who had the least amount of prior experience estimating distance to birds (short-dashed line in Fig. 1*a*). The mean error was 0 m (s.d. = 55 m, *n* = 29) when estimating distance to pied-billed grebes, 0 m (s.d. = 45 m, *n* = 72) to least bitterns, –24 m (s.d. = 32 m, *n* = 48) to black rails, –14 m (s.d. = 48 m, *n* = 115) to clapper rails and 6 m (s.d. = 50 m, *n* = 32) to Virginia rails. The mean error was 18 m (s.d. = 58 m, *n* = 27) to birds broadcast at 70 dB and –11 m (s.d. = 45, *n* = 263) to birds broadcast at 90 dB. We observed differences in distance estimates of 0–120 m ($\bar{x}$ = –22 m, s.d. = 39 m, *n* = 19) when the same surveyor estimated a distance to calls broadcast at different volumes (70 and 90 dB) from the same location. Surveyors estimated different distances to calls broadcast at different volumes from the same location in 63% of the cases. The bias and precision of distance estimates to

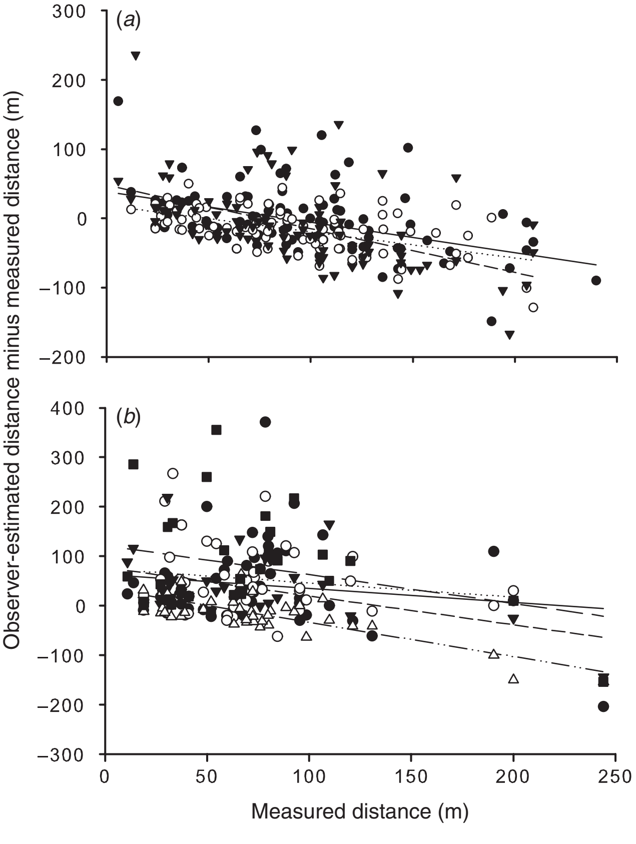

Fig. 1. Surveyors' abilities to estimate distance to a calling bird was linearly related to the distance to (*a*) CD players and speakers broadcasting calls of wetland-dependent birds during simulated point-count surveys, and (*b*) real birds during field trials. Each surveyor differed in the amount of prior experience and training in estimating distance to birds during surveys. Filled circles and the solid line represent Surveyor 1, open circles and the dotted line represent Surveyor 2, filled triangles and the short-dashed line represent Surveyor 3, open triangles and dotted-dashed line represent Surveyor 4, and filled squares and the long-dashed line represent Surveyor 5.

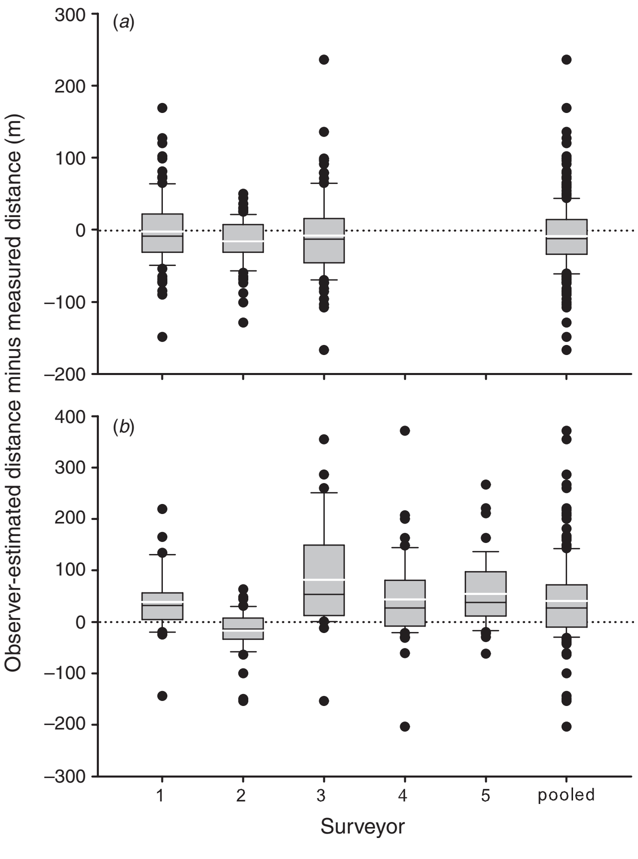

Fig. 2. Differences among surveyors in the bias and precision of distance estimates to (*a*) CD players and speakers broadcasting calls of wetland-dependent birds during simulated point-count surveys, and (*b*) real birds during field trials. Black lines in the box plot represent the median difference and white lines represent the mean difference between estimated and measured distances. The whiskers on each box represent the 10th and 90th percentiles of the estimation error. The dotted line in each panel indicates the optimal scenario where estimates of distance are without error.

Table 1. Ranked importance of eight explanatory variables at explaining the error associated with 291 distance estimates to CD players and speakers that were used to simulate birds in emergent wetlands during a point-count scenario, and four explanatory variables at explaining the error associated with 206 distance estimates to real birds in emergent wetlands during field trials

We used variable weights based on Akaike's information criteria adjusted for small samples (AICc) to rank the importance of each variable at explaining distance-estimation error

Fixed-effect explanatory variable	AICc-variable weight	
	Simulated point-count surveys	Real-bird trials
Measured distance	1.00	1.00
Surveyor	1.00	1.00
Species	1.00	0.52
Call volume (70 or 90 dB)	1.00	
Origin of sound visible	0.63	0.44
Call in front or behind surveyor	0.33	
Call directed towards or away from surveyor	0.24	
Call duration	0.20	
Number of individuals detected during the simulated point-count survey	0.16	

simulated birds also varied among surveyors (Fig. 2*a*). Surveyor 1, who had the most experience estimating distance to wetland-dependent birds, was less biased than the other surveyors. Surveyor 2, who had prior experience estimating distance to forest birds, was more biased than was Surveyor 1, and more precise than were all the other surveyors.

Error in the GPS units ranged from –36 to 30 m ($\bar{x} = 1$ m, s.d. = 10 m, Fig. 3). We observed error in the GPS units between 0 and 0.5 times the tape-measured distance ($\bar{x} = 0.06$, s.d. = 0.09 m). The bias and precision of the GPS errors differed slightly among GPS units, with the majority of the large errors occurring in one GPS receiver (open circles in Fig. 3). The number of satellites ($\bar{x}_{\text{satellites in marsh}} = 9.4$, s.d.$_{\text{satellites in marsh}} = 1.4$; $\bar{x}_{\text{satellites out of marsh}} = 10.0$, s.d.$_{\text{satellites out of marsh}} = 1.1$) and the GPS accuracy as reported by the GPS ($\bar{x}_{\text{accuracy in marsh}} = 4.6$ m, s.d.$_{\text{accuracy in marsh}} = 0.7$ m; $\bar{x}_{\text{accuracy out of marsh}} = 4.4$ m, s.d.$_{\text{accuracy out of marsh}} = 0.8$ m) were similar between measurements taken in and out of the marsh. GPS error was not correlated with the tape-measured distance, suggesting that GPS error cannot explain the relationship between surveyor-estimated distances and GIS-measured distances during the simulated point-count surveys (Fig. 3).

Estimating distance to real wetland-dependent birds

We obtained 206 distance estimates to real birds during the 59 field trials because there were 3–5 surveyors involved in each field trail. The trigonometry-estimated distances to the 206 real birds ranged from 11 to 244 m ($\bar{x} = 69$ m, s.d. = 43 m). Errors in distance estimates (i.e. surveyor-estimated distance minus trigonometry-estimated distance) to real birds ranged from –204 to 371 m ($\bar{x} = 39$ m, s.d. = 79 m; Figs 1*b*, 2*b*). We observed errors between 0 and 20.53 times the true distance ($\bar{x} = 1.18$, s.d. = 2.03). The trigonometry-estimated distance and the surveyor were the highest-ranked variables in explaining variation in the distance estimation error among the four variables we examined (Tables 1–3). Similar to our results for the simulated birds, all surveyors were more likely to overestimate distance to real birds close to them (<143 m) and underestimate distance to real birds farther away (>143 m; the

Table 2. Model averaged coefficients for linear mixed-effects models used to estimate the relative importance of eight explanatory variables at explaining the error associated with 291 distance estimates to CD players and speakers that were used to simulate birds in emergent wetlands during a point-count scenario, and four explanatory variables at explaining the error associated with 206 distance estimates to real birds in emergent wetlands during field trials

The reference groups for categorical variables were Surveyor 1, black rail, origin of sound not visible, call volume 70 dB, and call directed towards the surveyor

Fixed-effect-independent variable	Simulated point-count surveys		Real-bird trials	
	Standardised β	s.e.	Standardised β	s.e.
Intercept	–16.6	8.4	9.4	31.6
Measured distance	–18.8	2.4	–21.4	7.0
Surveyor 2	–13.8	4.9	–44.2	13.2
Surveyor 3	–3.9	5.0	43.5	13.4
Surveyor 4			10.9	12.5
Surveyor 5			20.6	13.1
Species – clapper rail	16.2	6.1	45.0	22.7
Species – common moorhen			11.9	50.7
Species – least bittern	16.4	7.0	69.5	25.1
Species – pied-billed grebe	35.9	8.5	131.5	51.3
Species – Virginia rail	27.7	8.7	77.3	34.3
Origin of sound visible – yes	–16.8	9.8	–20.4	16.2
Call volume – 90 dB	28.2	7.7		
Call directed towards or away from surveyor – away	–4.1	5.4		
Call duration	1.3	2.7		
Number of individuals detected during the survey	–0.9	3.2		

Table 3. Models with the lowest five values of Akaike's information criteria adjusted for small samples (AICc) from a suite of all possible models used to determine the relative importance of variables in explaining the error associated with observer-estimated distance during simulated point-count surveys and real bird trials

Each model also included random effects (see Materials and methods). The lowest AICc values were 2938.037 and 2306.761 for the simulated point-count surveys and real bird trials, respectively. K is the number of parameters in each model

Model	*K*	ΔAICc	AICc weight
Simulated point-count surveys			
Measured distance + Surveyor + Origin of sound visible + Species + Call volume	13	0.000	0.197
Measured distance + Surveyor + Species + Call volume	12	0.809	0.132
Measured distance + Call direction + Surveyor + Origin of sound visible + Species + Call volume	14	1.816	0.080
Measured distance + Call duration + Surveyor + Origin of sound visible + Species + Call volume	14	1.997	0.073
Measured distance + Number of individuals detected + Surveyor + Origin of sound visible + Species + Call volume	14	2.033	0.071
NULL	4	69.434	1.7E–16
Real bird trials			
Measured distance + Surveyor + Species	13	0.000	0.344
Measured distance + Surveyor + Origin of sound visible	9	0.507	0.267
Measured distance + Surveyor	8	1.099	0.199
Measured distance + Surveyor + Origin of sound visible + Species	14	1.570	0.157
Surveyor + Species	12	5.980	0.017
NULL	3	47.527	1.6E–11

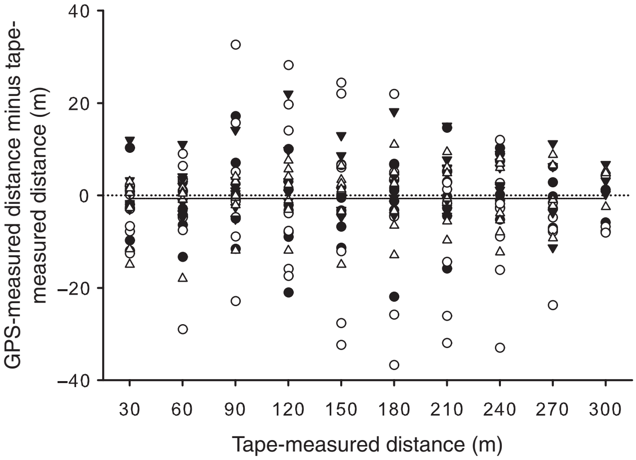

Fig. 3. Relationship between the GPS-measured and actual distances (measured with a tape measure). We observed the largest errors in one GPS receiver (open circles). The error associated with the GPS-measured distances was much smaller than the error associated with surveyor-estimated distances and we did not observe a linear relationship between the GPS-measured distance and the actual distance, as we did with surveyor-estimated distance. The dotted line represents no error in the GPS-measured distance and the solid line represents the observed linear trend in the GPS-measured distance as it is related to the actual distance.

x-intercept in Fig. 1*b* for all surveyors pooled) and the slope of this relationship was steepest for Surveyors 3 and 5 who had the least amount of prior experience estimating distance to birds. Surveyors differed in their bias and precision when estimating distance (Fig. 2*b*). Surveyors with more training and prior experience at estimating distance to birds were less biased and more precise (Surveyors 1, 2, and 4 in Fig. 2*b*).

Discussion

We observed both a greater degree of bias and imprecision in distance estimates than those reported in the two previous studies on aurally detected birds in forested ecosystems. Previous studies reported estimation errors between 0.25 and 4.00 times the true distance (Scott *et al.* 1981). Another study reported a mean error of only 9.0 m (s.d. = 25.8 m) with untrained surveyors and 7.6 m (s.d. = 21.4 m) with trained surveyors (Alldredge *et al.* 2007*b*). Our surveyors were similarly biased but much less precise. We may have observed larger errors for a variety of reasons. We used a much greater maximum distance in our field trials (244 m for real birds and 240 m for simulated birds) than did either of the previous studies (~75 m, Scott *et al.* 1981; and 96 m, Alldredge *et al.* 2007*b*). However, the error was still large when we truncated our data to measured distances <96 m ($\bar{x}_{\text{simulated birds}} = 7$ m, $\text{s.d.}_{\text{simulated birds}} = 40$ m, $\text{max}_{\text{simulated birds}} = 29.88$ times the measured distance; $\bar{x}_{\text{real birds}} = 48$ m, $\text{s.d.}_{\text{real birds}} = 75$ m, $\text{max}_{\text{real birds}} = 20.53$ times the measured distance). The results were also similar when we truncated the measured distance at 75 m ($\bar{x}_{\text{simulated birds}} = 9$ m, $\text{s.d.}_{\text{simulated birds}} = 40$ m, $\text{max}_{\text{simulated birds}} = 29.88$ times the measured distance; $\bar{x}_{\text{real birds}} = 42$ m, $\text{s.d.}_{\text{real birds}} = 70$ m, $\text{max}_{\text{real birds}} = 20.53$ times the measured distance). The distances we used in our field trials are representative of distances estimated during real point-count surveys for wetland-dependent birds (C. J. Conway, unpubl. data). The larger errors we observed in our field trials are more likely to be due to the nature of the environment we worked in and the nature of our field trials. Marshes are often composed of a monoculture of vegetation that does not provide a frame of reference on which to base distance estimates. This is especially true in the robust freshwater marshes where we conducted our field trials because the marsh vegetation was often >2 m tall and surveyors could often not see more than 1 m into the marsh. Hence, we may have observed larger errors because surveyors may have more difficulty judging the distance in marshes than in forests. Last, our simulated point-count surveys were more similar to an actual point-count survey than in past studies evaluating distance-estimation error. Past studies gave surveyors ample time to estimate distance to each focal bird and they did not ask surveyors to estimate distance to multiple birds calling simultaneously (Scott *et al*. 1981; Alldredge *et al*. 2007*b*). Surveyors in our simulated surveys were required to record distances quickly to multiple birds so as to ensure they could record all the birds they heard, which could have affected their ability to estimate distance. This is a potential scenario on actual point-count surveys.

Surveyors not only made large errors when estimating distance, they also tended to overestimate distances to birds close to the survey point. This pattern is especially serious because errors in distance estimates to birds close to the survey point are especially serious in any method using distance estimates to account for detection probability (Buckland *et al*. 2001). Overestimating distance to birds close to the survey point causes an overestimation of density estimated using distance sampling (Buckland *et al*. 2001). This tendency to overestimate distances to birds close to the point has been observed in the three other studies that evaluated surveyor error in distance estimates during avian point-count surveys (Scott *et al*. 1981; Alldredge *et al*. 2007*b*; Camp 2007). Overestimating distance to birds close to the survey point causes errors similar to those caused by evasive movement of target objects away from the survey point before detection; a known problem with point-transect sampling (Buckland *et al*. 2001). Grouping data so that objects that moved away from the point before detection are included in the first distance interval is one suggested solution to the evasive movement problem. This solution, combined with right-truncation to reduce errors caused by underestimating distance to birds far from the point, may help reduce the effect of distance-estimation error at the analysis stage.

The magnitude of the errors we observed suggests that surveyors would have often been inaccurate even if they collected data in *a priori* distance intervals, a method suggested by other authors to compensate for the errors inherent in distance estimation (Rosenstock *et al*. 2002; Ellingson and Lukacs 2003). Collecting distances in *a priori* distance intervals can be problematic for numerous reasons, including the following: (1) surveyors are subject to all the biases discussed here when they collect distances in *a priori* distance intervals, (2) the optimal distance intervals is likely to differ among species in a multi-species monitoring effort, and (3) the bias and precision of distance estimates differ among species (as demonstrated by our results). Furthermore, collecting distances in intervals will make the data much less flexible to data analysts. If data need to be analysed in grouped intervals, distances should be lumped into appropriate distance intervals during the analysis stage. Buckland *et al*. (2001) provided comprehensive guidelines for selecting intervals during analysis.

Our results suggest that some of the error we observed is avoidable. Training surveyors before conducting surveys (Reynolds *et al*. 1980; Scott *et al*. 1981; Buckland *et al*. 2001; Alldredge *et al*. 2007*b*) and encouraging surveyors to practice distance estimation to measurable distances repeatedly throughout the time when they are conducting surveys is likely to be the easiest way to reduce distance-estimation error. Our results suggest that training and experience in the environment where the monitoring is taking place can significantly improve a surveyor's bias and precision when estimating distance to calling birds. The trained surveyors in our study had limited training that did not involve estimating distance to simulated bird calls in the marsh vegetation. Extensive training using simulated birds could improve surveyors distance estimates. Training may also help eliminate the variation in distance-estimation error among surveyors, which could make modelling the effects of distance-estimation error more efficient by allowing analysts to pool data among surveyors in a study. Furthermore, the use of distance-estimation aides (e.g. range finders, flagging tape at known distances, aerial photographs with known distances from the survey point marked) is likely to improve distance estimates further (Buckland *et al*. 2001; Ransom and Pinchak 2003). Surveyors did not have these distance-estimation aides during our field trials. Range finders and flagging tape are often difficult to use in a wetland setting because of the inaccessibility and limited range of view caused by the wetland vegetation, whereas aerial photographs can be very helpful when estimating distance in wetlands.

Training surveyors and using estimation aides will not completely eliminate distance-estimation error because of the inability of surveyors to localise calling birds they cannot see (Alldredge *et al*. 2007*a*, 2007*b*). Distance-estimation errors caused by environmental variables such as bird behaviour (e.g. call volume) are difficult to measure and control because they are not measurable or predictable during an actual point-count survey. Our results suggest that changes in the volume of a bird's call will not only cause distance-estimation error, but could also cause surveyors to double-count birds that change the volume of their call during a point-count survey. Distance estimates during actual point-count surveys have varied by as much as four-fold for birds that remained in the same location but changed the volume of their call or turned their head during the survey (DeSante 1986). Changes in bird behaviour related to the distance from the surveyor could cause bias in the detection function generated from distance estimates. Black rails, for instance, often call softly when they are close to the surveyor (C. P. Nadeau, pers. obs.). Our results suggest that this behaviour could cause surveyors (especially inexperienced surveyors that are not aware of this behaviour) to overestimate distances to nearby birds.

Sound attenuation across different landscapes and vegetation types may also have a large effect on the perceived volume of the bird's call (Aylor 1972*a*, 1972*b*; Marten and Marler 1977) and therefore the perceived distance to the bird. Some wetland-dependent bird calls broadcast at 90 dB over open water can be heard up to 500 m away but can be difficult to hear at much closer distances when broadcast through dense vegetation (C. P. Nadeau, unpubl. data). Accounting for the effect of vegetation on distance estimates during an actual point-count survey may be difficult because the vegetation between the bird and the surveyor can be either unknown to the surveyor or so diverse that it would preclude generalisations about sound attenuation. Furthermore, different sound frequencies are attenuated by the same vegetation differently (Marten and Marler 1977). Therefore, different calls both within and among species, could attenuate differently from the same survey point. Hence, trends in vegetation changes over time could cause a bias in the distance estimates and the bias could vary among species (and among call types within species). Different frequency attenuation among species and call types might also explain why we observed differences in the accuracy of distance estimates among species. It is important to note that issues related to bird behaviour and sound attenuation are also problematic during the analysis of survey data that do not use distance estimates to attempt to estimate detection probability. More research is needed to address these issues (for wetland-dependent birds and other taxa) to help guide our interpretation of survey data and to help design more rigorous survey efforts.

Our results are part of a growing body of literature suggesting that estimating distance to aurally detected birds is difficult. However, the question remains whether estimating detection probability with inaccurate distance estimates during aural avian surveys is better than using count data that do not incorporate estimates of detection probability at all. Our study demonstrates that many of the variables thought to affect detection probability (e.g. vegetation, bird species) can also affect a surveyor's ability to estimate distance. However, many methods that do not use distance to estimate detection probability still require surveyors to estimate a distance to each bird. For example, fixed-radius point-count surveys require that someone chooses an arbitrary distance at which the investigator assumes detectability to be 100% (or homogeneous across space and time); an assumption that is likely to be invalid. Surveyors must then decide whether each bird detected was within the fixed-radius area. In our simulated bird surveys, only 65% of birds were correctly classified as within the fixed-radius area using a 50-m radius, and only 59% of birds were correctly classified using a 100-m radius. Errors in classifying whether the bird was in or out of the fixed-radius area caused a 43% and 29% inflation in bird density within the fixed-radius area using 50-m and 100-m radii, respectively. Not accounting for variation in detection probability related to distance by using an unlimited radius point-count method is also fraught with error (Anderson 2001, 2003; Rosenstock *et al*. 2002; Thompson 2002; Ellingson and Lukacs 2003). Furthermore, estimating distances to birds can help account for differences in detection probability among surveyors (Diefenbach *et al*. 2003), which is not possible from analyses that do not incorporate estimates of detection probability.

For these reasons, it seems premature to abandon distance-sampling methods altogether, merely because estimating distance to a vocalising bird includes substantial error. This and other studies (Alldredge *et al*. 2007*b*, 2008; Simons *et al*. 2007) have demonstrated how relatively simple field trials can be used to estimate the error associated with distance estimates used to estimate detection probability during avian point-count surveys. Evaluating distance-estimation errors will allow investigators to better evaluate the accuracy of avian density and trend estimates. Moreover, investigators who evaluate distance-estimation errors could employ recently developed models to incorporate distance-estimation errors into analyses (Borchers *et al*. 2010). We encourage further development of such models, including the inclusion of such models into distance analysis software. Future studies should use simulated bird populations of known size to compare results from point-count methods that account for detection probability using distance (e.g. distance sampling and fixed-radius point counts) and those that do not (e.g. unlimited-radius point counts). These studies should incorporate multiple simulated surveys where the size of the known bird population changes over time or the detection probability changes over time. Studies such as the one described above would allow a better understanding of how distance-estimation error (and violations of other assumptions of distance sampling) affects our ability to detect trends in population size. This may be the only way to determine which point-count methods are most valid when the majority of bird detections are aural.

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