Estimating the Breeding Population of Great Blue Herons (*Ardea herodias*) in Maine, USA, Using Dual-frame Sampling

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Abstract.—The Great Blue Heron (*Ardea herodias*) is a "Species of Special Concern" in the State of Maine, USA, due to declines along the Atlantic coast since the mid-1980s. To determine if this decline was statewide, an aerial survey was conducted from 1 May to 18 June 2015 to estimate the breeding population using a stratified dual-frame design accounting for imperfect detection of colonies. The strata were based on habitat and known colony densities. The area frame consisted of 10-km x 10-km plots. Stratum samples were searched by air independently by front and rear observers for known and new colonies. The list frame consisted of plots containing known colonies, a sample of which was checked for nesting activity. The dual-frame design combined the strengths of both list- and area-only surveys. Flying directly to known colonies in the list frame was very efficient, and accounting for new colonies in the area frame, allowed unbiased, statistically valid estimation. Estimates were calculated for a Maine statewide total of active Great Blue Heron colonies (n = 243, 90% credible interval (CI) = 193-352), total nests (n = 2,019, CI = 1,778-2,434), and active nests (n = 1,593, CI = 1,416-1,872). Observer detection ranged from 25 to 99%. The percentage of list frame colony coverage in the dual-frame estimate was 63%, but varied by stratum. The percent CV of the dual-frame statewide total active nests was 8.9%, but also varied by stratum. By repeating these methods, strata and statewide population trends could be obtained. *Received 31 January 2017 accepted 28 July 2017.*

Key words.—Aerial survey, *Ardea herodias*, binomial random effect, dual frame, Great Blue Heron, Maine, nesting colonies, population estimate.

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The Great Blue Heron (*Ardea herodias*) is currently listed in the State of Maine, USA, as a Species of Special Concern due to an apparent decline in the number and size of nesting colonies (Maine Department of Inland Fisheries and Wildlife 2008). A significant declining trend occurred between 1980 and 2007 (-5.5%, $P < 0.02$, n = 35) in the Breeding Bird Surveys (Sauer *et al.* 2014). Over that same time period, observations of predation by Bald Eagles (*Haliaeetus leucocephalus*) increased with Bald Eagle recovery in Maine (Todd *et al.* 1982; Todd 2004a, 2004b). Periodic surveys had been conducted for Great Blue Heron colonies, but these were primarily focused on coastal colonies (Korschgen 1979; Custer *et al.* 1980; Andrews 1990; Allen *et al.* 2012). The most recent aerial survey was in 2009, with 1,071 nesting pairs at 83 colonies statewide (D'Auria 2010). Between 1983 and 1995, the coastal breeding population (colonies located on coastal islands) experienced a 47% decline in nesting pairs (Allen *et al.* 2012). The 2009 survey revealed 430 pairs on nine coastal islands, a 33% decline from 1995 and a 64% decline from 1983 (D'Auria 2010). The 2009 survey was then the most geographically comprehensive survey of Maine's nesting Great Blue Herons.

Since 2009, we collected location and nesting activity data at 215 nesting colonies through a Maine Department of Inland Fisheries and Wildlife volunteer adopt-a-colony program; however, a current and reliable breeding population estimate was still lacking. With 90% of the State forested (Maine Forest Service 2009) and 17% covered by wetlands (Tiner 2007), most of the State of Maine, in the northeastern USA, could be considered potential Great Blue Heron nesting habitat. Several researchers have evaluated the accuracy of various survey methods for detecting Great Blue Heron colonies (Gibbs *et al.* 1988; Frederick *et al.* 1996; Rodgers *et al.* 2005; Green *et al.* 2008), but few have developed a reliable method for estimating the nesting population based on a sample (Green *et al.* 2010).

Sampling only known (list frame) colonies would be very efficient by only having to fly point to point. By including only the known colonies, the estimates would be biased downward. Sampling only randomly chosen (area frame) plots would observe few colonies, resulting in an unbiased but highly variable estimate at a much greater expense.

Our objective was to demonstrate that a dual-frame survey could translate well from occupied nests to estimating the nesting colonies of Great Blue Herons due to their highly visible nests that persist over many years (Haines and Pollock 1998; U.S. Fish and Wildlife Service 2009). This approach takes advantage of our volunteers' monitoring efforts. We plan to repeat this sampling strategy and survey methodology at future intervals of 5 years to obtain a population trend.

METHODS

Study Area

This study was conducted in Maine, USA. We first divided the State of Maine into a grid of 10-km x 10-km plots using Lambert equal area projection. We stratified the plots based on ecoregion boundaries as mapped by Bailey (1998) and the distribution of known Great Blue Heron colonies. We combined adjacent ecoregions based on differences in density, distribution, and size of known colonies, resulting in three strata: coastal, south central, and north (Fig. 1).

Sample Determination

Dual-frame sampling consisted of two frames: the list frame and the area frame. The list frame consisted of all plots (10-km x 10-km squares) containing at least one known colony. The area frame consisted of all plots including those that contain known colonies. In sample list plots, observers flew to and counted total nests and active nests in each known colony. In sample area plots, they searched the habitat within each plot for both new and known colonies. To save on flight time, all area sample plots with known colonies were also made part of the list frame, hereafter referred to as combined (list and area) plots. After the habitat had been searched, any known colonies that were missed were checked. New colonies found in list plots or outside sample plots were not used in the estimation. In processing the survey, the new colonies were "unduplicated," i.e., they were separated from the known list colonies. Only the new colonies were used in the estimation of the area frame. The list frame was used to estimate the total known colonies, total nests, and active nests (Haines and Pollock 1998).

The list frame was composed of 215 known colonies, all of which had been active within the past 20 years (1995 or later) and surveyed within the past 8 years by Maine Department of Inland Fisheries and Wildlife staff and volunteers (Table 1; Fig. 1). We overlaid the grid on a map of known colony locations, and associated each colony with a plot. We calculated the per-plot means and standard deviations of the number of colonies for each stratum, which formed the fundamental information for allocation of samples.

The survey was designed to give an 80% chance of detecting a 25% change between surveys at a 10% significance level over the whole survey. This required an 8.3% CV of the dual-frame statewide total active nests. The frame and stratum sample sizes were allocated to attain the survey goals at the least cost. To obtain optimal stratum sample sizes, we simulated samples and minimized flight costs within our precision requirements. Starting with the densities of nests in known colonies, we varied the stratum-specific proportion of active nests from 0.3 to 0.8 and the list coverage from 0.4 to 0.9. The simulations then varied the number of active and new nests. Due to time requirements, we did not account for the added complexity of nests occurring in colonies. For the list, area, and combined plots, we regressed the simulated flight hours on the sample size by stratum. This regression became the cost function for the sample size calculation. We used a Lagrange multiplier (Thompson 2012) to minimize overall cost with an upper limit on the overall CV. The estimation was done following U.S. Fish and Wildlife Service (2009) methodology. We used Generalized Random Tessellation Stratification methodology (Theobald *et al.* 2007) for sample selection (U.S. Fish and Wildlife Service 2009).

Field Methods

Between 1 May and 18 June 2015, we surveyed plots in list and area samples using a four-seat Cessna 185 airplane, flown 60-200 m above the ground depending upon the terrain, at approximately 160 kmph. All pilots had extensive experience flying low altitude wildlife surveys. In addition to the pilot, there were two experienced observers on each survey.

We stored the locations of known colonies as GPS point locations in GIS Pro (Garafa, LLC 2014) on an iPad, and checked colonies within the chosen sample of list plots by flying directly to the colony and circling it until both observers obtained independent counts of total nests and active nests. We did not use a double-observer protocol for detection of list colonies.

We searched plots within the area frame for new colonies by flying transects spaced approximately 0.8 km apart. We determined flight routes for area plots in advance using ArcGIS (Environmental Systems Research Institute 2013), and transferred start and end locations to mobile GPS units for use during the flight. We used a double-observer protocol whereby observers did not communicate that they observed a colony until after the colony was behind the wings of the plane. For this initial observation, we recorded a capture history for each observer (including the pilot) according

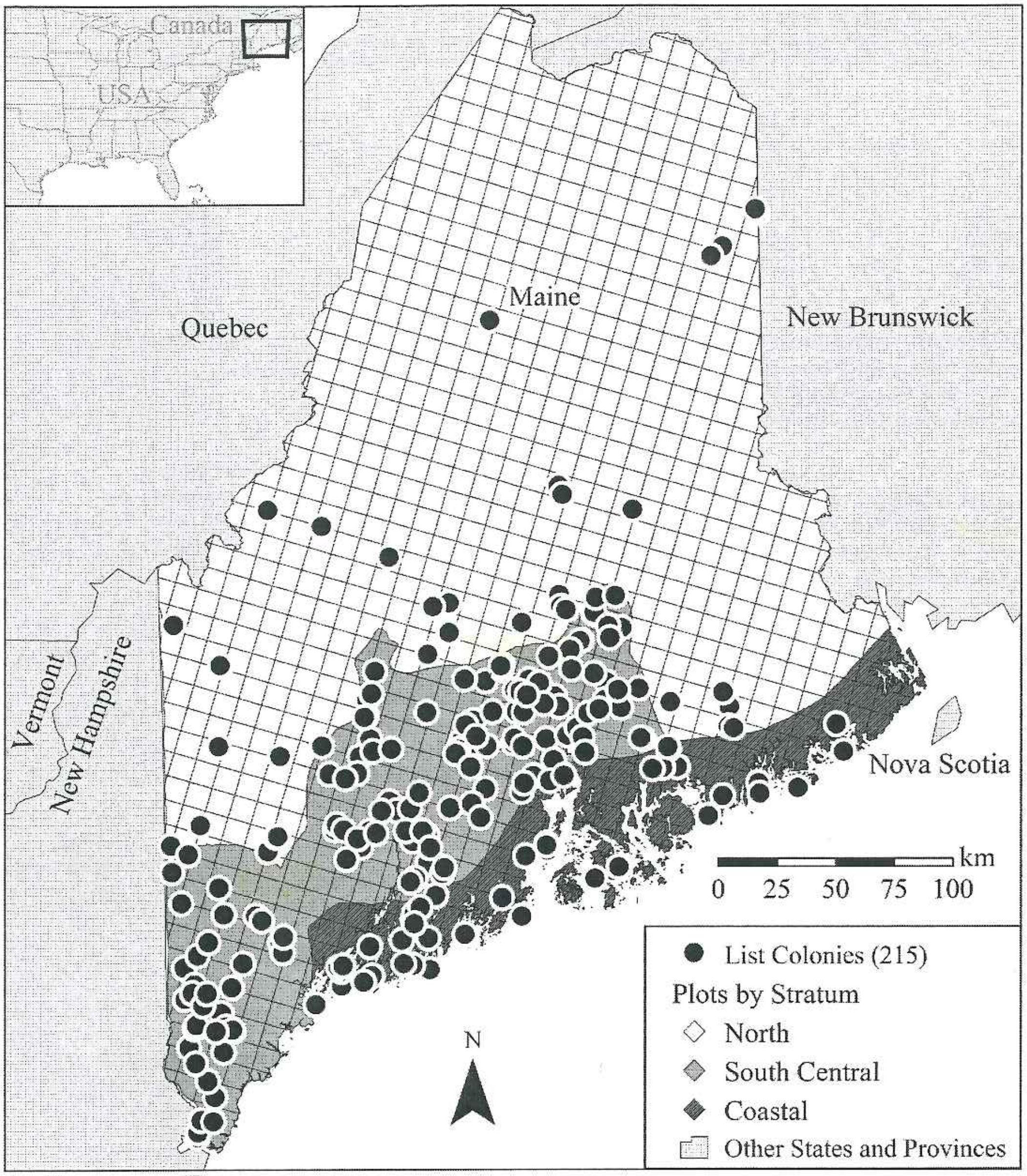

Figure 1. Distribution of known Great Blue Heron (*Ardea herodias*) colonies, "List Colonies," in Maine, overlain on area plots for each stratum.

to Nichols *et al.* (2000), noting each as having seen the colony, not having seen it, or not looking. The plane then circled back to the colony so that the front and rear observers could conduct independent counts of total nests and active nests. We did not vocalize these counts until both observers determined their counts.

For combined plots, we first surveyed them as if they were area plots (i.e., scan habitat for colonies using double-observer protocol), and then we surveyed them as list plots (i.e., return flight through the plot to record the status of all known colonies that were missed). To avoid the potential for observers to search for known colonies during the area plot portion of the survey, we toggled a GIS layer on and off showing known colonies within area plots. Pilots and observers did not know which area plots were combined plots until after they searched the entire plot for colonies. We opportunistically observed known colonies outside the plots and new colonies within list plots. We did not include these colonies in the dual-frame estimate; however, they will be used to inform the colony list for the next sample period.

To help inform estimates of observer detection probability, we used ground counts where we were confident

Table 1. Area, number of colonies, total nests (at active and inactive colonies), and active nests in the list frame (known colonies), number and types of plots surveyed, and median estimates and 90% credible intervals (CI) for the percent coverage of the list frame within each stratum and throughout the State of Maine.

		List Frame			Plots Surveyed			% Coverage	
Stratum	Area (km^2)	Colonies	Total Nests	Active Nests	List	Area	Combined	Median	CI
South Central	17,603	141	732	649	38	12	4	100	(93-100)
Coastal	6,746	41	386	322	14	10	2	69	(43-94)
North	59,490	33	122	69	14	12	0	24	(10-61)
Maine Total	83,839	215	1,240	1,040	66	34	6	63	(40-84)

that the observer thoroughly surveyed the colony and did so at the appropriate time in the season. Unlike the aerial observations, we treated these ground observations as "truth," thus the ground counts have certain detection.

Analytical Methods

We generalized nest occupancy of the Bald Eagle post-delisting dual-frame survey (U.S. Fish and Wildlife Service 2016) to colonies. A colony was occupied if it contained at least one nest, otherwise it was unoccupied if it no longer existed, i.e., no nests were detected at the historic colony location. A colony was defined as active if it contained at least one active nest. A nest was active if an adult was in or next to the nest, or if eggs and/or young were visible in the nest. In the list frame sample plots, we observed the proportion of known occupied colonies by stratum and summed the number of occupied colonies accounting for imperfect detection. To extrapolate to the colonies in the non-sampled plots, we multiplied the estimated proportion of occupied colonies with the number of known, non-sampled colonies by stratum. In the area frame, we estimated the stratum densities of new colonies and extrapolated those densities by the stratum area to obtain the total new colonies. Independent, double-observer counts were used to estimate number of colonies, and an n-mixture model was used to estimate nests within colonies while accounting for observer detection (Royle and Dorazio 2008). We did not have enough observations to account for imperfect detection in new colonies and thought the observation process was too different to assume it was the same as for known colonies. Finally, we used Bayesian estimation with non-informative or diffuse priors to obtain all estimates (Royle and Dorazio 2008).

List estimation. We used an occupancy model for colony detection (Royle and Dorazio 2008). No formal capture-recapture protocol was used for colonies in the list frame; instead, after an observer announced finding the first nest, both observers independently started counting. We estimated the proportion of occupied colonies, ψ_i, by stratum. We used non-informative prior Beta(1,1) distribution, equivalent to a uniform 0-1. The occupancy indicator for each colony was:

$$Z_{ij} \sim \text{Bernoulli}(\psi_i)$$

where i was the stratum of the j^{th} colony; Z_{ij}, was either one if the colony existed or zero if not.

The number of occupied colonies was the sum of the occupancy indicators for all known colonies:

$$Occ_i^{List} \sim \Sigma_j^{N^L} Z_{ij} \cdot (1)$$

Occ_i^{List} was calculated for every simulation of the Bayesian estimation. Summary statistics (mean, standard deviation, median, and 90% credible intervals) were calculated from the simulations. We summarized our results using medians and 90% credible intervals.

The equation for nests per colony,

$$\log \quad Log(\xi_i^f) = S_i + \gamma_f \ (2)$$

was on the log scale. The S_is were the stratum effects and γ_f, was a displacement for being a new colony. If $f = List$, then $\gamma_{List} = 0$. Both the stratum and frame effects had diffuse N(1,100) prior distributions (Gelman and Hill 2006). The results did not change (before the third significant digit) when we tried another prior distribution, a uniform from -10 to 10. If the number of nests, N_{ij}, was positive, i.e., the colony existed (Z_{ij} = 1), then the size estimate, ξ_i^{List}, was a function of both stratum and frame effects.

The nest size latent variable equation was:

$$N_{ij} \sim \text{Poisson}(Z_{ij}\xi_i^{List}).$$

A model without imperfect detection yielded similar results, and non-intuitively the imperfect detection estimates were slightly lower. The observer counts, n_{ijo}, were modeled by a Poisson rate with a latent variable of the true nest count apart from observer detection,

$$n_{ijo} \sim \text{Poisson}(p_o N_{ij}).$$

The subscript o was the front- or rear-seat observer, and p_o was the observer detection.

The latent variable for number of active nests was:

$$A_{ij} \sim \text{binomial}(p_i^{Act}, N_{ij}).$$

The proportion of active nests, p_i^{Act}, varied by stratum. The number of active nests was estimated for all colonies, and the sum of the colonies with active nests greater than zero became the number of active colonies in the list frame, Act_i^{List}.

Usually observed active counts, a_{ijo}, are modeled as a binomial of the true number of nests, but we modeled them as a Poisson distribution because the ground counts were assumed to be truth. In a few cases, they were less than the aerial survey counts. The Poisson form of the equation allowed for the higher aerial counts. We still assumed detection probabilities, not rates, i.e., limited between zero and one. The observed active nests, a_{ijo}, were a proportion, p_o, of the latent variable for active nests:

$$a_{ijo} \sim \text{Poisson}(p_o A_{ji}).$$

We assumed the detection of active nests was the same as for inactive nests. Observers noted that they primarily looked for nests rather than birds.

The total nests, $Nest_i^{List}$, and active nests, $Nest_i^{List,Active}$, were estimated in a similar way to Equation 1:

$$Nest_i^{List} = \sum_j^{N_iL} N_{ij}$$

$$Nest_i^{List,Active} = \sum_j^{N_iL} A_{ij}.$$

New colony estimation. Each capture history was estimated as a multinomial based on combinations of front seat-rear seat observer probabilities (Nichols *et al.* 2000). Assuming the larger colonies were more easily detected, we used a version of the Royle-Nichols formulation to relate detection to colony size (Royle and Dorazio 2008). But the four capture histories observed in the area frame new colony searches were not enough to estimate new colony detection probability. We tried several variations of the Royle-Nichols model that could possibly work for larger surveys with sufficient capture histories.

For nests within colonies, we assumed that new colonies were on average smaller than the known colonies on the list, or they would have been found already, as described in Equation 2. The displacement, , allows a consistent reduction factor for the size of new colonies.

The proportion of new occupied colonies that had at least one active nest was a binomial with a probability that was the complement of the probability that there were no active nests in a colony with a given average number of active nests:

$$Act_i^{New} \sim \text{binomial}\left(Occ_i^{New}, 1\text{-}Pr\left(\text{Poisson}\left(Nest_i^{New,Active} = 0 \mid \lambda = \xi_i^{Area} p_i^{Act}\right)\right)\right)$$

Because there was no list of new colonies, we had to indirectly estimate the number of new active colonies per stratum as times the stratum area:

$$Occ_i^{New} \sim \text{Poisson}\left((\text{Stratum Area})_i \xi_i^{A}\right).$$

We did not distinguish between the sampled and non-sampled plots because the sampled plots were subject to observer detection. Once the number of new colonies was determined, the estimates for total nests and active nests were calculated:

$$Nest_i^{New} \sim \text{Poisson}(Occ_i^{New} \xi_i^{Area})$$
$$Nest_i^{New,Active} \sim \text{bionomial}(Nest_i^{New}, \rho i^{Act}).$$

i should be subscript

We assumed the active nest proportion was the same for the list and area frames. For the new nests, the sample and non-sample estimates were treated the same.

Observer detection. The observer detection probabilities, for each observer ρ_o, were estimated as a random effect, except for the ground detection which was fixed at one. A combination of gamma and beta functions was used to generate a uniform 0-1 distribution (Link and Barker 2006). The random effects were correlated with each other with correlation with uniform 0-1 marginals ~~(W. A. Link, pers. commun.)~~. The result was a non-informative prior for the observer detection probabilities:

$$\begin{array}{lll} \tau & \sim & \Gamma(3.289,7.8014) \\ \rho & \sim & B(1,1) \\ \mu_0 \mid \tau,\rho & \sim & N(0,\tau/\rho) \\ \sigma_0 \mid \tau,\rho & = & \tau/(1\text{-}\rho) \\ \text{logit}(\rho_o) & \sim & N(\mu_o,\sigma_o) \end{array}$$

These observer detection probabilities were used for both total and active nests.

Dual-frame totals. Since all the list or known colonies were removed from the area frame and only new colonies were estimated, the list and new estimates were independent. We summed the list and new total colonies, total nests, and active nests to obtain the dual-frame totals for each strata and statewide total (U.S. Fish and Wildlife Service 2016):

$$\begin{array}{lll} Occ_i^{DF} & \sim & Occ_i^{List} + Occ_i^{New} \\ Nest_i^{DF} & \sim & Nest_i^{List} + Nest_i^{New} \\ Nest_i^{DF,Active} & \sim & Nest_i^{List,Active} + Nest_i^{New,Active} \end{array}$$

RESULTS

We surveyed a total of 66 list plots and 34 area plots, six of which were combined plots, in 76.5 hours of aerial surveys (Table 1; Fig. 2). We surveyed for 108 known colonies in 66 list plots, and observed nests in 86 colonies. Twenty-two previously known colonies did not contain nests, and we were unable to survey one colony due to sudden bad weather conditions. We searched for new colonies in 34 area plots and found four with a total of 17 nests, seven of which were active. In combined plots, we found eight known colonies, but failed to find two known colonies, probably since they no longer contained any nests. Our out-of-sample observations included 14 known colonies (six active with 22 active nests) and four new colonies with 31 active nests. Not counting our out-of-sample observations, we observed 87 active colonies with 933 active nests. These 87 colonies ranged in size from 1-70 active nests per colony ($\bar{x}$ =

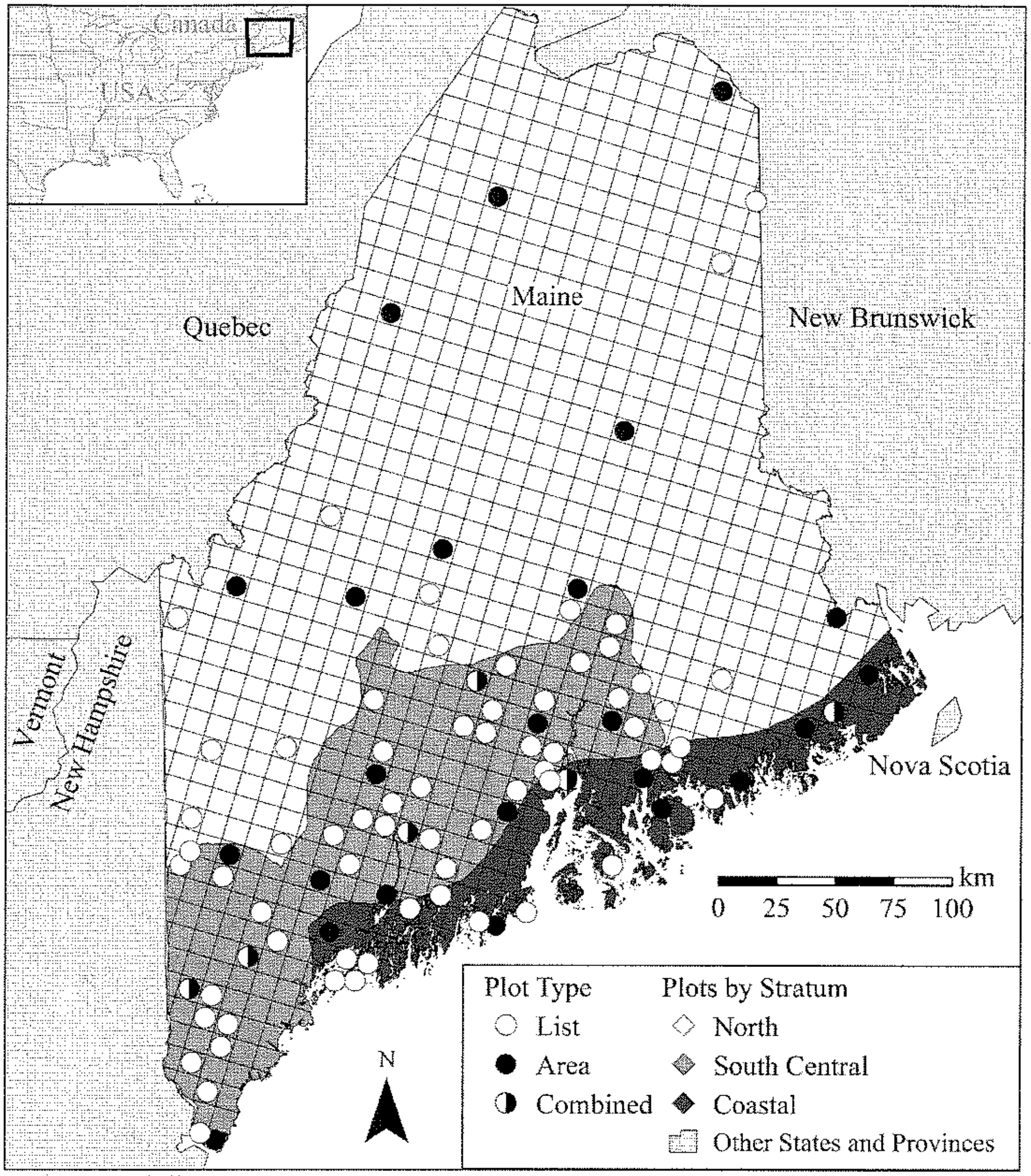

Figure 2. Locations of plots surveyed for Great Blue Heron (*Ardea herodias*) colonies.

10.7 active nests per colony), and more than half contained six or fewer active nests. Fig. 3 shows the estimates of number of nests per colony for each stratum and frame. The area frame colony sizes were only 28% of those in the list frame.

We estimated 243 active colonies containing 2,019 total nests and 1,593 active nests for the State: 170 colonies with 1,750 total and 1,413 active nests in the list frame, and an additional 73 new colonies with 260 total and 172 active nests in the area frame (Table 2). No new colonies were found in the area frame's south central stratum; however, the stratum density, ξ_{SC}^{New}, still accounts for the chance of colonies existing given none were found in the south central area sample plots, 0.0002 colonies per 100 km^2 (frame effect that estimated a factor of 0.0001 and 90% credible interval of 0-0.051). Based on

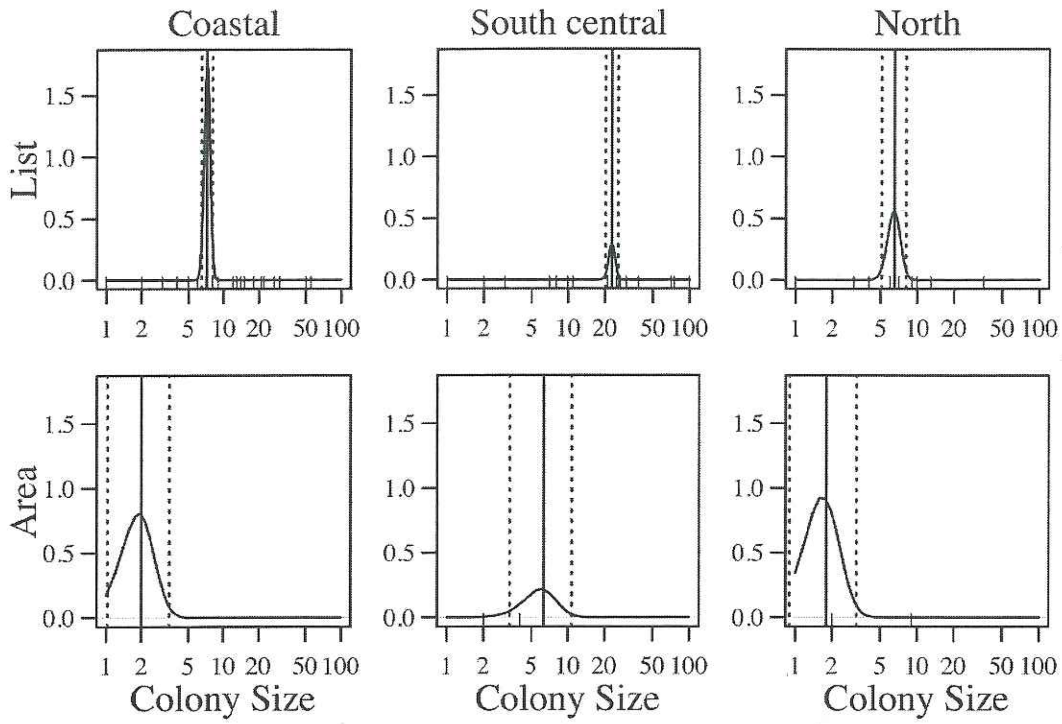

Figure 3. The posterior density curves of the frame and stratum estimates of number of nests per Great Blue Heron (*Ardea herodias*) colony. The black lines are the medians and the dotted vertical lines are the 90% credible intervals. The tick marks at the bottom of each plot are the maximum of the observer nest counts for each colony.

the number of new colonies found, we calculated our list coverage in Table 1.

The overall percent CV for active nests was 8.9% (Table 3). The new CVs were an order of magnitude larger than their corresponding list CVs, but because the new active nest estimates were so small, the dual-frame CVs were not much larger than the list CVs.

Observer detection probabilities were very high with a couple of exceptions (Table 4). Two observers with low flight hours and few observations had low, uncertain detection probabilities. This was not an issue because it is more important that observers count consistently. For 41 colonies, we used ground counts of total nests and active nests from surveys conducted on foot by volunteers and staff not corrected for observer detection.

DISCUSSION

This study constituted the first statistical sampling technique used to estimate the statewide breeding population of Great Blue Herons in Maine. Prior aerial survey efforts focused only on known colonies and did not consist of a sampling methodology that could extrapolate to non-sampled areas of the State. These surveys did not incorporate searching for new colonies, except opportunistically as researchers flew between known colonies or if they received a tip regarding a new colony location. The dual-frame survey allows us to make inferences of the statewide nesting population without having to survey all potential nesting habitat. Repeating the survey at future time intervals will also allow us to determine the nesting population trend. This information is essential to understanding whether or not the decline occurring along the coast of Maine is restricted to the coast, and will inform appropriate State-level protection measures for Great Blue Herons.

The North American Waterbird Conservation Plan (Kushlan *et al.* 2002) estimated 83,000 breeders; our estimate of 3,186 breeders would indicate Maine hosts 3.8%

Table 2. Median estimates and 90% credible intervals (CI) for active colonies, total nests (includes active and inactive nests in active and inactive colonies), and active nests, by frame, stratum, and throughout the State of Maine.

Frame and Stratum	Active Colonies		Total Nests		Active Nests	
	Median[a]	CI	Median[a]	CI	Median[a]	CI
List Frame (Known Colonies)						
South Central	116	(108-122)	853	(774-932)	759	(687-834)
Coastal	31	(27-35)	723	(609-827)	546	(458-629)
North	23	(20-26)	174	(143-209)	107	(85-132)
Maine Total	170	(161-178)	1,750	(1,608-1,886)	1,413	(1,296-1,527)
Area Frame (New Colonies)						
South Central	0	(0-8)	0	(0-19)	0	(0-17)
Coastal	14	(2-41)	87	(13-292)	65	(9-221)
North	54	(11-161)	148	(27-482)	88	(16-292)
Maine Total	73	(24-181)	260	(81-660)	172	(54-433)
Dual Frame						
South Central	117	(108-125)	855	(776-938)	762	(688-839)
Coastal	45	(33-72)	819	(672-1,036)	619	(505-787)
North	78	(34-184)	323	(195-662)	196	(118-404)
Maine Total	243	(193-352)	2,019	(1,778-2,434)	1,593	(1,416-1,872)

[a]The median summary statistics for the stratum subtotals are not expected to add to the state totals. This is not a bias in the statistics but a function of the skewness. The stratum subtotals differ from the state totals by 2% or less for the list frame and dual frame, and by 11% or less for the area frame.

of the North American breeding population. This is higher than expected, given the broad range of the Great Blue Heron across North America. The estimate of 392 breeders in northern Maine is higher than expected. While Maine's contribution needs to be confirmed in the next survey, no other statistical surveys accounting for new nests have been done in other States or Provinces.

This survey estimated our knowledge of existing colonies at 63% for the State, and varied widely by stratum. We knew most about the south central stratum, estimated to be 100% due to no new colonies found. It is an area with abundant wetland resources, rich waterbird diversity, and the majority of Maine's human population. This area was the most frequently surveyed portion of the State due to its proximity to aircraft fueling stations used by those conducting aerial surveys; thus, even if surveys were not conducted in specific locations within this stratum, flyovers in route to other locations often revealed new colonies or confirmed activity at historic colonies.

Estimated list coverage for the coastal stratum (69%) was lower than we expected. Prior to 2009, the best data for Great Blue

Table 3. Percent CV of active nests by frame, stratum, and throughout the State of Maine.

Stratum	List	New	Dual Frame
South Central	5.9	343.0	6.0
Coastal	9.5	83.6	14.0
North	13.3	82.3	43.2
Maine Total	5.0	62.0	8.9

Table 4. Median estimates and 90% credible intervals for observer detectability rates. Ground Observer = ground counts and were assumed to be the truth, thus the detection is 100 percent. Starred (*) median values are rounded up to 100%.

	Median	Credible Intervals
Front Seat Observer		
DD	100*	(99-100)
Rear Seat Observers		
A	99	(81-100)
B	36	(13-71)
C	98	(55-100)
D	25	(11-44)
E	99	(91-100)
F	100*	(98-100)
G	99	(81-100)
H	99	(87-100)
I	99	(85-100)
J	100*	(96-100)
K	100*	(98-100)
Ground Observer	100	Fixed

Heron colonies were for those along the coast. This was due to incidental observations of Great Blue Heron colonies during intensive survey efforts for nesting Bald Eagles, surveys focused on wintering waterfowl concentrations, and purposeful observations during coastal colonial waterbird surveys.

List coverage of the north stratum was 24%, but with a large credible interval (10-61%). This is a very large area that has not been surveyed as intensively as the other two strata. Much of it is remote and far from the fueling stations typically used for aerial surveys. It also contains mountainous terrain that is difficult to survey by small fixed-wing airplanes due to the abrupt changes in elevation and the associated weather conditions. Since 2009, we surveyed historic colonies within the north stratum for activity and found some new sites. In addition, a few new sites were found and reported by partner agencies and organizations as well as the public. The lack of colonies or knowledge of colonies in this stratum could be due to three possible factors: 1) the sparse human population, providing less opportunity for people to encounter a given colony; 2) overall differences in habitat quality; and 3) the primary land management practice for timber, which may cause colonies to shift locations more frequently as stands get altered and prevent them from growing to a size noticeable by the few people who would encounter them. While we expected our coverage of the north stratum to be less than the other two strata, we did not expect it to be so low.

Such low coverage of the north stratum warrants greater sample allocation within this stratum in future surveys, which will increase the overall cost of the survey effort. If we can find a habitat or another variable that predicts the density of colonies well, we may be able to include it as a weighting variable to sample in areas with a higher probability of finding a colony.

Our estimate for the area frame was calculated by extrapolating on a per hectare basis, rather than by habitat. It is unclear how to best use suitable habitat as the factor considering Great Blue Herons do not have rigid requirements for nesting substrate (Gibbs *et al.* 1987; Gibbs and Kinkel 1997). They use a wide variety of tree species of varying size and status (dead, dying, and live), and within varying ecological settings (uplands, coastal islands, and wetlands). Nesting habitat is primarily determined by abundance, type, and quality of wetlands within foraging distance, and low disturbance from humans and predators (Gibbs 1991; Gibbs and Kinkel 1997). Furthermore, it is unknown how the proximity of other Great Blue Heron colonies or nesting Bald Eagles or Ospreys (*Pandion haliaetus*) may influence distribution (Norman *et al.* 1989; Gibbs and Kinkel 1997; Vennesland and Butler 2004).

Aerial survey is one of the most efficient and least disturbing methods for detecting Great Blue Heron colonies and counting total and active nests within colonies over a large study area (Gibbs *et al.* 1988; Dodd and Murphy 1995; Frederick *et al.* 1996; Green *et al.* 2008). There are many factors that can influence the accuracy and precision of aerial surveys including, but not limited to, observer skill and experience, pilot skill and experience, weather, lighting, terrain, timing, speed and altitude of the aircraft, size of the colony, and habitat setting of the colony and individual nest trees. Ground counts take more time than aerial surveys and can cause more disturbance to the nesting birds; however, they tend to be more accurate as long as a complete view of the colony can be obtained. The select ground counts aided the estimation of aerial observer detection probabilities. Only a few times were ground counts slightly less than aerial survey counts, which was not unexpected. Many studies have looked at aerial survey counts compared to ground counts, with differing results depending on the species being counted, the stage of the nests, and the size of the colony (Gibbs *et al.* 1988; Frederick *et al.* 1996, 2003; Green *et al.* 2008). Overestimates are probably due to the difficulty of counting clustered nests within a small area during the short time period the aircraft is over the colony. Quick judgment and estimates need to be made based on a limited view. This can be difficult even when repeat passes over a colony are made.

We found only four new colonies during area plot searches, and the new colonies found were relatively small. This was close to what was expected from our sample design simulations. We assume this is because we would likely know about the larger colonies after having conducted 6 years of media outreach regarding our need for colony information and volunteer monitors. In this study, sample size selection assumed only a certain number of nests per plot. In future surveys, we need to incorporate the number of colonies per plot and the number of nests per colony in the sample allocation.

The few new colonies found resulted in few capture histories to estimate detection of colonies apart from nests in colonies. We did not expect to have many new colony observations, and that was reflected in 80% CVs for the stratum active nest estimates (not including south central that had a zero CV denominator). Although the dual-frame CV was 43.2% for the north stratum, the overall CV was 8.9%. This was slightly larger than our required CV of 8.3%. Knowing now about the lower than expected list coverage, especially in the north stratum, we would have allocated more plots to the area frame in the north stratum. The estimates are still a useful baseline for trend estimates, and the results give us good directions to improve future surveys.

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