Research Article

Composite Analysis of Black Duck Breeding Population Surveys in Eastern North America

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ABSTRACT Waterfowl are monitored in eastern Canada and the northeastern United States with 2 surveys: a transect survey from fixed-wing aircraft and a plot survey conducted from helicopters. The surveys vary in extent, but overlap exists in a core area of 9 strata covering portions of all provinces from Ontario east to Newfoundland. We estimated population change for American black ducks (*Anas rubripes*) and mallards (*Anas platyrhynchos*) from these surveys using a log-linear hierarchical model that accommodates differences in sample design and visibility associated with these survey methods. Using a combined analysis of the surveys based on total indicated birds, we estimate the American black duck population to be 901,700 (95% CI: 715,200–1,274,000) in 2011, with 526,900 (95% CI: 357,500–852,300) mallards in the surveyed area. Precision of estimates varies widely by species and region, with transect surveys providing less precise results than plot surveys for black ducks in areas of overlap. The combined survey analysis for black ducks in the eastern survey region produced estimates with an average yearly coefficient of variation (CV) of 12.1% for the entire area and an average CV of 6.9% in the plot survey area. Mallards, which had a more limited distribution in the region, had an average yearly CV of 22.1% over the entire region, and an average CV of 27.7% in the plot survey area. Hierarchical models provide a rich framework for analyzing and combining results from complex survey designs, providing useful spatial and temporal information on population size and change in these economically important species.

KEY WORDS American black duck, *Anas rubripes*, breeding population, hierarchical model, plot surveys, transect surveys, trend analysis.

Harvest and habitat management of the American black duck (*Anas rubripes*) has historically been based on winter surveys such as the mid-winter inventory (MWI; Conroy et al. 1988, Diefenbach et al. 1988). These data provide a time series spanning >50 years of black duck counts that have been used for both population assessment and for developing and testing population models for this species (Conroy et al. 2002). Because the MWI has been criticized for inconsistent coverage and incomplete counts (Montalbano et al. 1985, Conroy et al. 1988), management agencies in the United States and Canada have devoted efforts toward developing population estimates for breeding waterfowl that cover the black duck breeding range in eastern Canada (i.e., eastern Ontario, Quebec, and the Atlantic Provinces), Maine, and northern New York.

Although several surveys provide breeding population information on black ducks (e.g., Dennis et al. 1989), 2 primary surveys cover the central part of the black duck breeding range (hereafter eastern survey area); a plot survey conducted by the Canadian Wildlife Service (CWS) and a transect survey conducted by the United States Fish and Wildlife Service (USFWS). The plots are surveyed by the CWS using helicopters, whereas transects are surveyed by fixed-wing aircraft that fly along each transect's centerline. During most years, some transect segments are subsampled by the USFWS from helicopters to provide data for estimating visibility rates. Although both surveys cover unique regions (Fig. 1), they overlap on approximately 45% of the survey area. The plot survey was initiated in 1990, whereas the transect survey was not fully implemented until 1998.

Historically, surveys of black ducks on their breeding grounds have encountered a variety of logistical and design difficulties (e.g., Chamberlain and Kaczynski 1965, Kaczynski and Chamberlain 1968). Both the plot and transect surveys are limited by imperfect and heterogeneous detection of birds, and by limited spatial and temporal coverage. In this study, we describe an analytical approach for aggregating the plot and transect surveys in eastern North America into a single breeding population estimate. If both transect and plot surveys provided unbiased estimates of the population size, then aggregating estimates would be relatively uncomplicated. Unfortunately, both surveys contain complications in their design that invalidate approaches involving simple averaging of mean counts.

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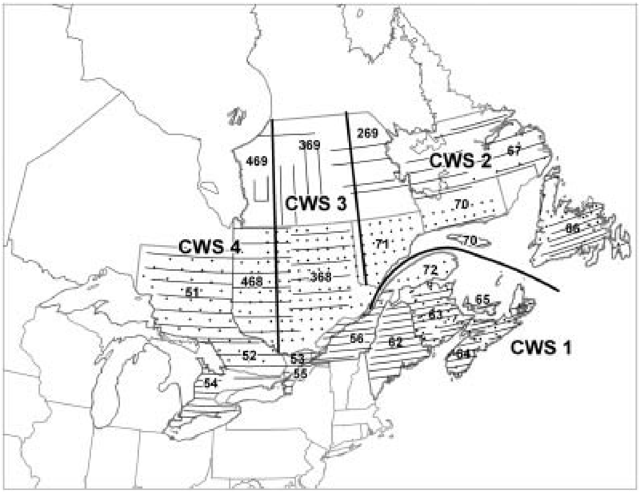

Figure 1. Map of 20 breeding waterfowl survey strata in eastern Canada and Maine, with transect (lines) and plot (dots) locations. Bold lines delineate the 4 black duck regions (CWS 1–4) defined by the Canadian Wildlife Service, which provide stratum boundaries in Quebec.

Incomplete counts of ducks create the need to control for differential visibility during plot and transect surveys. Although counting from helicopters presumably detects a larger proportion of ducks than does counting from fixed-wing aircraft, neither platform produces a census of waterfowl populations. Consequently, to produce a consistent population estimate, 1 of the surveys must be scaled to the level of the other survey. For strata where both plot and transect surveys occur, regional comparisons of abundance from the helicopter plot surveys and the fixed-wing transect surveys can be used to scale the transect data to the population level of the plots. Other complicating factors include stratification (see Study Area Section), sampling design differences between the plot and transect surveys (see Surveys Section in the Methods Section), and differences in data collection protocol between the 2 surveys (see Total Indicated Birds Section in the Methods Section).

Our specific objectives were to develop a hierarchical modeling approach to accommodate the repeated measures sampling design used by both surveys, incorporate visibility correction, and efficiently control for heterogeneity associated with combining data collected using methods that varied over space and time. Our focus was on black ducks and mallards (*Anas platyrhynchos*) over the region covered by the eastern survey because accurate population and trend information for black ducks in this region meet a critical information need for waterfowl management. For example, the developing black duck harvest strategy depends on breeding season population estimates for black ducks, as well as estimates for mallards to assess hypotheses about competition between the 2 species (Conroy et al. 2002).

STUDY AREA

The plot survey was initiated in 1990 throughout the boreal forest and Atlantic northern forests in eastern Canada (Fig. 1). In western and central portions of the survey, plots were systematically located, but in Newfoundland, Labrador, New Brunswick, and Nova Scotia, plots from earlier surveys were sometimes maintained to ensure consistency with earlier data. As of 2011, transect surveys covered most of eastern Canada south of Hudson Bay. With a few exceptions, transect surveys were implemented between 1990 and 1998 in the eastern survey area. We analyzed data from both surveys from their initiation through 2011.

The USFWS organized the survey area into 17 strata based on physiographic and political strata (Fig. 1). For black ducks, the CWS recognized 4 strata, which represented potential subpopulations based on banding data. To meet information needs, survey results must aggregate to both USFWS survey strata and CWS strata, as well as to survey-wide results. Consequently, we organized the eastern survey area into 20 strata by intersecting the 4 CWS strata with the 17 USFWS (Fig. 1). This required separation of 2 original USFWS strata (USFWS strata 68 and 69) into multiple strata (Fig. 1). We renumbered the portions of USFWS stratum 68 that occurred in CWS strata 3 and 4 as strata 368 and 468, respectively. Similarly, we renumbered the portions of USFWS stratum 69 located in CWS strata 2, 3, and 4 as strata 269, 369, and 469, respectively.

Plot surveys have been conducted in 11 strata since 1990: strata 51, 52, 63, 64, 66, 67, 368, 468, 70, 71, and 72. The area covered by these strata is termed the plot survey area. The USFWS has conducted transect surveys within a portion of the plot survey area: strata 51 and 52 since 1990; strata 63, 64, 66, 67, 368, and 468 since 1996; and stratum 70 since 1998. These 9 strata are termed the overlap area since both CWS plot and USFWS transect surveys were conducted in them concurrently for at least some years. The USFWS also began transect surveys in strata 53, 54, 55, and 56 in 1990, which in combination with the plot survey area, makes up the core breeding range of black ducks (hereafter the core area) that has been surveyed by at least 1 platform every year since 1990. The USFWS also initiated transect surveys in stratum 62 in 1995, stratum 65 in 1996, and strata 269, 369, and 469 in 1998. The combination of all 20 strata makes up the total area, which has been surveyed consistently since 1998 (see Appendix for a complete list).

METHODS

Surveys

Plot survey.—Counts in plots were conducted by front- and back-seat observers from helicopters. Within plots, wetlands were identified, and roving surveys throughout the acceptable habitats were used to count ducks (Bordage et al. 2003). Counts in plots are not censuses. In the early years of the survey, provincial crews tended to spend varying amounts of time searching wetland habitats, leading to crew differences in the counts (B. Collins, Canadian Wildlife Service, unpublished report). In recent years, consistent standard operating procedures have led to more consistent survey efforts in plots among crews, but un-modeled variation in detection rates contributes to measurement error in the surveys.

Over the survey period, funding limitations resulted in a variety of modifications to the original design. Originally, plots were 10 km × 10 km, but in 1996 plots were changed to 5 km × 5 km. Original plots were divided into quarters and 1 of the quarters was randomly selected as the new plot for future surveys. We used only data from the resulting 5 km × 5 km plots in analysis; CWS staff extracted subplot information from earlier surveys from the field data (B. Collins, unpublished analysis). Plots were also initially surveyed every year, but a rotating panel design was implemented in 1996, in which plots were surveyed in panels that overlapped to permit comparable data within subsets of plots for any time period (B. Collins, unpublished report).

Transect survey.—Transects were surveyed by fixed-wing aircraft, with counts conducted by the pilot and an additional observer. A fixed distance from the centerline (0.2 km) was surveyed on each side of the plane, which was flown along the midline of the transect. Transects were of unequal lengths, and were surveyed in 29-km segments. Smith (1995) provided details on the survey protocols and historical analysis methods for the traditional survey area. Methods for the boreal region in the traditional survey applied directly to the methods in the eastern survey area.

Because counts collected from fixed-wing aircraft are not censuses, protocols for surveys require a double-sampling procedure in which an intensive counting method (such as a ground or helicopter survey) was conducted on selected segments of the transects, and the ratio of counts from the intensive method to those from the aerial survey were used to adjust the extensive aerial survey for visibility (Pollock and Kendall 1987, Smith 1995). These visibility adjustments are referred to as visibility correction factors (VCFs; Smith 1995). In eastern Canada, preliminary studies demonstrated that ground counts on segments were not feasible, and helicopter surveys were conducted by USFWS personnel on a subsample of transect segments for estimating VCFs. Unfortunately, these counts were only available for selected periods and strata, and limited data precluded detailed evaluation of temporal and spatial variation in VCFs. We used USFWS helicopter data from 1999 to 2004, within strata 51 (1999–2000); 51, 52, 53, 54, 55, and 56 (2001); 62, 63, 64, 65, and 68 (2003); and 68 and 69 (2004) to estimate mean VCFs for each crew area, which were aggregates of strata surveyed by a single pilot and observer in a given year.

Total indicated birds.—Protocols for recording observations of birds varied slightly between the plot and transect surveys. The CWS recorded the number of hens, drakes, and unknown sex birds, whereas the USFWS recorded the number of pairs, single drakes, and flocked drakes for dimorphic species (e.g., mallards) and the numbers of single and grouped birds for monomorphic species (e.g., black ducks). Converting these observations to a population estimate requires assumptions about the pairing status of the observations (Dzubin 1969). For black ducks, the USFWS and CWS agreed that single birds observed during surveys have undetected mates and, thus, count as 1 total indicated pair (TIP). Birds in groups of 2, regardless of the sexes of the birds recorded during CWS surveys and the social status recorded during the USFWS surveys, were counted as 1.5 TIP. This agreement was made because male and female black ducks are difficult to accurately distinguish during surveys, so some observations of pairs are actually 2 males with unobserved mates (i.e., 2 TIP) and other times a true male–female pair (i.e., 1 TIP; K. Ross, Canadian Wildlife Service, personal communication). Observations of black ducks in groups ≥3 were classified as open and not used to calculate TIP. Total indicated birds (TIB) were then calculated as: (2 × no. of TIP) + the number of birds in the open category. For all other species, the USFWS and CWS agreed to convert the CWS observations to the USFWS definition (e.g., observations by sex to social pairings) and then used the USFWS definition of TIP and TIB. Specifically, for the CWS data, we matched all males and females that could be matched into pairs and categorized any remaining males as singles or flocked drakes (e.g., 3 males and 2 females = 2 observed pairs and 1 single male). We calculated TIPs as (no. of single males + no. of observed pairs + no. of flocked drakes). We calculated TIBs as (2 × [no. of single drakes + no. of observed pairs + no. of flocked drakes] + no. of birds in the open category). The USFWS definition for the open category was defined as >4 individuals, a collection of birds that were not obviously paired, or birds of unknown sex in the CWS observations. Use of this TIB definition allowed consistent estimation between surveys where data were collected under different protocols.

Model

We used a hierarchical model (Royle and Dorazio 2008) to simultaneously analyze and aggregate results from the plot and transect surveys. Hierarchical models provided a structure in which we could formulate a statistical model for population change that accommodated count data and the statistical complications of analyzing a repeated measures design. Further, hierarchical models can efficiently incorporate VCFs, account for the panel design, and analyze data from different strata and years. Here, we describe a hierarchical model and its application to the black duck surveys. Similar models are used for the analysis of the North American Breeding Bird Survey (Link and Sauer 2002, Thogmartin et al. 2004) and the Christmas Bird Count (Link et al. 2006).

Conditioned on their means ($\lambda_{s,t,m,i}$), counts ($y_{s,t,m,i}$) are assumed to be Poisson random variables ($y_{s,t,m,i} \sim$ Poission[$\lambda_{s,t,m,i}$]); i indexes plot or transect, $i = 1,\ldots,$ total number of sample units; t indexes year; $t = 1,\ldots,22$; s indexes stratum ($s = 1,\ldots,20$); m indexes method $m = 1$ for CWS plot surveys and 2 for USFWS transect surveys. The model states that the natural log of the expected value of the counts ($\ln[\lambda_{s,t,m,i}]$) is a function of explanatory variables and random error to account for overdispersion:

$$\ln(\lambda_{s,t,m,i}) = T_{t,i} + \gamma_{s,t,m} + \omega_i + \varepsilon_{s,t,m,i}$$

where $T_{t,i}$ is the ln of the area surveyed in sample unit i in year t and $\gamma_{s,t,m}$ is a year effect for stratum s in year t for method m. Year effects are random, governed by the distribution $\mathrm{NORM}(\mu_{s,m}, \sigma^2_{s,m}[t])$; we assumed $\mathrm{NORM}(0.0, \sigma^2_m)$ prior distributions for $\mu_{s,m}$. The random subject or site effects

ω_i account for the repeated sampling of plots and transects among years (Gelman and Hill 2007) and are described by underlying normal distributions that vary by method, $\mathrm{NORM}(0.0, \sigma^2_m[\omega])$. The variance of the random error term also varies by method, with $\varepsilon_{s,t,m,i} \sim \mathrm{NORM}(0, \sigma^2_m[\varepsilon])$. We assumed diffuse inverse gamma prior distributions for all variance parameters. Although the year effect structure in this model is slightly simpler than those in the Link and Sauer (2002) model, this model is complicated by the need to accommodate the 2 different surveys with area offsets that account for area sampled during surveys.

Abundance.—For each survey, a yearly stratum-specific abundance is defined from model components and associated variances. For plot surveys,

$$n_{s,t,1} = \exp[\gamma_{s,t,1} + 0.5\sigma^2_1(\omega) + 0.5\sigma^2_1(\varepsilon)]$$

whereas for transect surveys,

$$n_{s,t,2} = \exp[\gamma_{s,t,2} + 0.5\sigma^2_2(\omega) + 0.5\sigma^2_2(\varepsilon)]$$

Transect surveys are adjusted for visibility,

$$n'_{s,t,2} = \exp[\gamma_{s,t,2} + 0.5\sigma^2_2(\omega) + 0.5\sigma^2_2(\varepsilon)] \times \exp(\nu_s)$$

where ν_s is a visibility adjustment from the CWS plot data in overlap strata or the USFWS helicopter data (see below) in strata where only transect surveys have been conducted. Variance components are added to accommodate asymmetries in estimating means from log normal distributions (Sauer and Link 2011).

A composite population size is defined as the mean of the sample-unit-specific abundances of each species,

$$n_{s,t,.} = \frac{n_{s,t,1} + n'_{s,t,2}}{2}$$

The total population size in the stratum is defined as the yearly site-specific density estimates multiplied by the number of km^2 in the stratum (A_s), e.g.,

$$N_{s,t,2} = A_s \times n_{s,t,2}$$

Population change estimation.—Status reports of waterfowl summarize population change as 1) percentage change in population between the current year and the preceding year and 2) percent change of the current year relative to the mean of all prior years. We calculated these change estimates as the posterior median from ratios of the appropriate population estimates for strata with long-term data.

We also calculated an interval-specific trend estimate to evaluate long-term pattern in population change for each of the individual strata. Following analyses used in the North American Breeding Bird Survey, we defined the trend estimate as the ratio of the endpoints of the time series for each species in each stratum converted to a yearly percentage change (Link and Sauer 2002).

Visibility Correction Factors

The concerns about VCF adjustments relate to 3 issues: 1) Do counts conducted from helicopters on transect segments provide a means of adjusting fixed-wing transect survey results to be comparable to the plot survey (i.e., are the helicopters on plots providing an estimate comparable to those on segments)? 2) Do counts from either helicopter survey provide reasonable statistical information for adjustment (i.e., are the estimated ratios biased or inefficient)? and 3) Do the spatial and temporal scales of those counts provide sufficient information for adjusting fixed-wing counts over the survey range (i.e., at what scale can the information be applied for estimation of visibility)?

We address these questions by adopting 2 approaches for estimating VCFs. Both of these approaches derive estimated populations for helicopter (both CWS and USFWS) and fixed-wing survey methods, then use the differences in these counts (on the log scale) to estimate VCFs. The 2 approaches were negotiated by an international committee, to ensure that plot data were the benchmark for scaling in the combined survey region (M. Koneff, United States Fish and Wildlife Service, unpublished report).

Visibility rates in overlap strata.—For areas in which both plot and transect data are available, differences in the estimated mean population size for each survey are used to provide a direct estimate of survey level differences.

$$\nu_s = \frac{n_{s,.,1}}{n_{s,.,2}}$$

where $n_{s,.,1}$ is the mean of the annual population estimates for the plot survey in stratum s and $n_{s,.,2}$ is the mean of the annual population estimate for the transect survey. In practice, plot surveys were conducted over more years than the transect surveys. We limited the estimation of VCFs in each stratum to time periods in which data were collected by both surveys. Thus, ν_s is defined as $\tilde{n}_{s,.,1}/\tilde{n}_{s,.,2}$, where the tilde indicates that $\tilde{n}_{s,.,1}$ and $\tilde{n}_{s,.,2}$ are estimated from data only for the common time period. We refer to VCFs estimated from these regional mean comparisons as plot-transect VCFs, or V_{PT}.

Visibility rates in non-overlap strata.—We used helicopter data collected on selected segments of the transects to derive a visibility adjustment in strata where only transect surveys were conducted. We refer to VCFs estimated from these comparative transect survey subsamples as transect VCFs or V_{T}.

For mallards, we used combined ratio analyses of helicopter-based and fixed-wing counts on segments to estimate ν_s at the scale of fixed-wing crew areas (groups of strata surveyed by the same pilot and crew in a year), with variances (Smith 1995). We transformed these estimates to the log-scale using a delta method approximation and entered them into the hierarchical model as means and variances of a normally distributed ν_s.

For black ducks, we used more extensive information to develop a hierarchical model for regional visibility. This analysis constructs a log-linear model using the helicopter data collected on segments, and estimates additive year and stratum-specific differences between helicopter counts and comparable data collected on the same segments by the fixed-wing aircraft. The modeling is constrained by limited data over space and time, precluding estimation of interactive year by strata effects as defined for the model for estimating population change. Instead, the log-linear model is constructed to model helicopter counts on segments as additive year and stratum effects.

$$\log(\lambda_{s,t,h,i}) = \varphi_t + \alpha_s + \varepsilon_{s,t,h,i}$$

where φ and α represent additive effects of year and strata, i indexes segment, t indexes year; and s indexes stratum. In this case, all surveys are conducted on segments and the h indicates data based on helicopter survey.

For the helicopter data, the same general structure of Poisson counts ($y_{s,t,h,i} \sim \text{POISSON}[\lambda_{s,t,h,i}]$) and overdispersion is used as in the overall population change model. Year effects are fixed, and method-specific variances govern stratum effects ($\sigma_h^2[\varphi]$) and overdispersion errors ($\sigma_h^2[\varepsilon]$).

Fixed-wing counts are modeled as helicopter counts (in the stratum and year) plus year (ν'_t)- and stratum (υ_s)-specific visibility effects:

$$\ln(\lambda_{s,t,f,i}) = (\varphi_t + \alpha_s + \varepsilon_{s,t,h,i}) + \nu'_s + \nu_s + \varepsilon_{s,t,f,i}$$

Indexing is similar, but we use f to indicate parameters associated with the fixed-wing counts. As with the helicopter counts, fixed-wing counts are Poisson-distributed with overdispersion. Stratum effects for visibility (υ_s) are governed by a common variance $\sigma^2(\upsilon)$, and error variance is method-specific ($\sigma_f^2[\varepsilon]$).

Log-visibility ($\nu_{s,t}$) in year t and stratum s is estimated by adding $\nu'_t + \nu_s$, and is exponentiated to provide the standard visibility estimate. For scaling the transect survey in the actual analysis, we calculated the mean for each stratum, and then log-transformed the inverse of that mean to estimate ν_s for black ducks.

Fitting the Model

We fit the model using Markov-chain Monte Carlo (MCMC) methods, as implemented in program WinBUGS (Lunn et al. 2000, Spiegelhalter et al. 2002). The approach is Bayesian, in that prior distributions are specified for each random quantity, and the MCMC procedure uses simulations that produce correlated Markov Chains that provide estimates from the posterior distributions of the quantities of interest. We refer readers to Lunn et al. (2000) and Link and Sauer (2002) for a more detailed summary of the approach. To implement the model fitting, prior distributions must be specified for quantities (see the Model Section for our prior distributions). Prior distributions for visibility estimates are similarly defined. The analysis is iterative, in that estimates are derived from a simulation-based procedure that converges to a series of estimates from which summary statistics such as medians and credible intervals can be derived. Results are presented as medians and 95% 2-sided credible intervals summarized from 25,000 iterations from 3 chains after a 475,000 iteration burn-in period for each chain. The VCF model is fit during analysis of the hierarchical model for population change, and provides estimates that feed directly into each iteration of the MCMC fitting. This ensures that variances in the visibility rates are adequately incorporated into the primary analysis.

Comparative Analysis

The hierarchical model permits comparison of transect, plot, and composite survey results at several geographic scales. Because inconsistencies between surveys are a primary concern, direct comparisons of plot, transect, and composite results were made for the 9 overlap strata (Fig. 1). We evaluated consistency of year-to-year changes between plot and transect surveys in overlap strata by estimating first-difference correlations of the time series (Zar 1999). If confidence intervals from the transformed correlation parameter (z; Zar 1999:382–383) overlapped 0, we concluded no correlation between the 2 surveys. For both species, we compared precision of estimates for transect, plot, and composite surveys by calculating mean differences in CV. We compared VCFs from the plot-transect comparison to the independently estimated VCFs from the segment-level helicopter data.

Because of temporal differences over which the plot and transect surveys occurred, composite results for the entire survey area can only be calculated for 1998–2011; time series from 1990 to 2011 can only be conducted for the core area; and direct comparisons of composite results and the plot survey results can only be conducted using the overlap strata. We present annual estimates and trends by species for the composite survey area, and evaluate species associations by correlating first-differenced times series between black ducks and mallards from the composite analysis by stratum. This analysis permits assessment of consistency of year-to-year population changes between the species in each stratum.

RESULTS

Visibility Correction Factor Estimation

With a few exceptions, VCF estimates from the plot-transect comparison and the helicopter-transect analysis provided generally similar, yet often imprecise, results (Fig. 2). Although credible intervals overlapped in all comparable strata for black ducks, we note that the plot-transect ratio had larger estimated VCFs in strata 63 and 64, where plots tended to occur in more coastal habitats, and smaller estimated VCFs in stratum 67, where plot samples tended to have limited distribution through Labrador. Coefficients of variation for plot-transect VCFs ranged from 17% (stratum 368) to 38% (stratum 52). The crew-area estimates of segment helicopter VCFs had CVs ranging from 32% (stratum 51) to 44% (stratum 52).

Aside from strata 51 and 52 and the plot-transect VCF in stratum 468, VCFs for mallards were generally close to 1.0. Plot-transect VCFs for mallards were generally very imprecise, varying between 30% and 87% in CVs. Crew-area segment helicopter VCFs varied from 18% to 105%.

Strata Population Estimates

Mean population estimates by stratum for the composite survey results showed large variation in both population size and estimated precision among strata in eastern Canada (Table 1). Black duck populations were small in the southwestern part of the survey area (USFWS strata 53, 54, and 55), whereas mallard populations were small in northern and

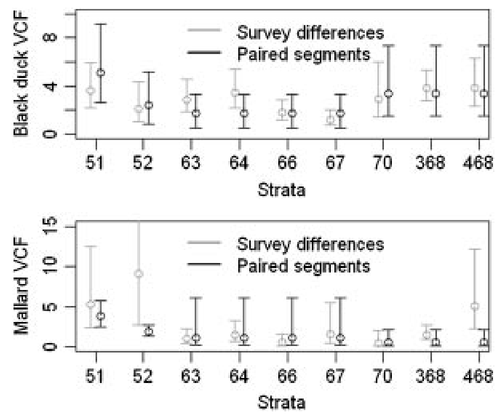

Figure 2. Visibility correction factors (VCFs) for the 9 overlap strata for black ducks and mallards. Survey difference estimates are based on the mean difference in stratum abundances for plot and transect surveys; paired segment comparisons are based on direct fixed-wing aircraft and helicopter survey segments. Paired segment comparisons are summarized by crew areas (multiple strata surveyed by the same pilot and observer).

eastern regions (Atlantic Provinces and northern Quebec). We produced a time series of population estimates for 4 individual strata to show examples of the range in time periods sampled, geographic conditions, and combinations of the 2 survey types. Stratum 51 contained complete information for both surveys, and a plot of the results highlights the differences between the methods (Fig. 3). Stratum 368 had transect data only from 1996 to 2011, so composite and plot results were identical prior to 1996 (Fig. 3). We note

Table 1. Estimated mean population sizes and coefficients of variation of black ducks and mallards by stratum in eastern Canada. Note that number of years varies depending on the starting year of survey in the stratum. Composite estimates are presented for overlap strata and single survey estimates (transect or plot) are presented for all other strata.

		Black duck		Mallard	
Stratum	Data	$\bar{x}$	CV (%)	$\bar{x}$	CV (%)
51	Composite	105,000	14	193,200	34
52	Composite	16,910	24	117,700	70
63	Composite	57,520	12	3,650	31
64	Composite	52,510	14	2,163	36
66	Composite	37,010	14	246	49
368	Composite	135,500	9	13,370	23
468	Composite	85,310	16	48,080	38
70	Composite	34,690	19	646	80
67	Composite	60,930	17	794	64
54	Transect	8,669	48	71,760	28
55	Transect	4,788	55	22,150	36
56	Transect	30,750	48	25,380	28
469	Transect	31,490	59	459	97
269	Transect	78,910	50	821	83
62	Transect	67,100	29	7,124	47
65	Transect	10,940	40	710	61
53	Transect	2,166	50	7,929	114
369	Transect	82,390	47	851	79
71	Plot	26,800	15	514	42
72	Plot	6,757	30	2,630	67

that plot and transect results often do not change in the same direction from year to year. Although this is not particularly controversial given the relatively imprecise results, some of the differences were quite extreme (e.g., 1996–2000 in

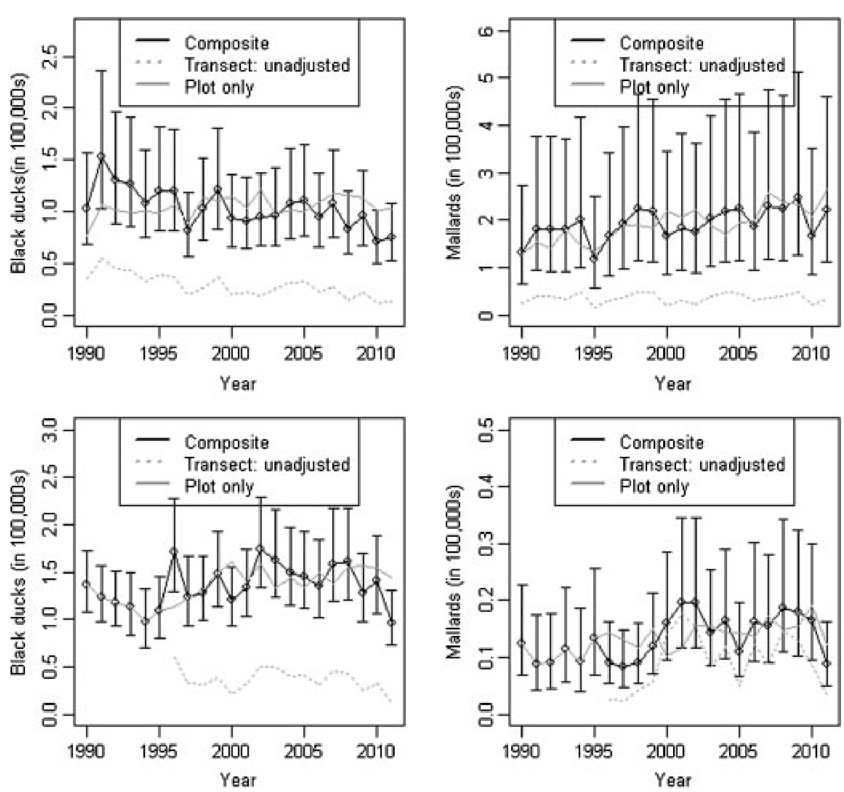

Figure 3. Estimated numbers of breeding mallards and black ducks in stratum 51 where plot and transect surveys were conducted concurrently since 1990 (upper graphs) and in stratum 368 where plot surveys were conducted since 1990 and transect surveys were conducted since 1996 (lower graphs). Estimates are presented for the composite analysis, an analysis using only transect data unadjusted for visibility, and analysis using only plot data.

stratum 368 for both species). Stratum 54 and 71 had transect and plot surveys only, respectively, from 1990 to 2011 (Fig. 4). Estimates from the composite survey analysis for all strata are available from the USFWS and United States Geological Survey Migratory Bird Data Center web page (https://migbirdapps.fws.gov/).

Year-to-year changes from the black duck surveys were positively correlated between transect and plot surveys in strata 64 and 66 ($z_{64} = 0.70$, 95% CI: 0.14–1.27; $z_{66} = 0.98$, 95% CI: 0.41–1.55). In all other overlap strata, confidence intervals for the z-transformed correlation coefficients overlapped 0, and 3 of the 9 correlation estimates were negative. In contrast, we observed strong negative correlations in annual changes from the 2 survey platforms for mallards in 1 strata ($z_{63} = -0.59$, 95% CI: -1.16 to -0.03) and no strong positive correlations. Correlations in 7 of the remaining 9 overlap strata were weakly negative and 1 was weakly positive.

We also correlated year-to-year changes in composite estimates of mallard and black duck populations by stratum. Of the 20 strata, 15 of the estimated correlations were positive, and the correlations were significant and positive in strata 62 and 63, indicating that positive changes in black duck populations were associated with positive changes in mallard populations.

Comparison of the average trends by strata indicated a positive association between trends of the species, $z = 0.57$ (95% CI: 0.12–1.02). Apparent increases in both black duck and mallard populations occurred in strata 63 and 64, whereas both species appeared to decline in strata 54. Black ducks appeared to decline in strata 368, 52, and 56, where mallards appeared stable; and mallards appeared to increase in stratum 51, where black ducks remained stable (Fig. 5). Estimates of trend were particularly imprecise for mallards, reflecting their low abundances and sporadic occurrences in northern Canada (strata 66, 70, 67, 269, 369, and 469).

Precision of Results

Analysis of composite data by strata indicated black duck CVs were larger than mallard CVs only in strata 54–56, where mallards were much more abundant than black ducks (Table 1). The average annual mallard CV was larger than the CV for black ducks from 1998 to 2011 in both the plot survey area ($\bar{x}_{\text{CV mallards}} = 27.7\%$, $\bar{x}_{\text{CV black ducks}} = 6.9\%$) and the total area ($\bar{x}_{\text{CV mallards}} = 22.1\%$, $\bar{x}_{\text{CV black ducks}} = 12.1\%$).

Mean CVs for black ducks averaged over all years in the 9 overlap strata were 20.8% for the plot survey, 32.3% for the transect survey, 53.3% for the V_T-adjusted transect estimates, 28.2% for the V_{PT}-adjusted transect estimates, and 20.7% for the composite results. Although variation in relative precision occurred among strata, for black ducks the composite survey had smaller CV by year relative to either the plot survey (average CV 0.2% smaller) or the transect survey (11.4% smaller; Table 2). The plot survey results were more precise than unadjusted transect results (11.2% smaller) and V_{PT}-adjusted transect estimates (7.1% smaller), and much more precise than V_T-adjusted transect estimates (32.5% smaller).

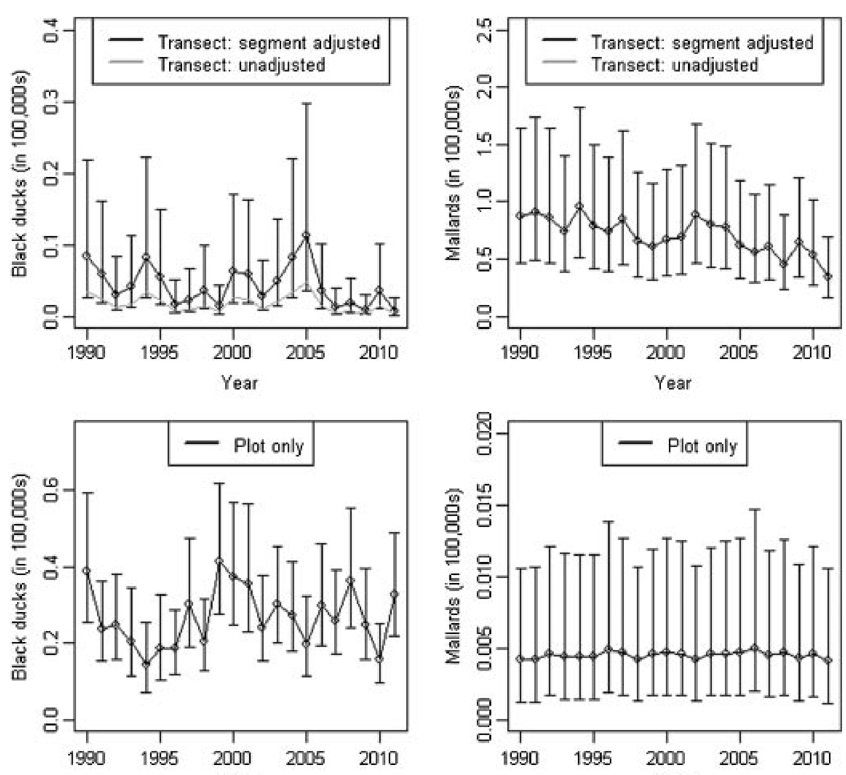

Figure 4. Estimated numbers of breeding mallards and black ducks in stratum 54, where only transect surveys have been conducted (upper graphs) and stratum 71, where only plot surveys have been conducted (lower graphs). Estimates are presented for an analysis using only transect data unadjusted for visibility, an analysis in which transect data are adjusted for visibility using data from segment-level helicopter surveys, and analysis using only plot data in stratum 71.

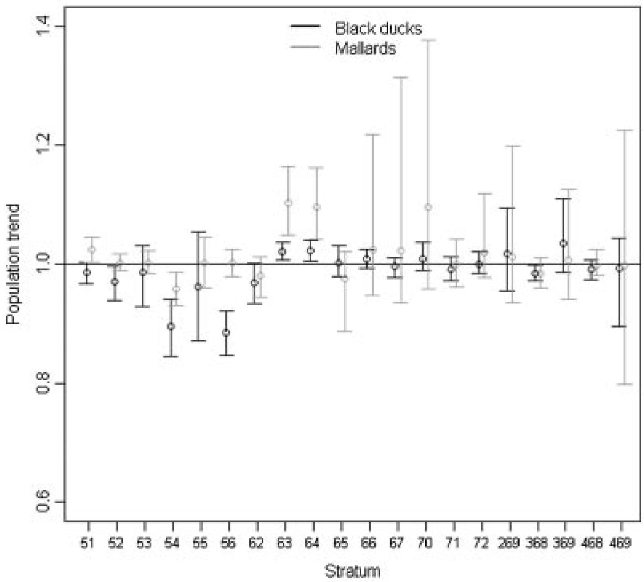

Figure 5. Comparison of estimated yearly population changes for black ducks and mallards by stratum in eastern Canada and the northeastern United States, 1990–2011.

For mallards, precision varied greatly among strata and survey, and mean CV averaged over years and over the 9 overlap strata were 87.6% for the plot survey, 50.7% for the transect survey, 92.1% for the V_T-adjusted transect estimates, 63.4% for the V_{PT}-adjusted transect estimates, and 70.7% for the composite results. Only 4 of the overlap strata (51, 52, 368, and 468; Table 1) contained substantial numbers of mallards. Differences in precision were quite inconsistent among strata (Table 3). In 3 of the 4 overlap strata with substantial numbers of mallards, the plot survey had a larger estimated CV than the transect survey, and overall the plot survey had a 31.7% larger CV than the transect survey. Plot surveys had smaller CVs in 3 of the 4 major mallard strata relative to both visibility-adjusted transect counts. The composite survey had smaller CVs than the plot survey in all 4 major mallard strata, but the composite survey had smaller CVs than the transect survey in only 1 of the 4 strata.

Regional Results

In the area covered by the plot survey, addition of composite data only slightly modified annual population estimates and trends for both species (Fig. 6). However, adding the transect data available for regions in the core area but not in the plot survey area (i.e., USFWS strata 53, 54, 56, and 62) did present a slightly different picture of population change and size, and adding all the strata available from 1998 to 2011 clearly showed that a significant portion of the black duck population occurred outside the region of overlap between the transect and plot surveys. A mean of 317,203 black ducks appeared in transect-only areas, representing 33.9% of the estimated total black duck population. Only 3.6% of the black duck population within the total survey area occurred in strata 71 and 72, which were surveyed only in the plot survey. Similarly, a mean of 137,184 mallards appeared in transect-only areas, representing 26.4% of the estimated total mallard population. Plot-only areas contained only 0.6% of the mallard population (Table 1).

Regional Population Change Estimates for Current Year

Population change estimates using the plot survey and combined survey results at different scales (11 strata comparable with plot survey, 15 strata initiated in 1990, and all 20 strata) showed differing yet imprecisely estimated population trends for both species. Estimated population changes for black ducks from 2010 to 2011 were slightly negative in the plot survey and core areas, and slightly positive in the total area for black ducks and at all 3 scales for mallards. However all 3 estimates were very imprecisely estimated as all credible intervals overlapped 0 (Table 4). Estimated change in 2011 from long-term means varied among regions and survey mode. With the exception of mallards in the plot survey area, which indicated a slight and non-significant increase, all decreased relative to the long-term mean and the decline appeared significant for black ducks in the core area (Table 4).

DISCUSSION

The pioneering efforts of Chamberlain and Kaczynski (1965) identified the fundamental logistical and visibility constraints on waterfowl surveys in eastern Canada. Many places are difficult to reach by air and impossible to survey from the

Table 2. Comparison of stratum-specific differences between coefficients of variation for estimates of black duck numbers derived using different survey methods and analyses. The difference and the 95% credible interval (CI) of the difference are presented for comparisons of unadjusted transect versus plot survey estimates, transect with United States Fish and Wildlife Service helicopter adjustment (V_T) to plot, composite results to plot, composite results to unadjusted transect, and transect with Canadian Wildlife Service plot survey adjustment (V_{PT}) to plot.

	Transect-plot		Transect (V_T)-plot		Composite-plot		Composite-transect		Transect (V_{PT})-plot	
Stratum	ΔCV[a]	95% CI	ΔCV[a]	95% CI	ΔCV[a]	95% CI	ΔCV[a]	95% CI	ΔCV[a]	95% CI
51	17.2	(16.7, 17.8)	31.0	(30.5, 31.5)	2.1	(1.6, 2.7)	−15.1	(−15.9, −14.3)	12.5	(11.7, 13.3)
52	16.0	(14.2, 17.9)	35.6	(34.1, 37.2)	−0.3	(−0.9, 0.3)	−16.3	(−17.8, −14.9)	10.7	(8.6, 12.7)
63	6.7	(6.2, 7.3)	30.7	(30.3, 31.0)	−1.9	(−2.1, −1.8)	−8.7	(−9.1, −8.3)	1.0	(0.6, 1.4)
64	10.4	(8.9, 12.0)	32.3	(31.3, 33.3)	0.1	(−0.3, 0.5)	−10.3	(−11.5, −9.1)	8.3	(6.8, 9.8)
66	2.9	(2.5, 3.4)	27.6	(27.3, 27.9)	−2.7	(−2.9, −2.5)	−5.6	(−6.0, −5.3)	0.3	(−0.1, 0.8)
368	15.0	(12.4, 17.7)	38.3	(36.5, 40.1)	2.4	(2.0, 2.8)	−12.6	(−15.1, −10.2)	12.2	(9.4, 14.9)
468	9.3	(8.2, 10.4)	31.8	(31.1, 32.5)	−0.1	(−0.5, 0.2)	−9.4	(−10.2, −8.7)	6.2	(5.2, 7.2)
70	21.4	(19.6, 23.1)	40.0	(38.5, 41.4)	1.3	(0.2, 2.3)	−20.1	(−22.3, −17.9)	12.4	(10.4, 14.3)
67	2.0	(1.2, 2.8)	25.6	(25.0, 26.2)	−2.2	(−2.6, −1.9)	−4.3	(−4.8, −3.8)	0.6	(−0.2, 1.3)

[a] Comparisons are presented by calculating differences for each year and then calculating the mean of the differences among years.

Table 3. Comparison of stratum-specific differences between coefficients of variation for estimates of mallard numbers derived using different survey methods and analyses. The difference and the 95% credible interval (CI) of the difference are presented for comparisons of unadjusted transect versus plot survey estimates, transect with segment helicopter adjustment (V_T) to plot, composite results to plot, composite results to unadjusted transect, and transect with plot survey adjustment (V_{PT}) to plot.

	Transect-plot		Transect (V_T)-plot		Composite-plot		Composite-transect		Transect (V_{PT})-plot	
Stratum	ΔCV[a]	CI	ΔCV[a]	CI	ΔCV[a]	CI	ΔCV[a]	CI	ΔCV[a]	CI
51	−3.3	(−3.8, −2.9)	2.7	(2.3, 3.1)	−2.2	(−2.5, −1.9)	1.2	(0.9, 1.4)	2.2	(1.8, 2.7)
52	−22.6	(−22.8, −22.3)	−18.2	(−18.5, −18.0)	−1.0	(−1.1, −0.9)	21.6	(21.4, 21.8)	−0.2	(−0.3, 0.0)
63	−9.5	(−13.1, −5.8)	71.2	(68.1, 74.4)	−10.0	(−12.3, −7.7)	−0.5	(−2.3, 1.2)	−5.2	(−8.4, −2.1)
64	−26.7	(−34.7, −18.8)	55.0	(47.0, 62.9)	−19.8	(−27.4, −12.2)	6.9	(5.7, 8.2)	−17.6	(−25.5, −9.7)
66	−16.4	(−34.6, 1.9)	70.2	(48.4, 92.0)	−28.7	(−37.1, −20.2)	−12.3	(−22.9, −1.7)	0.9	(−17.9, 19.6)
368	5.4	(2.2, 8.5)	53.1	(51.0, 55.2)	−1.5	(−2.1, −0.9)	−6.9	(−9.7, −4.2)	8.3	(5.2, 11.4)
468	−4.6	(−6.5, −2.8)	42.8	(41.4, 44.3)	−0.7	(−1.0, −0.3)	4.0	(2.3, 5.6)	5.9	(4.2, 7.5)
70	−127.7	(−163.6, −91.7)	−86.4	(−122.4, −50.4)	−27.9	(−88.3, 32.4)	99.7	(57.8, 141.6)	−108.4	(−145.6, −71.2)
67	−80.0	(−82.8, −77.2)	−76.0	(−78.8, −73.2)	−48.2	(−54.6, −41.8)	31.8	(26.8, 36.9)	−56.3	(−58.7, −54.0)

[a] Comparisons are presented by calculating differences for each year and then calculating the mean of the differences among years.

ground, and birds are difficult to detect even when sites can be accessed. Unfortunately, these issues are still hampering waterfowl survey efforts, and the imprecision and uncertainties associated with the present survey efforts stem from the same problems. Consequently, fixed-wing aircraft tend to detect a relatively small fraction of the ducks present, and although helicopters detect more birds, their detection probabilities are likely <1. Given these sources of imprecision, we were encouraged that a composite survey for black ducks in the eastern survey region can produce annual population estimates with an average yearly CV of 12.1%. Mallards had a more limited distribution in the region and an average yearly CV of 22.1%. The eastern waterfowl survey thus provides critical information regarding waterfowl population abundance and distribution in eastern Canada and Maine, but a variety of issues associated with the survey merit further analysis and research.

Survey Precision

The stated goal for precision of the range wide black duck survey was 12% (Black Duck Joint Venture, unpublished memorandum). The plot survey area originally considered

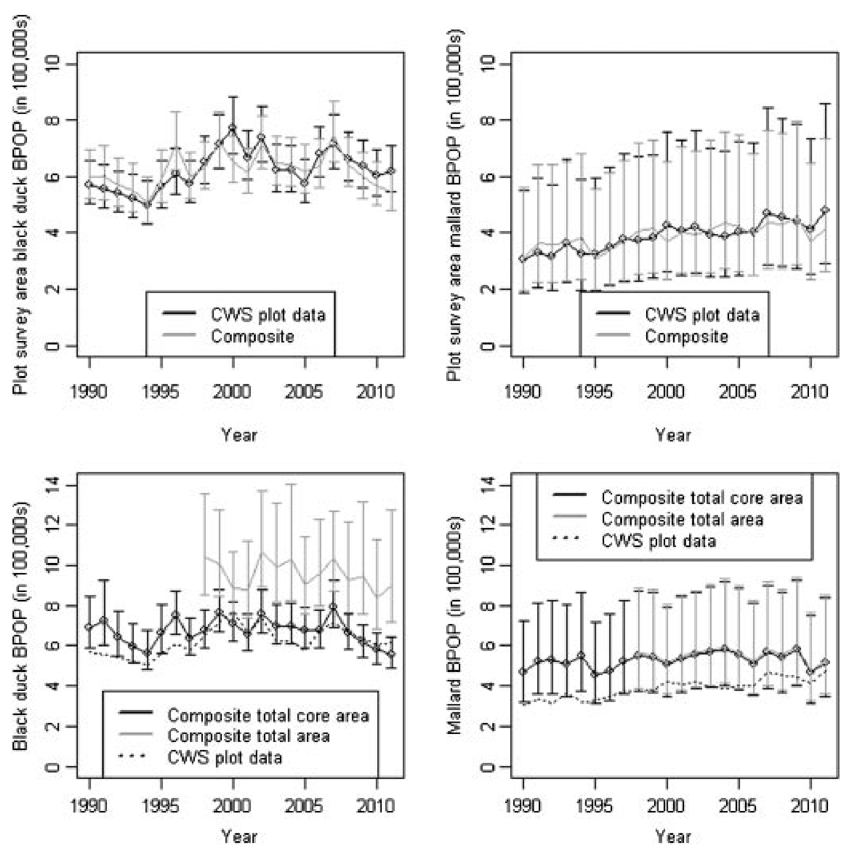

Figure 6. Comparative times series of black duck and mallard breeding population estimates (BPOP) based on Canadian Wildlife Service (CWS) data alone versus composite estimates for the portion of the region surveyed by CWS plot surveys (top panels), and estimates from an analysis of the core black duck breeding range surveyed from 1990 to 2011 and an analysis of the entire composite survey starting in 1998 (bottom panels).

Table 4. Estimates of percent relative population change for black ducks and mallards in eastern Canada and the northeastern United States. Change is estimated as the difference between years 2010 and 2011 and as the difference from the long-term (1990–2010) mean to 2011.

Time period comparison	Black duck		Mallard	
	% Change	95% CI	% Change	95% CI
2010–2011				
Combined 11[a] strata	−3.71	(−14.85, 8.52)	12.05	(−10.78, 46.52)
Combined 15[b] strata	−3.63	(−14.80, 9.13)	10.16	(−9.47, 38.52)
Combined 20[c] strata	6.87	(−8.37, 29.51)	10.46	(−9.60, 39.58)
Mean–2011				
Combined 11 strata	−13.26	(−20.48, −5.00)	6.41	(−10.26, 30.89)
Combined 15 strata	−17.66	(−25.76, −8.80)	−5.36	(−18.87, 12.89)
Combined 20 strata	−6.92	(−17.79, 12.67)	−2.67	(−17.10, 17.37)

[a] Strata numbers 51, 52, 63, 64, 66, 67, 368, 468, 70, 71, and 72.
[b] Strata numbers 51, 52, 53, 54, 55, 56, 63, 64, 66, 67, 368, 468, 70, 71, and 72.
[c] Strata numbers 51, 52, 53, 54, 55, 56, 62, 63, 64, 65, 66, 67, 368, 468, 269, 369, 469, 70, 71, and 72.

by the Joint Venture exceeded this goal with a CV of approximately 7%, whereas the total eastern survey area CV was slightly over the goal. Smith (1995) presented CVs of the primary waterfowl species surveyed in mid-continent North America. Of the 10 primary taxa he summarized, only the canvasback (*Aythya valisineria*), at 13.5%, had a CV larger than the 12.1% estimated here for black ducks in the eastern survey area.

The eastern survey tends to yield large CVs at the scale of USFWS strata for both species, although the CVs tend to be smaller and more consistent among regions for black ducks than for mallards. Although the CVs for strata are larger than the regional goals set for precision (15% CV), black ducks are presently managed as a single breeding population ranging from Ontario to the Atlantic Provinces (Conroy et al. 2002), and at this scale the survey results have CVs very close to the goal. However, large CVs among yearly estimates would make short-term population changes difficult to detect using the survey. For example, a 10% change in the population between 2 years is not detectable using any of the regions we defined for composite analysis for black ducks, and even a 25% change in population would not be detectable for mallards. We detected significant changes from long-term means for black ducks, primarily because of the magnitudes of the changes.

Survey costs and agency budgets have changed dramatically in recent years, and changes in United States–Canada currency exchange rates and fuel costs have limited funds for surveys. Under these conditions, optimization of the survey for cost becomes an important issue. Sample allocation has historically been considered separately for each survey. Transect surveys have been optimized using standard optimal allocation procedures for stratified surveys with visibility adjustments applied at different scales (J. R. Sauer et al., United States Geological Survey, unpublished memorandum), whereas plot surveys have been optimized for the goals of estimation of either long-term population trend or sample means (B. Collins, unpublished memoranda). None of these procedures adequately incorporated the complexity associated with the replicate counts over time on the sample units and the panel design used in the plot survey. The estimates of precision and model structure produced here provide the basis for combined optimization of the 2 surveys in a framework that includes an appropriate model structure.

Why Conduct 2 Surveys?

The concurrent use of transect and plot surveys has been controversial because of the apparent redundancy of effort and inefficient use of information. However, neither survey nor aircraft type alone is suitable for a range-wide survey of black ducks in eastern Canada.

Plot surveys conducted by helicopter are much preferred by biologists who work in eastern Canada, as additional sightings of ducks enhance a wide variety of studies and facilitate local-scale habitat modeling exercises (e.g., Bordage et al. 2001). Helicopters can also conduct surveys in mountainous areas that are unsafe for fixed-wing aircraft, such as the Laurentian Mountains in stratum 71. However, helicopters are relatively expensive (approx. 2.5 × the cost/hr of fixed-wing aircraft in 2003), and escalating costs have forced a variety of cutbacks in sampling over the survey period (e.g., the reduction in plot size in 1996 and the implementation of a rotating panel plan for partial survey; Bordage et al. 2003). Continuing rise in helicopter costs calls into question the continuation of extensive helicopter surveys.

The extensive transect survey provides coverage of a much larger area, and is the only source of information for approximately a third of the black duck population in eastern Canada. However, the differential visibility of fixed-wing and helicopters introduces the necessity of additional comparative survey effort, with VCF estimation either through geographic overlap with plot surveys or additional helicopter surveys within the transect sample units. Although the 2 approaches provided generally similar VCF results, both provided imprecise estimates of relative visibility.

These considerations associated with costs and the need for visibility estimation suggest that any future survey will likely require composite analyses that accommodate the need to collect data from both fixed-wing and helicopter-based surveys, but that the relative contributions of the surveys will continue to vary. Our analysis establishes that information from the 2 surveys can be combined into a composite time series for black ducks and mallards. Further, we demonstrate that a meaningful VCF for scaling transect data to plot data can be accomplished via either direct comparison of results between the plot and transect surveys or by sub-sampling segments along transects with helicopters.

Use of the Composite Analysis

Our analysis provides the first estimates of black duck population change from breeding population surveys that adequately accommodate the statistical constraints imposed by the repeated surveys of sample units, the panel designs used in the plot survey, and the need to accommodate visibility adjustments in the analysis. Hierarchical models are flexible in their application, and we considered a variety of alternative model forms. Alternative models that estimate a single set of year effects with survey offsets, for example, might be more efficient alternatives to our model. However, our model allowed us to maintain the distinctive aspects of the 2 surveys during the analysis, which addressed the concerns of the biologists associated with the surveys that were advocates of either plot or transect surveys and a priori considered the other survey to be of lesser value. Consequently, socio-political realities dictated that the analysis should permit direct comparisons between surveys, and be applicable when the amount of overlap changed over time. Our analysis accommodates these realities by 1) providing separate year effects that enabled direct comparisons of the 2 survey results; 2) retaining the capability to have separate variances components by survey type; and 3) providing a single metric using all available data in a single modeling platform.

Alternative approaches to aggregation exist, and recent work on combining information from mourning dove surveys have used models that posit a latent underlying population and model individual survey results as scaled realizations of the latent population (Otis et al. 2009). We are exploring the use of these models for the eastern waterfowl surveys, but in this analysis, we were primarily interested in exploring differences among surveys. The simple aggregation approach we chose allowed great flexibility in comparing survey results while also estimating a composite result in the context of visibility adjustments.

A great advantage of hierarchical modeling is that additional structure can be embedded into the model, and additional data sources, such as demographic models and their uncertainty, can be directly integrated with population status information. For example, band-recovery models can be placed as submodels and population change information can be used in conjunction with survival to construct derived variables for estimating productivity or exploring associations among survival and population size. The MCMC fitting procedure is particularly useful for these complicated models, as inference is made directly from the estimated posterior distributions of model parameters and derived statistics.

Remaining Uncertainties in Surveys

As with any survey, a variety of statistical and practical issues continue to complicate the logistics, analysis, and interpretation of black duck surveys. A primary concern is un-modeled components of detection. Although both helicopters and fixed-wing craft can be modified to facilitate observation, detectability of birds is always <1 and incomplete counts remain a concern in aerial surveys. In particular, a statistical relationship exists between counts and the amount of time spent surveying, and comparative surveys documented crew-specific differences in helicopter counts on plots due primarily to survey effort (B. Collins, unpublished report).

Our analyses show that, despite many years of effort in refining approaches to estimating detection by subsampling transects from helicopters, it is difficult to precisely estimate visibility adjustments between fixed-wing and helicopter surveys from that approach or from the regional plot-transect adjustments. We conclude that estimates of visibility of sufficient precision to permit evaluation of year and spatial effects are not feasible using our current survey and analytical approaches. However, the overlap estimates of visibility or accommodation of survey effects in the analysis appear to provide the very large-scale adjustments with little loss of credibility.

MANAGEMENT IMPLICATIONS

The composite hierarchical model provides a reasonable framework for analysis of transect and plot data, and provides a means for aggregate analysis regardless of extent of overlap of surveys. Managers can use the results of this analysis for setting black duck harvest regulations, and the procedure should be integrated directly into modeling associated with adaptive harvest management and integrating harvest and habitat management. Population estimates at the scale of the eastern survey meet precision goals for black ducks. However, mallard results are very imprecise, reflecting the very low abundance of the species in most of eastern Canada. We suggest that precision goals be re-evaluated in the context of the needs of habitat and adaptive harvest management, which will likely depend on black duck and mallard breeding population data in the future. The model structure and results presented here can be used to simulate needed samples under a wide variety of scenarios of costs and alternative surveys. Because visibility estimation adds a great deal of variation into transect results, further development of field and analysis approaches for efficient estimation of visibility rates for both differential and absolute adjustment of counts should remain a high priority research activity, particularly in light of escalating costs and proposed reductions in effort (of 25–50% in 2012) for the plot survey (E. Reed, Canadian Wildlife Service, personal communication). We also suggest that the hierarchical modeling framework be used to incorporate additional information (e.g., the north-eastern plot survey (Heusmann and Sauer 2000), banding data) into a comprehensive annual population model to provide more geographically extensive information for black duck habitat and harvest management.

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Appendix. Aggregations of United States Fish and Wildlife Service (USFWS) strata to larger scales for summarizing breeding population sizes for eastern waterfowl. When applicable, areas that are covered by the 4 administrative strata defined for black duck surveys by the Canadian Wildlife Service (CWS) are also indicated.

USFWS strata	CWS strata	Plot survey area	Core area	Total area
51	4	✓	✓	✓
52	4	✓	✓	✓
53			✓	✓
54			✓	✓
55			✓	✓
56			✓	✓
62				✓
63	1	✓	✓	✓
64	1	✓	✓	✓
65				✓
66	2	✓	✓	✓
67	2	✓	✓	✓
368	3	✓	✓	✓
468	4	✓	✓	✓
269				✓
369				✓
469				✓
70	2	✓	✓	✓
71	2	✓	✓	✓
72	1	✓	✓	✓