Aerial Strip-transect Surveys: Indexing Autumn-winter Waterbird Abundance and Distribution in South Carolina

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Abstract: Aerial surveys integrating probability-based sample designs have been implemented successfully to estimate relative abundance of wintering ducks in Arkansas, Louisiana, Mississippi, and Missouri, but these approaches have not been evaluated in the Atlantic Flyway except for American black ducks (*Anas rubripes*) along the Atlantic coast. Furthermore, these surveys have not been used to index abundance of other nonbreeding waterbirds. Given elimination or reduction of resources allocated to the Midwinter Waterfowl Survey in the Atlantic Flyway and elsewhere, the South Carolina Department of Natural Resources (SCDNR) expressed a need for reliable surveys to monitor waterfowl and other waterbirds during autumn through winter. We designed stratified aerial strip-transect surveys to estimate population indices for migrating and wintering dabbling ducks (Anatini), diving ducks (Aythini, Mergini, Oxyurini), pelagic and piscivorous waterbirds (Anhingidae, Laridae, Pelicanidae, Phalacrocoracidae), and wading birds (Ardeidae, Ciconiidae, Threskiornithidae) in coastal and inland regions of South Carolina during autumn-winter 2017–2019. We used unequal probability random sampling to estimate population indices with deemed adequate precision (i.e., coefficient of variation [CV] ≤ 20%) and estimated theoretical survey efforts needed to achieve desired precision for future aerial surveys. Indices met our goal for precision in September and January 2018 for wading birds, in February and November 2018 for pelagic waterbirds, and in February 2018 for diving ducks, but never for other ducks during South Carolina waterfowl hunting season. We detected peak abundance of dabbling and diving ducks in January and wading birds and wood storks (*Mycteria americana*) in September. We estimated ~2.5 times greater survey effort was needed across waterbird taxa than was expended to achieve a CV = 20%. We also used survey data to depict spatiotemporal variation in waterbird distributions across the study area. Our surveys are applicable for the SCDNR and other agencies seeking to monitor autumn-winter waterbird populations. Although survey refinements are necessary to increase precision in South Carolina, our waterbird indices are useful to assess population trends through time, guide habitat management and restoration efforts, refine local harvest regulations, inform law enforcement to detected illicit activities (e.g., baiting), and monitor possible shifting waterbird distributions in response to land-use and climate change.

Key words: aerial survey, abundance estimation, design-based sampling, precision, South Carolina, survey effort, waterfowl, waterbirds

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Aerial surveys are effective for monitoring wildlife population trends and habitat use, assessing environmental and anthropogenic influences across landscapes, and targeting areas for habitat conservation (Williams et al. 1999, Pearse et al. 2008a, 2012, Denes et al. 2015). A prominent example of long-term wildlife population and habitat monitoring in North America is the extensive aerial and ground transect surveys in the United States and Canada to estimate annual breeding populations of waterfowl (Smith 1995). Population estimates from these surveys are used in statistical models to inform annual harvest regulations (Williams et al. 1996, Brasher et al. 2002). Wildlife resource agencies across the continent also have used aerial inventories to monitor trends in migrating and wintering waterfowl abundance and distributions (e.g., Midwinter Waterfowl Survey [MWS]; Heusmann 1999, Pearse et al. 2008a, Hennig et al. 2017, Whittaker et al. 2019).

The North American Waterfowl Management Plan (NAWMP)

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recommended that researchers improve population surveys at local, regional, and continental scales (U.S. Department of the Interior and Environment Canada 1986, NAWMP 2018). Despite widespread use of aerial inventories to monitor wintering duck populations, these methods were criticized for lack of explicit survey design; variation in conduct among states, biologists, and years; and for fixed-area surveys generating only raw counts of ducks, geese, and swans (Heusmann 1999, Pearse et al. 2008a, U.S. Fish and Wildlife Service [USFWS] 2017). Consequently, the incorporation of flyway-wide winter estimates from these surveys into federal databases and ultimately fiscal support from the USFWS for the MWS was discontinued in 2016 (USFWS 2017, Hagy 2020). Declining federal support and erosion of confidence in the MWS left many Atlantic Flyway states with the decision to: 1) discontinue aerial survey monitoring efforts for waterfowl altogether; or 2) evaluate new or adapted aerial survey designs and in-flight methodology.

Improvements to aerial survey methodology using probability-based sampling has generated precise estimates of wintering duck populations across the entire Atlantic Flyway coastal regions for American black ducks (Conroy et al. 1988), and in the Mississippi Alluvial Valley for mallards (*A. platyrhynchos*) and other dabbling ducks (Reinecke et al. 1992, Pearse et al. 2008a,b). Following these evaluations, Arkansas, Louisiana, and Missouri adopted similar protocols to survey wintering waterfowl (Lehnen 2013, Herbert et al. 2018, Whitaker et al. 2019). However, these approaches have not been evaluated or adopted in Atlantic Flyway states. Additionally, the North American Waterbird Conservation Plan emphasized the need for standardized surveys to estimate non-breeding waterbird abundance and their habitats (Kushlan et al. 2002); however, few agencies in North America have evaluated any aerial surveys for waterbirds other than waterfowl to address these needs (Kingsford and Porter 2009).

In hopes that aerial surveys could be implemented to reliably index waterfowl and other waterbird abundance and distribution in South Carolina and become operational in the future, we worked with the South Carolina Department of Natural Resources (SCDNR) to evaluate aerial survey sampling methodology, estimation procedures, statistical precision, and logistical and economic considerations (Masto 2019). We designed generalizable aerial strip-transect surveys to estimate population indices of migrating and wintering waterfowl and other waterbird taxa in coastal and inland regions of South Carolina during autumn-winter 2017–2019. To assess survey performance, we quantified precision of abundance indices with an a priori goal of achieving coefficient of variation (CV) ≤ 20% (e.g., Pearse et al. 2008a). Furthermore, we quantified survey effort needed to achieve CV = 20% in future aerial surveys. Finally, we demonstrated utility of aerial surveys to illustrate spatiotemporal distributions of waterbird densities across our study area.

Methods

Study Area

We conducted aerial surveys during autumn-winter 2017–2019 in coastal and inland regions (i.e., strata) of South Carolina (Figure 1). We selected these strata based on expert knowledge of the state's winter waterbird habitats, reconnaissance flights during the previous winter, and prior MWS data collected by the SCDNR and USFWS (Epstein and Joyner 1998; Gordon et al. 1998; USFWS 2008, 2017). Our 10 geographic strata encompassed 5,676 km^2 of waterbird habitats including impoundments, coastal marsh, estuaries, tidal and freshwater rivers, reservoirs, and ponds in both coastal and inland regions of the state.

Survey Design

We used stratified random sampling and indexed waterbird abundance with an a priori goal for precision of CV ≤ 20% of the overall population size (Pearse et al. 2008a). Across 10 strata we created a sample frame of 1,447 east-west, 250-m transects (i.e., sample units). We randomly selected transects with replacement and unequal probability proportional to their length (Pearse et al. 2008a). We restricted adjacent transects from being selected within a single survey to reduce the probability of re-counting individual waterbirds and re-selected transects if adjacent transects were selected (Reinecke et al. 1992, Pearse et al. 2008a). We acknowledge that transect weights were altered slightly by restricting selection of adjacent transects; however, re-selection only occurred during a single survey and bias resulting from double-counting was more concerning to us than unquantified bias due to transect re-selection. Further, we randomly selected new sets of transects for each survey to reduce serial autocorrelation of data among surveys (Reinecke et al. 1992, Pearse et al. 2008a). We allocated survey effort in proportion to stratum area and sampled at 7.5%–10% of total transect length within each stratum.

Aerial Survey Methodology

We conducted 9 aerial surveys during autumn-winter 2017–2019 from a fixed-winged, single-engine Cessna 172. The pilot navigated along east-west, 250-m wide transects using an on-dash global positioning system (GPS) and maintained an altitude of ~60 m above ground level using the aircraft's altimeter. We delineated transect boundaries of 250 m using tape marks on the passenger window of the aircraft (Norton-Griffiths 1978, Koneff et al. 2008).

Observers voice-recorded the number of dabbling ducks, diving ducks, pelagic and piscivorous waterbirds, and wading birds to

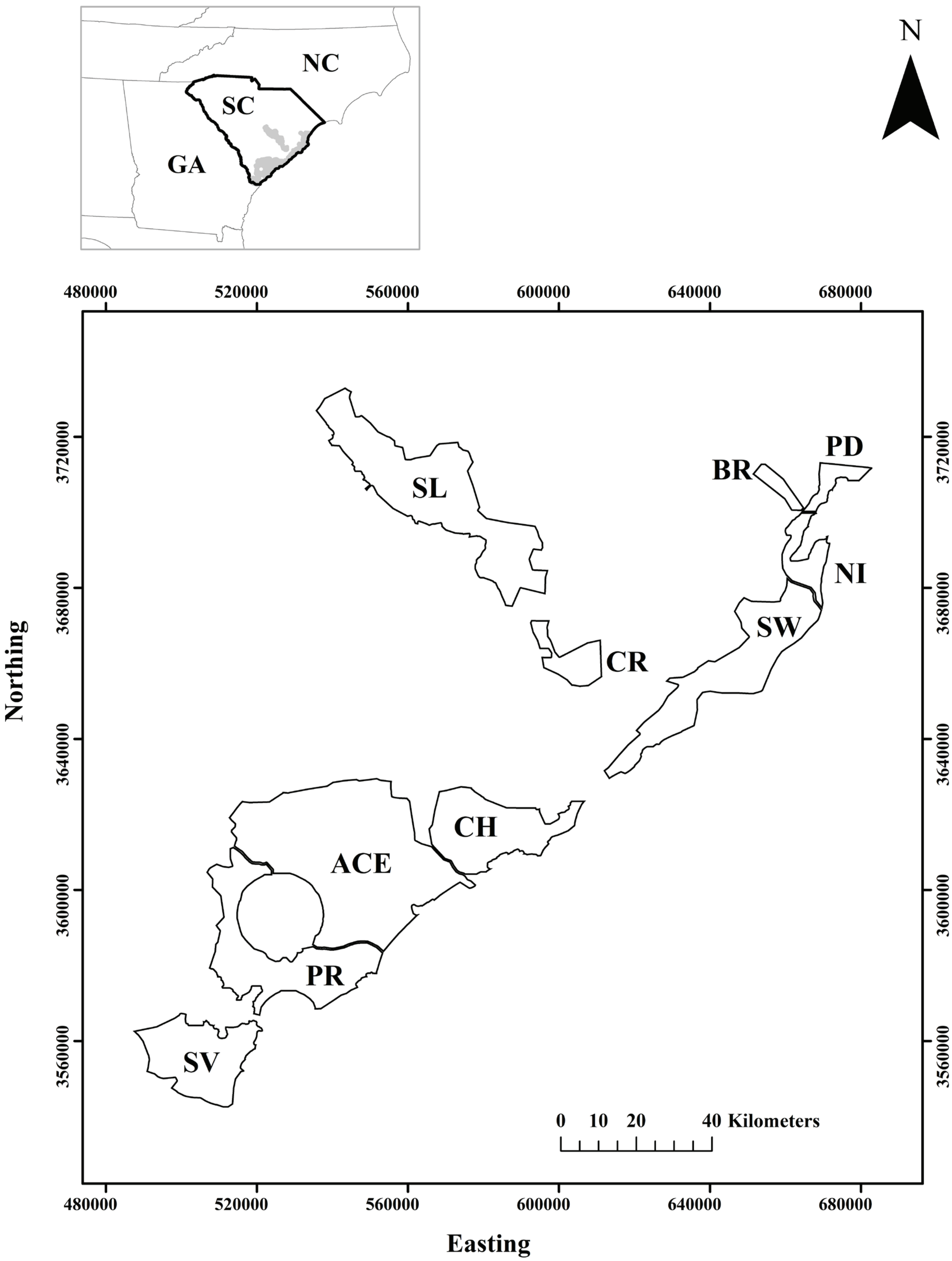

Figure 1. Ten geographic strata in South Carolina (SC), USA, encompassing important coastal and inland waterbird habitats surveyed during 2017–2019 including the Ashepoo-Combahee-Edisto Rivers Basin (ACE), Black River Basin (BR), Charleston region (CH), Cooper River (CR), North Inlet (NI), Pee Dee Basin (PD), Santee Lakes region (SL), Savannah (SV), and Santee Delta-Winyah Bay regions (SW).

species-level along each transect using tablet computers and aerial survey software (RECORD and TRANSCRIBE; J.I. Hodges, USFWS, unpublished software[2]). Aerial survey software enabled geographical referencing of detected birds during surveys (RECORD) and enabled efficient transcription of voice-recorded and georeferenced survey data (TRANSCRIBE). We followed USFWS aerial survey protocol for counting waterfowl and other waterbirds (USFWS 1987; Bowman 2014, 2015).

Estimation and Related Analyses

We estimated population indices ($\hat{I}$; relative abundance, not corrected for imperfect detection [*sensu* Pearse et al. 2008b]) for the aforementioned waterbird taxa by two different observers (i.e., Observer 1, autumn-winter 2017–2018; Observer 2, 2018–2019). We calculated stratum-level indices $\hat{I}_i$, for each survey and waterbird taxa combination from the mean waterbird counts (y) on the j^{th} transect divided by the probability the transect was selected p_{ij} across the number of transects per strata n_i expressed as $\hat{I}_i = \Sigma_{j=1}^{ni} y_{ij}/p_{ij}$. We then calculated an overall population index ($\hat{I}$) by summing h strata indices ($\hat{I}_j$) where $\hat{I} = \Sigma_{i=1}^{h}\ \hat{I}_i$. Similarly, we calculated population variance by summing strata variances $V(\hat{I}) = \Sigma_{i=1}^{h} V(\hat{I}_i)$, a standard error (SE) as the square root of the population variance $\text{SE}(\hat{I}) = (\sqrt{(V[\hat{I}])})$, and a CV as $\text{CV}(\hat{I}) = (\text{SE}[\hat{I}]/\hat{I}) \times 100$ for each waterbird taxa during 2017–2019 aerial surveys (Pearse et al. 2008a, Skinner 2016).

Observer 1 served as front-seat observer during autumn-winter 2017–2018 and Observer 2 served as front-seat observer during autumn-winter 2018–2019. However, Observer 2 also served as rear-seat observer during January and February 2018. During the latter surveys, tandem-seated aerial observers 1 and 2 independently counted and recorded waterbirds. We tested the prediction that front- and rear-seat (i.e., Observer 1 and 2, respectively) waterbird estimates correlated positively during these surveys using a Spearman rank-order correlation ($n = 91$ and 88 transects in January and February 2018, respectively).

For abundance indices that were not zero, we calculated survey effort (i.e., proportion of transect length sampled in each strata) needed for future aerial surveys based on survey and waterbird taxa-specific variance that would achieve CV = 20%. We specified f as the ratio of deemed adequate and observed variance

$$f = \frac{\Sigma_{i=1}^{h}\Sigma_{j=1}^{n_i}(n_i[n_i-1])^{-1}(y_{ij}p_{ij}^{\ -1}-\hat{I}_i)^2\ adequate}{\Sigma_{i=1}^{h}\Sigma_{j=1}^{n_i}(n_i[n_i-1])^{-1}(y_{ij}p_{ij}^{\ -1}-\hat{I}_i)^2\ observed}$$

in which all terms are previously defined. Simply expressed,

$$f = \frac{\Sigma_{i=1}^{h} V(\hat{I}_i) adequate}{\Sigma_{i=1}^{h} V(\hat{I}_i) observed},$$

where the numerator is the summation of strata i variances across h strata and is equal to CV = 20% (i.e., deemed adequate precision). Likewise, the denominator was our population-level variance calculated for each survey-waterbird taxa combination. Therefore, f may be expressed as the ratio of adequate and observed margins of error,

$$f = \frac{\frac{1}{\sqrt{kn_i}}}{\frac{1}{\sqrt{n_i}}} = \frac{1}{k},$$

where n_i is the number of transects sampled per strata (i.e., expended survey effort) and is adjusted by an unknown factor k in the numerator. We assumed numerator and denominator population indices to be equal and only allowed k to vary. We then solved $f = \frac{1}{\sqrt{k}}$ for $k = \frac{1}{f^2}$. The resulting factor $k \times$ the original survey effort (%) estimated a theoretical survey effort (%) that would be needed to achieve CV = 20% around population indices for each survey and waterbird taxon.

To demonstrate the utility of our surveys to depict potentially important areas of waterbird space-use and areas for potential habitat conservation, we interpolated observed locations of taxa-specific waterbirds across the study area for 2017–2019 surveys based on GPS locations and counts of waterbirds. We followed a three-step process outlined by Pearse et al. (2008a) to prepare the vector layer needed for interpolation. Separately for each waterbird taxon, we first imported GPS locations and associated counts into a geographic information system (GIS) for each survey. Next, we generated null points (i.e., waterbird count = 0) spaced 1,000 m apart along sampled transects; this spatial vector represented portions of strata that were surveyed but where no waterbirds were detected. Last, we combined aforementioned waterbird and transect vectors which created a spatial layer representing the number of waterbirds observed across the sampled area.

We used the above spatial vector layer and inverse-distance weighting (IDW) interpolation using the Geospatial Analysis extension in ArcGIS Desktop 10.5 to visualize relative densities of waterbirds across our study area (Johnston et al. 2001, Pearse et al. 2008a). We selected IDW interpolation, because it is simple yet robust (Babak and Deutsch 2009). We chose a distance-decay function of 1 for all survey-taxa combinations because larger power functions did not substantially change distributions and have been shown to result in greater estimated variance (Babak and Deutsch 2009). Following interpolation, we established five density categories for each waterbird taxon-survey combination (i.e., low, low-medium, medium, medium-high, and high). We desig-

2. At the time of publication, data are not available from the U.S. Fish and Wildlife Service or data have limited availability owing to proprietary restrictions.

nated density categories using geometric intervals of the predicted density distributions within ArcGIS, where class breaks (i.e., transition from one density category to another) of survey-specific waterbird densities are selected based on geometric progressions within class intervals (Johnston et al. 2001, de Smith et al. 2009). We selected geometric intervals because we wished to produce cartographically aesthetic maps of individual surveys for SCDNR and partners without reducing interpretation by transforming the raw count data.

To evaluate spatiotemporal variation in waterbird densities among surveys we averaged class breaks, separating density categories across November 2017, January 2018, February 2018, November 2018, December 2018, January 2019, and February 2019 for each waterbird taxon. We reclassified maps with our estimated mean low-high class breaks based on winter survey averages (Cromley 1987, Pearse et al. 2008a). Thus, class breaks were waterbird-specific but consistent and empirically derived among surveys enabling us to depict both spatial and temporal variation in waterbird relative densities across surveys and years. We performed all spatial analyses at a 1 km^2 spatial scale.

Results

Inter-observer Correlations of Waterbird Abundance

We conducted nine aerial surveys during autumn-winter 2017–2019. We acknowledge unknown directional bias in estimates by two different observers between 2017–2018 and 2018–2019. However, estimates were correlated between observers among waterbird taxa in January and February 2018, when they served simultaneously as front- and rear-seat observers, respectively (Spearman's rho [ρ]: dabblers = 0.64 and 0.76; divers = 0.64 and 0.75; pelagic birds = 0.53 and 0.70; waders = 0.76 and 0.84; $P = < 0.001$; $n = 91$ and 88; January and February 2018, respectively).

Waterbird Abundance and Precision

Greatest indices of dabbling and diving ducks were observed in January 2019 ($\hat{I} = 77,978$ dabblers and $\hat{I} = 24,443$ divers, respectively; Table 1). Wading bird indices were greatest in Septembers and Novembers of 2017 and 2018, ranging from 13,065–26,339 birds ($13\% \leq CV \leq 43\%$; Table 1). Pelagic waterbird indices ranged from 5,281–16,581 birds, with ≥11,572 birds in all surveys ($18\% \leq CV \leq 47\%$) except September 2017 ($\hat{I} = 8,047$) and January 2018 ($\hat{I} = 5,281$; Table 1). Overall, estimates across all waterbird taxa and surveys ranged from 25,633–121,983 birds with greatest estimated population indices observed in January 2019. Across September 2017–February 2019 and when differential species detections were likely, ducks accounted for 71.6% of total waterbirds and, excluding September surveys, accounted for 77.1% of all waterbirds. Only six and 13% of all waterbirds were ducks in September 2017 and 2018, respectively, and 91% of these were blue-winged teal (*Spatula discors*). However, September surveys captured peak abundance of wading birds and wood storks (Table 1). Dominant species of wintering dabbling ducks included green-winged teal (*A. carolinensis*; 35%) and gadwall (*Mareca strepera*; 33%); the most dominant diving duck was ring-necked ducks (*Aythya collaris*; 61%). Dominant wading birds were American white ibis (*Eudocimus albus*; 43%) and great egrets (*Ardea alba*; 28%); dominant pelagic and piscivorous birds were double-crested cormorants (*Phalacrocorax auritus*; 70%).

Generally, diving duck estimates were more precise than dabbling duck estimates. Nonetheless, we achieved our a priori goal of precision ($CV \leq 20\%$) for diving ducks only in February 2018 (Table 1). We achieved our precision goal for pelagic waterbirds in February 2018, November 2018, and January 2019 and for wading birds in September 2018 and January 2019 (Table 1). The most precise estimate of abundance across surveys was for wading birds

Table 1. Population indices ($\hat{I}$), standard errors (SE), and coefficients of variation (CV) for dabbling ducks, diving ducks, pelagic and piscivorous waterbirds, and wading birds estimated from aerial surveys conducted in South Carolina, USA during autumn-winters 2017–2019.

		Dabbling ducks			Diving ducks			Pelagic waterbirds			Wading birds		
Survey[a]	n[b]	$\hat{I}$	SE	CV(%)[c]	$\hat{I}$	SE	CV(%)	$\hat{I}$	SE	CV(%)	$\hat{I}$	SE	CV(%)
1	83	1,558	434	28	0	0	–	8,047	2,409	30	16,028	4,151	26
2	85	64,105	25,388	40	5,421	1,595	29	16,581	7,798	47	23,459	10,178	43
3	91	51,606	17,947	35	22,897	7,180	31	5,281	1,211	23	16,106	6,380	40
4	88	58,183	25,388	36	8,302	1,434	17	15,776	3,229	20	7,716	3,206	42
5	94	9,431	4,325	46	0	0	–	13,524	4,769	35	26,339	3,510	13
6	100	67,835	23,423	35	11,264	4,023	36	10,678	2,033	19	13,065	4,470	34
7	101	43,704	12,845	29	20,619	5,617	27	15,715	3,804	24	7,851	1,810	23
8	96	77,978	33,522	43	24,443	5,103	21	11,572	2,059	18	7,990	1,589	20
9	88	36,562	14,694	40	18,517	4,694	25	13,211	2,939	22	7,197	2,119	29

a. Survey dates: Survey 1, 20–22 Sep 2017; Survey 2, 12–15 Nov 2017; Survey 3, 14–16 Jan 2018; Survey 4, 12–15 Feb 2018, Survey 5, 21–23 Sep 2018, Survey 6, 16–18 Nov 2018, 13–17 Dec 2018, 17–19 Jan 2019, 13–15 Feb 2019
b. n = number of transects sampled
c. CV = SE / $\hat{I}$ * 100

Table 2. Survey effort ($Effort_{orig}$), margin of error adjustment to achieve desired precision of coefficient of variation (CV) = 20% (*k*), and percent survey effort needed ($Effort_{need}$) for dabbling ducks, diving ducks, pelagic and piscivorous birds, and wading birds estimated from aerial surveys conducted in South Carolina USA during autumn-winters 2017–2019.

		Dabbling ducks		Diving ducks		Pelagic waterbirds		Wading birds	
Survey[a]	Effortorig[b]	*k*[c]	$Effort_{need}$[d]	*k*	$Effort_{need}$	*k*	$Effort_{need}$	*k*	$Effort_{need}$
1	0.083	1.96	0.16	–	–	2.25	0.19	1.69	0.14
2	0.082	4.00	0.33	2.10	0.17	5.52	0.45	4.62	0.38
3	0.078	3.06	0.24	2.40	0.19	1.32	0.10	4.00	0.31
4	0.078	3.24	0.25	0.72	0.06	1.00	0.08	4.41	0.34
5	0.085	5.29	0.45	–	–	3.06	0.26	0.42	0.04
6	0.081	3.06	0.25	3.24	0.26	0.09	0.07	2.89	0.23
7	0.086	2.10	0.18	1.82	0.16	1.44	0.12	1.32	0.11
8	0.082	4.62	0.38	1.10	0.09	0.81	0.07	1.00	0.08
9	0.085	4.00	0.34	1.56	0.13	1.21	0.10	2.10	0.18

a. Survey dates: Survey 1, 20–22 Sep 2017; Survey 2, 12–15 Nov 2017; Survey 3, 14–16 Jan 2018; Survey 4, 12–15 Feb 2018; Survey 5, 21–23 Sep 2018; Survey 6, 16–18 Nov 2018; Survey 7, 13–17 Dec 2018; Survey 8, 17–19 Jan 2019; Survey 9, 13–15 Feb 2019

b. Original survey effort as a proportion of transect length surveyed in each strata of total transect length

c. Factor derived from survey and taxa-specific variance that adjusts the margin of error to achieve adequate survey precision of CV = 20%

d. Survey and group-specific survey effort (%) needed to achieve adequate survey precision of CV = 20%

in September 2018 ($\hat{I}$ = 26,339, SE = 3,510, CV = 13%). The range in precision of abundance estimates across surveys and taxa was CV = 26%–37%, with pelagic waterbirds and diving ducks exhibiting the greatest average precision (26% [SD = 9%] and 27% [6%], respectively) and wading birds and dabbling ducks exhibiting the least average precision (30% [11%] and 37% [6%], respectively).

Expended survey effort (i.e., the proportion of transect length surveyed of cumulative transect length) across surveys averaged 8% (Table 2). The estimated survey effort ($Effort_{need}$) that was needed to achieve CV = 20%, based on survey and taxon-specific variance, averaged 29% (SD = 10%) for dabbling ducks across all surveys, with least effort needed in September 2017 ($Effort_{need}$ = 16%; k = 1.96) and greatest effort needed in September 2018 ($Effort_{need}$ = 45%; k = 5.29; Table 2). Diving ducks needed the least survey effort to achieve CV = 20%, averaging 15% (SD = 7%) across surveys, followed by pelagic and wading birds that averaged 16% (SD = 13%) and 20% (SD = 12%), respectively (Table 2). An average of 20% (SD = 11%) survey effort across all surveys and taxa was needed to achieve a priori adequate precision, with November 2018 needing greatest survey effort (33% [SD = 12%]) and December 2018 needing least survey effort (14% [SD = 3%]). Effort needed for January 2018 and 2019 averaged 21% (SD = 9%) and 16% (SD = 15%), respectively.

Waterbird Spatial Distributions

We averaged class breaks across winter surveys for dabbling ducks, diving ducks, pelagic waterbirds, and wading birds to depict spatial distributions and temporal variation in waterbird densities. Class breaks separating dabbling duck density categories were low (<0.29 dabblers/km^2), low-medium (0.29–1.02 dabblers/km^2), medium (1.02–6.46 dabblers/km^2), medium-high (6.46–53.53 dabblers/km^2), and high (>53.53 dabblers/km^2). Diving duck density class breaks were low (<0.09 divers/km^2), low-medium (0.09–0.20 divers/km^2), medium (0.20–0.78 divers/km^2), medium-high (0.78–4.76 divers/km^2), and high (>4.76 divers/km^2). Class breaks dividing pelagic waterbirds were low (<0.12 pelagic birds/km^2), low-medium (0.12–0.21 pelagic birds/km^2), medium (0.21–0.70 pelagic birds/km^2), medium-high (0.70–4.20 pelagic birds/km^2), and high (>4.20 pelagic birds/km^2). Finally, wading bird densities were divided into low (<0.07 waders/km^2), low-medium (0.07–0.14 waders/km^2), medium (0.14–0.61 waders/km^2), medium-high (0.61–3.97 waders/km^2), and high (>3.97 waders/km^2). As examples, we report predicted distributions of waterbirds across coastal and inland South Carolina for January 2018 and 2019 (Figure 2). We present distributions for January only because that is when historical MWS was conducted for waterfowl and the period generally of greatest duck abundance in South Carolina.

Discussion

Precision

Adequate precision (e.g., CV ≤ 20%) is critical for reliable population estimates (Pearse et al. 2008a). We achieved CV ≤ 20% only five times across nine surveys and for four taxa, with pelagic waterbirds meeting adequate precision in three surveys and diving ducks and wading birds meeting adequate precision in one survey each. However, most survey-taxa combinations exhibited CVs > 20%, which suggests that waterbird densities and distributions were highly variable and spatially clustered (Figure 2).

Although we employed stratified random sampling, our survey effort was inadequate to generate precise estimates across our stra-

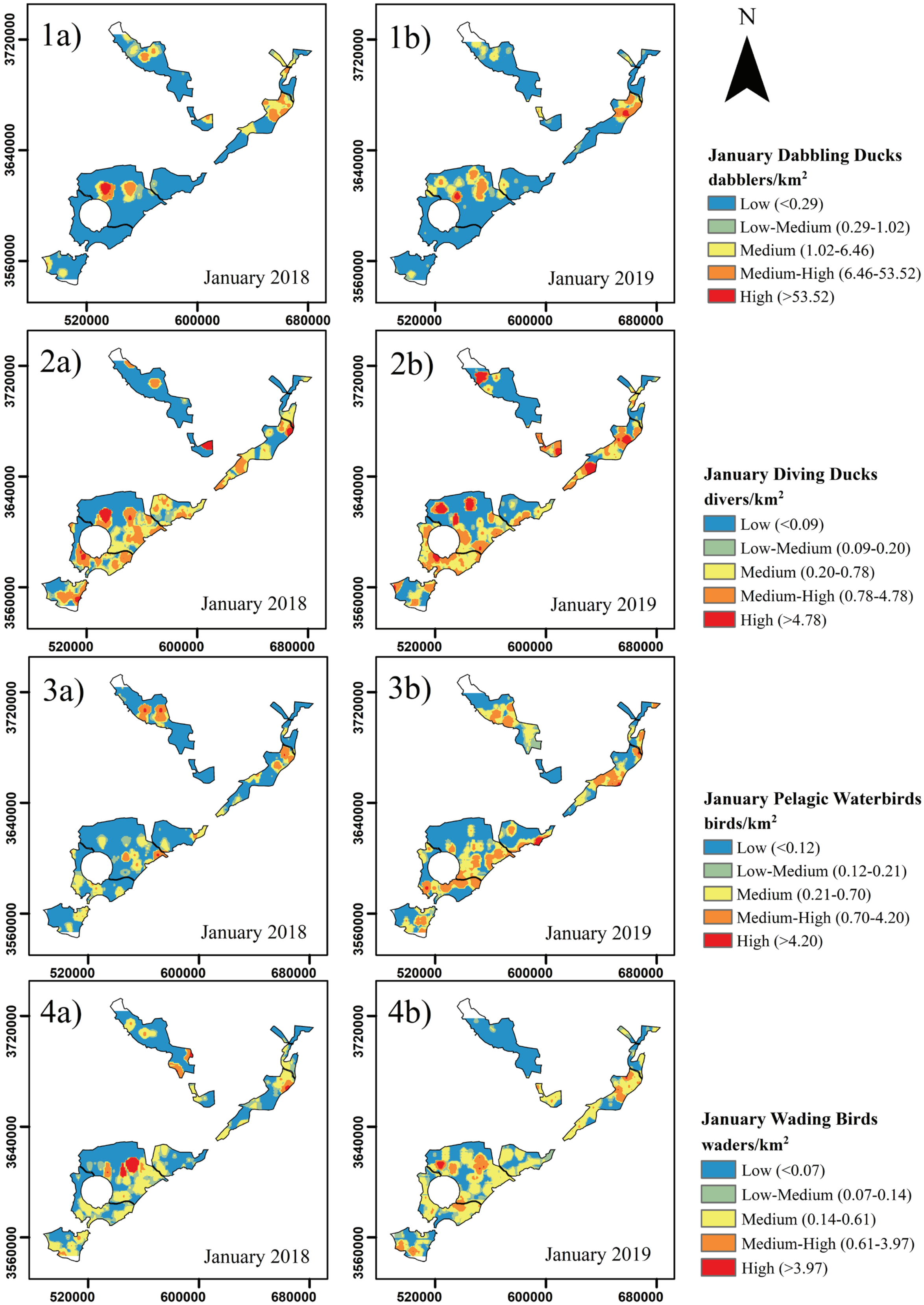

Figure 2. Estimated spatial distributions of dabbling ducks (1), diving ducks (2), pelagic and piscivorous waterbirds (3), and wading birds (4) during January 2018 (a) and January 2019 (b) interpolated across coastal and inland South Carolina, USA.

ta when allocated proportionally. Conroy et al. (1988) concluded that increasing stratification of aerial surveys across coastal Atlantic Flyway regions improved precision of black duck population estimates, although they never were able to achieve precise estimates at the stratum-level (i.e., Atlantic Flyway states). In addition, computer simulated mallard aerial survey designs which incorporated "high-density" duck strata exhibited superior precision compared to those that did not include such strata (Pearse et al. 2009). Finally, post-stratification using spatial interpolation is a proven method to increase precision and reduce bias of original population estimates (Alisauskas 1997, Breidt and Opsomer 2008). Therefore, we conclude that additional stratification based on our interpolated duck and other waterbird densities should increase precision. Possible increases in stratification in South Carolina may include 1) stratifying the Santee Delta region by dividing the South Winyah-Bulls' Bay stratum into separate north and south strata; 2) two substrata within the ACE basin stratum, one along the Combahee River and the other between the Edisto and Ashepoo rivers; and 3) an additional stratum in the Santee Lakes region that encompasses Santee National Wildlife Refuge and surrounding private waterfowl management units (Figure 3). Other states designing aerial surveys to monitor winter waterfowl and other waterbird populations should anticipate significant variation in population indices if their strata contain wetland complexes managed actively, or not, for waterfowl and other waterbirds, as is the case in South Carolina (Gordon et al. 1998, Masto 2019). Thus, states should consider establishing strata that integrate management complexes where high concentrations of waterbirds can be expected to occur. These "high-density" strata can be discontinuous, nested within larger strata, and vary among surveys to capture expected greater concentrations of waterbirds. Finally, if high-density strata encompass minimal areal coverage (e.g., ≤ 2,000 ha; Hagy 2020) and the aerial observer is experienced, states may even consider complete survey effort for known and consistently important areas which can be incorporated into the stratified random sampling design (Gilbert et al. 2020, Hagy 2020).

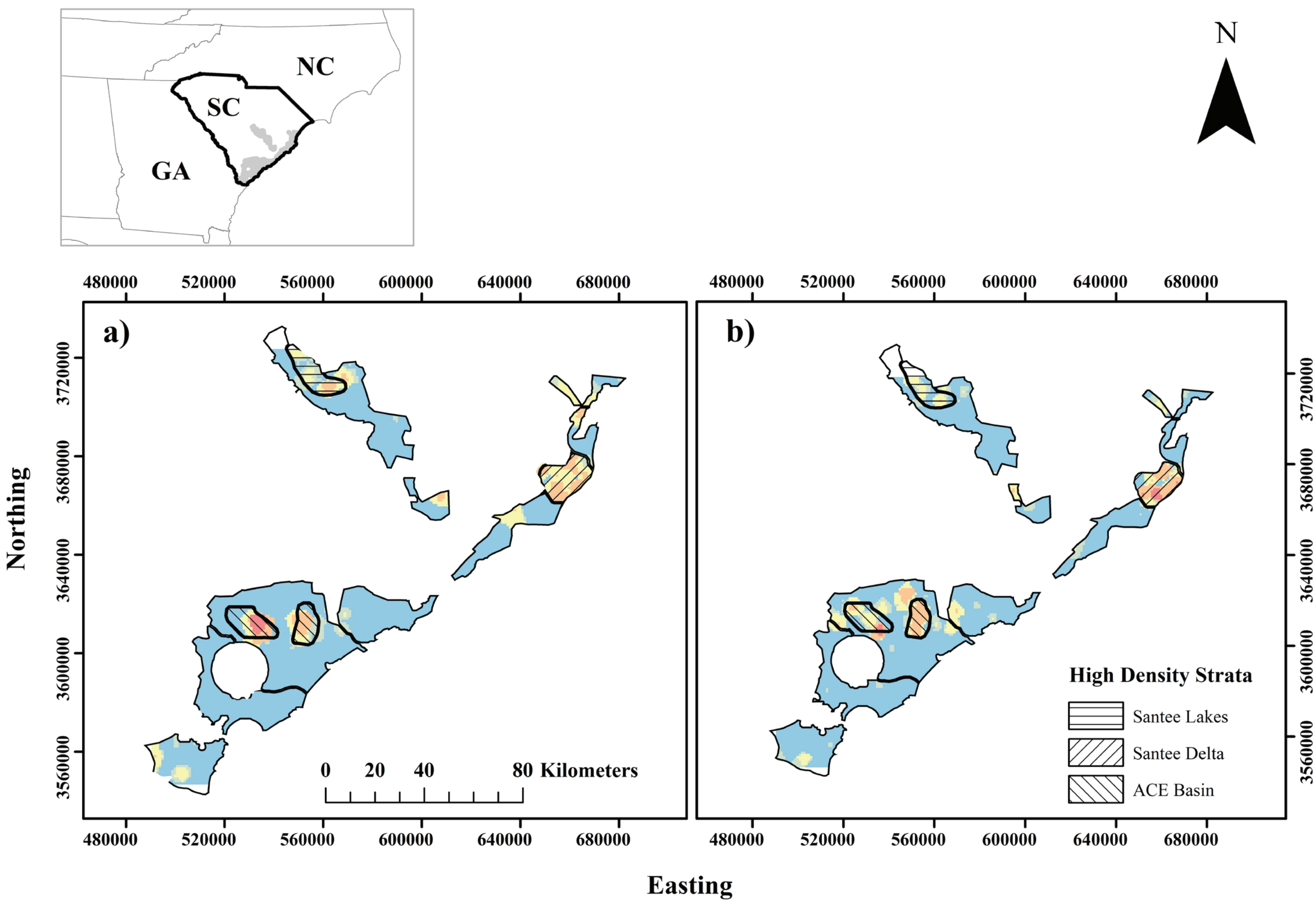

Figure 3. Possible "high-density" strata in the Ashepoo-Combahee-Edisto (ACE) Rivers Basin, Santee Delta, and Santee Lakes superimposed on 50% transparent interpolated January 2018 (a) and January 2019 (b) dabbling duck densities which may reduce overall variance of duck and other waterbird estimates (compare proposed high-density strata with other January waterbird distributions in Figure 2).

We allocated sample effort proportional (i.e., 7.5%–10%) to cumulative transect length among strata and surveys because we did not have a priori knowledge of sample variance within strata among surveys. Estimated variance from November–February 2017–2019 could be used in future surveys to allocate survey effort optimally per strata for each survey (Cochran 1977:98). However, decision-makers would need to reconcile which waterbird taxa to allocate survey effort optimally or combine taxa variances and partition survey effort based on all combined taxa (but see optimal adaptive sampling below). Neyman optimal allocation procedure, which is a type of variance partitioning, might be preferred because it allows for substantially different variances among strata (Lohr 1999), which was the case in ours and similar surveys (e.g., Pearse et al. 2008a). If researchers elect to designate high-density strata for surveys in South Carolina, optimal allocation can be used for existing strata and variances from our and any future surveys can be used to allocate new high-density strata (Pearse et al. 2008a).

If additional stratification and optimal allocation are not implemented for subsequent surveys, increasing sample effort is necessary to generate increasingly precise estimates of winter waterbird abundance in South Carolina. For example, increasing sample effort by 2% reduced CVs by 2% for mallards and by 3% for other dabbling and diving ducks in Mississippi (Pearse et al. 2008a). We presented survey efforts needed to achieve CV = 20% for each waterbird taxa and survey. Resource agencies that implement similar surveys may use this analytical tool to weigh cost-benefits of increasing sampling effort to improve precision of population indices. For example, we estimated that a survey effort of ~20% (i.e., the proportion of sampled transect length of total transect length per strata) was needed to achieve CV = 20% across all surveys and waterbird taxa. However, implementing a 20% survey effort would increase cost by 2.5 times what we expended (i.e., $\text{Effort}_{orig} = 8.22\%$ [SD = 0.30%]) over six-seven days and ~50 hours flight time/survey = ~$12,500 at US$250/hour, (2019 dollars). Thus, geographically strategic increases in sample effort (e.g., high-density areas) based on strata variances and available funds may be preferred. However, implementing high-density strata plus optimal allocation has the potential to improve precision with marginal increases in cost (Pearse et al. 2008a, 2009). In fact, Conroy et al. (1988) concluded that "stratifying as much as possible" would be the best strategy for future aerial surveys in the Atlantic Flyway for black ducks. Furthermore, Lehnen (2013) improved Arkansas' probability-based aerial transect surveys by delineating strata based on watersheds in that state. Therefore, future researchers and biologists might consider implementing a combination of these designs to increase precision while prioritizing those that minimize additional cost.

We presented survey efforts needed to achieve CV = 20% in response to a need expressed by the SCDNR for reliable and precise future waterfowl and waterbird surveys, as mentioned. However, optimal and adaptive sample designs incorporating previously proposed variance-reduction methods for wintering and breeding waterfowl aerial surveys also exist (Pearse et al. 2009, Hooten et al. 2012). Monitoring programs often are limited by cost and the appropriated budget may fluctuate through time. Natural resource agencies may consider optimal adaptive sampling in future aerial surveys to maximize precision relative to changing available funds and priorities (Hooten et al. 2012). For example, some strata in South Carolina contributed little to the overall population index and estimated variance and may not need to be sampled during every survey, every year, or at all. Furthermore, our aerial surveys monitor many species across four waterbird taxa. No single sample design is optimal for every taxa (Bailey et al. 2007). Thus, optimal adaptive sampling may be useful to optimize survey designs across waterbird taxa and at different times of year (Reynolds et al. 2011, Sanderlin et al. 2014). For example, September aerial surveys in our study identified peak and precise wading bird (CV = 13%) and wood stork abundance but did not perform well for ducks during the same time, likely due to sporadic abundances of blue-winged teal (Table 1). Therefore, an optimal sampling design may allocate sampling in September for wading birds when they are most abundant and save resources for increased sampling during late fall-winter when waterfowl are most abundant.

Bias

Population indices can be inherently biased; however, we could not assess accuracy of our indices because the numbers of waterbirds and their detection probabilities were not explicitly known in this study. Double-observer reconciliation methods (Koneff et al. 2008), sightability experiments (Pearse et al. 2008b), aerial-ground counts (Smith 1995), and analyses that incorporate detectability into likelihood estimation (Lyet et al. 2016, Masto 2019) present opportunities to estimate detection probability and reduce bias. However, practical utility of these methods may not be feasible in all situations. For example, implementing two simultaneous observers requires a spacious aircraft to accommodate a pilot, two observers, and their gear. Nevertheless, efforts to correct for observation bias can help achieve accurate population estimates. For example, aerial counts of known numbers of decoys placed in different wetlands in Mississippi produced visibility correction factors for dabbling ducks which were used to inflate population estimates by the proportion of missed individuals (Pearse et al. 2008b).

Nonetheless, indices of relative abundance can be useful in determining population status, spatiotemporal trends, and habitat use assuming correlation between the indexed and true population sizes (Johnson 2008, Barker et al. 2014). Indeed, Pearse et al. (2008a) demonstrated strong correlations between their population indices and bias-corrected abundance estimates for mallards ($r = 0.998$), dabbling ducks ($r = 0.990$), diving ducks ($r = 0.940$), and total ducks ($r = 0.991$). Given these correlations, we believe bias within surveys and years is not as concerning as precision in our study, assuming bias remains constant and the variability in detection probability is less than the variability in estimated population size (Johnson 2008). Although estimates by our simultaneous aerial observers were correlated, we have evidence that our observers estimated abundance differently for several taxa, namely pelagic waterbirds and diving ducks (Masto 2019:51). Thus, we emphasize the need for consistency of aerial observers among years and, when possible, the use of aerial-ground derived correction factors to reduce bias (Frederick et al. 2003, Pearse et al. 2008a). Furthermore, we urge rigorous training of aerial observers through both inflight experience and wildlife computer simulators (Elphick 2008).

Survey Applications

Although our surveys did not yield consistently precise population indices, we extended work of Pearse et al. (2008a) by monitoring and estimating abundance of waterbirds other than waterfowl. Steep declines of waterfowl hunters and associated conservation dollars have been observed nationwide (Vritska et al. 2013). Furthermore, we recognize that all waterbirds contribute significantly to state economies (USFWS 2013) and are bio-indicators of wetland conditions and overall ecosystem functioning (Green and Elmberg 2014, Hagy et al. 2017). Thus, our surveys are widely applicable for SCDNR and other resource agencies seeking to monitor waterbird populations, their habitat use, and the effectiveness of agency management strategies. For example, seasonal variation in species abundance across waterbird taxa may influence wetland management and drawdown timing (Weber and Haig 1996, Taft et al. 2002, Bauer et al. 2020) or be used to allocate law enforcement resources. Furthermore, peak abundance may be used to adjust local hunting boundaries and seasons (Pearse et al. 2008a) or generate eco-tourism opportunities and dollars from inland and coastal birdwatching (USFWS 2013). Additionally, population size and resource use often are used to leverage conservation dollars for wetland improvement and restoration projects (e.g., North American Wetland Conservation Act). Likewise, waterbird abundance and diversity can index the success of restoration efforts (Weller 1995, Kaminski et al. 2006, Hagy et al. 2017, Tapp et al. 2018). Finally, our surveys have revealed practical usage, such as identifying locations with planted and inundated corn and other management practices for waterfowl, tracking number and location of wood duck boxes across the state, and monitoring illegal activities during the waterfowl hunting season (e.g., baiting).

Climate change is expected to alter migration phenology (Gordo 2007) and shift wintering waterbird distributions northward (e.g., La Sorte and Thompson 2007, Lehikoinen et al. 2013, Reese and Skagen 2017). Therefore, habitat management and harvest regulations to satisfy the needs of migratory waterbirds and the public also may change in the future for many southern states including South Carolina. However, traditional inventory-style surveys which monitor the same locations year after year may never detect shifting distributions of waterbirds. Instead, inventory-style surveys likely would conclude spurious statewide positive or negative changes in abundance. Our widespread survey and stratified random sampling protocol enable illustration of duck and other waterbird distributions across our survey areas, which provides an opportunity to display spatial and temporal distributions of birds for use by conservation partners and the public (Figure 2). Additionally, we generated empirically derived standard density categories for each waterbird taxa. Thus, our framework and associated low-high waterbird densities are useful to detect spatiotemporal changes and therefore shifting distributions of these birds across South Carolina through time.

Pearse et al. (2008a) suggested that their survey methods may be broadly applicable across flyways. We demonstrated that more work is needed in the Atlantic Flyway wherein waterbird distributions are more heterogeneous than in the Lower Mississippi Alluvial Valley (see Hennig et al. 2017 for grid-based aerial surveys). If state resource agencies seek to monitor waterbird population abundance and cannot afford to simply increase sampling effort, further evaluation using proposed variance-reduction and optimal adaptive survey designs is needed. Moreover, most states and provinces no longer conduct winter waterbird surveys amid expanding northward wintering ranges of waterfowl and other avian populations (La Sorte and Thompson 2007). Winter aerial transect surveys across flyways combined with other data streams, similar to the waterfowl breeding population and habitat surveys, may be the most reliable way to monitor waterbird populations and distributions moving forward.

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