Coordinated aerial and ground surveys document long-term recovery of geese and eiders on the Yukon–Kuskokwim Delta, Alaska, 1985–2014

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Abstract: Severe declines of waterfowl populations on the Yukon–Kuskokwim Delta (YKD), Alaska, from the 1960s through the mid-1980s, prompted the initiation in 1985 of standardized surveys of the region's breeding birds. These entailed coordinated annual aerial and ground-based surveys, tiered by area and intensity of coverage, which have provided data for this area critical to waterfowl production. Aerial surveys were used to provide broad-scale indices of breeding pairs and the total bird population along the YKD's entire coast, while ground surveys provided finer-scale estimates of breeding chronology, egg production, nesting effort, habitat use, and predation within core breeding habitats. The extensive coverage of the aerial surveys also provided objective data for expansion of the ground-based sampling, while the nest surveys contributed to a better understanding of aerial survey data, including indices of detection rates. Here we describe patterns of long-term population growth of the Cackling Goose (*Branta hutchinsii minima*), Greater White-fronted Goose (*Anser albifrons frontalis*), and Emperor Goose (*Chen canagica*) relative to population objectives for the Pacific Flyway. We also describe significant growth in the western Alaska population of the Spectacled Eider (*Somateria fischeri*) following the species' listing as threatened under the Endangered Species Act in 1993. Growth rates of population indices were positive for the four species from 1985 to 2014, but rates varied within this interval. We found no evidence that dates of nest initiation and hatching advanced significantly between 1985 and 2014. The proportion of waterfowl recorded as pairs by aerial survey crews was correlated with the surveys' start date for geese but not for the Spectacled Eider. The ratio of nests to aerially observed pairs was 4.8 for Cackling Geese, 5.2 for Greater White-fronted Geese, 5.4 for Emperor Geese, and 2.4 for Spectacled Eiders. The nest-to-pair ratio is one tool by which indices based on aerial surveys can be converted to an estimate of the number of breeding pairs. Together these aerial and ground-based surveys provide the information needed to implement waterfowl management and recovery plans, assess waterfowl distribution across the YKD, measure nesting chronology relative to changes in climate, develop indices to detection rate in aerial surveys, and assess waterfowl vulnerability.

Keywords: aerial survey, Cackling Goose, detection rate, Emperor Goose, Greater White-fronted Goose, monitoring, nesting chronology, population change, Spectacled Eider

The coastal zone of the Yukon–Kuskokwim Delta (YKD), western Alaska, has long been recognized as one of the most important areas for nesting waterfowl in North America (Spencer et al. 1951). The YKD supports the entire subspecies *Branta hutchinsii minima* of the Cackling Goose, over 95% of Pacific Greater White-fronted Geese (*Anser albifrons frontalis*), and over 80% of Emperor Geese (*Chen canagica*) in the world (Eisenhauer and Kirkpatrick 1977, Timm and Dau 1979, King and Dau 1981). In addition, virtually all of the western Alaska population of the Spectacled Eider (*Somateria fischeri*) breeds on the YKD (Dau and Kistchinski 1977).

Significant declines in populations of geese and eiders between the 1960s and 1980s are well

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documented. Changes in goose populations during this period were dramatic. Numbers of the Cackling Goose declined by >90% from over 350,000 in the 1960s to 26,000 in the early 1980s, and of the Greater White-fronted Goose declined by >80% from highs over 450,000 in the 1960s to 73,000 by the early 1980s (O'Neill 1979, Timm and Dau 1979, Raveling 1984). At the same time, on the basis of periodic surveys from 1964 to 1981, Petersen and Gill (1982) estimated a 34% decline in spring abundance of Emperor Geese from 139,000 to 91,000, a finding that prompted initiation of annual spring surveys that subsequently documented a further 36% decline through 1986 (USFWS 2017). Coinciding with changes in goose populations, the Spectacled Eider's population on the YKD also declined, with estimates ranging from a loss of 79% between 1969 and 1992 (Ely et al. 1994) to 96% between 1971 (48,000 pairs) and 1992 (1721 pairs) (Stehn et al. 1993). Declines in goose populations during this period were attributed to overharvest by sport and subsistence hunters (Raveling 1984, King and Derksen 1986), whereas that of the Spectacled Eider was attributed to additional factors including avian and mammalian predation, poisoning from lead shot, changes to marine wintering habitats, and winter conditions (Stehn et al. 1993, Ely et al. 1994, USFWS 1996, Petersen and Douglas 2004).

Declines in goose populations on the YKD prompted bold actions in the form of unprecedented harvest restrictions, formalized in the 1985 Yukon–Kuskokwim Delta Goose Management Plan and subsequent Pacific Flyway Goose Management Plans (Pamplin 1986). Declines in populations of the Spectacled Eider led to its listing as a threatened species and the subsequent development of a recovery plan (USFWS 1993, 1996).

Measuring progress toward population-size objectives, such as those detailed in flyway-management plans and recovery plans, requires monitoring designed specifically to measure population indices and trends (Nichols et al. 2007). Accordingly, in 1985 two independent but coordinated aerial and ground-based monitoring programs were instituted specifically to assess the population trends and productivity of geese and eiders (Stehn et al. 1993, Butler et al. 1995a). In this paper we describe how these programs have been instrumental in measuring waterfowl status relative to conservation objectives. We discuss factors that may have influenced population growth, describe changes in nesting chronology and its influence on estimates derived from aerial surveys, discuss how aerial and ground-based survey data can be used to develop correction factors for estimates based on aerial surveys, and describe additional uses of survey data for conservation planning and vulnerability assessments.

Methods

Study Area

The YKD is the largest intertidal wetland in North America (Thorsteinson et al. 1989). We surveyed its waterfowl from the air and from the ground from 1985 to 2014. Our survey area comprised 12,832 km^2 of wetlands from the coast of the Bering Sea to approximately 40 km inland, bounded by Norton Sound to the north and Kuskokwim Bay to the south (Figure 1). In this region, numerous rivers, sloughs, and shallow water bodies are interspersed with sedge–graminoid meadows and limited areas of upland dry tundra (Tande and Jennings 1986, Kincheloe and Stehn 1991). These coastal wetlands sit atop discontinuous permafrost and are characterized by an extremely low elevational gradient, rising by just 1 m from the coast to 7.5 km inland (Jorgenson and Ely 2001). The region is subjected

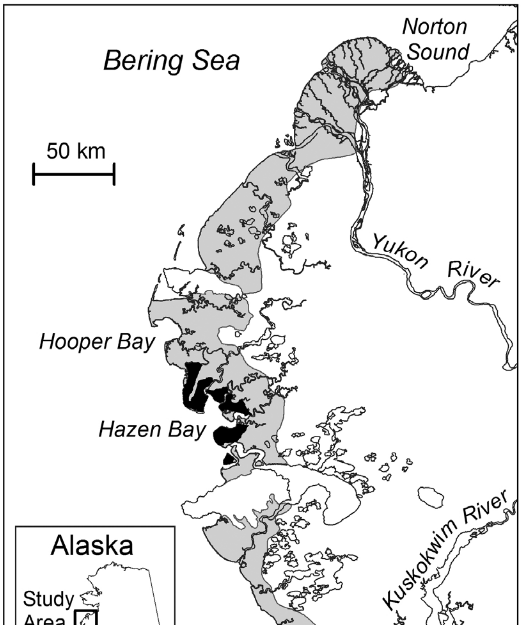

Figure 1. Location of study area, including areas of aerial surveys (gray) and ground surveys (black) on the Yukon–Kuskokwim Delta, Alaska, 1985–2014.

to periodic flooding from extreme high tides and storm surges that inundate wetlands up to 37 km inland (Terenzi et al. 2014). Tidal rivers generally freeze in October or November, and spring breakup (when ice melts) occurs in late May or early June (Jorgenson and Ely 2001). The mean summer temperature is 10 °C, the mean winter temperature –14 °C (Thorsteinson et al. 1989). Average annual precipitation is 178 cm, of which 71% is snowfall (Thorsteinson et al. 1989).

Field Methods

Aerial Surveys

From 1985 to 2014, we recorded observations of waterfowl along roughly 75,000 linear km of aerial transects. Our transects, oriented east–west, were spaced at intervals of 1.6, 3.2, 6.4, or 12.9 km, corresponding to decreasing levels of goose density (Butler et al. 1995a). Starting in 1998, we established four sets of systematic flight lines to be flown in successive years (rotating panel design), such that after four years we obtained essentially complete coverage with adjacent 400-m-wide transects in the stratum of highest goose density (1.6-km spacing) and 12% coverage in the stratum of lowest goose density (12.9-km spacing). The surveys' timing was adjusted annually to extend from the initiation of nesting to mid-incubation (Butler et al. 1995a).

Survey methods followed the standard protocol for aerial surveys of waterfowl breeding grounds in North America (USFWS and CWS 1987). The pilot and observer in the right front seat recorded single individuals, pairs, and flocks of geese, swans, swan nests, and cranes within 200 m of each side of the aircraft, except from 2012 to 2014 when only the observer in the right front seat recorded sightings. Starting in 1988 we added a third observer in the right rear seat to record observations of ducks, loons, and gulls within 200 m of the right side of the aircraft.

We used Cessna 206 fixed-wing aircraft as the survey platform in all years except 2012, when a Quest Kodiak 100 was used. While flying a transect, we maintained an elevation of 30–45 m above ground level and a speed of 145–170 km/hr. The pilot used LORAN (1985–1991) or the global positioning system (GPS, 1992–2014) to gauge the start and end points of transects and to maintain the correct course while flying.

Techniques for data collection were improved as technologies developed. Prior to 1998, we recorded observations to a cassette tape recorder running continuously during the survey (Butler et al. 1995a). Geographic point locations were then interpolated from the proportion of time elapsed between the recorded start and end points for each transect. Beginning in 1998, we used a computerized software package (RECORD; JIH, U.S. Fish and Wildlife Service unpubl. data) to record bird observations directly into a notebook computer connected to the aircraft's GPS receiver. Following each flight, we used a second software package (TRANSCRIBE; JIH, U.S. Fish and Wildlife Service unpubl. data) to merge georeferenced data on bird locations with the species name, group size, date, observer's initials, transect number, flight direction, and weather.

The composition of aerial survey crews was remarkably consistent over the 30-year duration of the survey, entailing only eight observers who collected goose data from the left front and right front seats. Eider data were collected from the right rear seat by just three individuals, with the same observer since 1991.

Nest Surveys

To estimate the annual numbers of nests of geese and eiders, we used a ground-based sampling procedure from 1985 to 2014 (Stehn et al. 1993). During this period, we sampled 2400 ground plots totaling 76,800 ha. Each year we used geographic information systems (GIS) and custom-written True BASIC computer programs to randomly select plots within the Spectacled Eider's "core nesting area" in the central coastal zone encompassing 716 km^2 surrounding Hazen Bay (Figure 1). Several patches of privately owned nesting habitat within the core nesting area were excluded from sampling because annual access could not be ensured. Prior to 1994, and in 1998, 1999 and 2014, some plots were also selected from other adjacent regions of the YKD's coastal zone, but for this analysis we only used data from plots within the standard core area. The number of plots searched varied from year to year but averaged 62 per year (SE = 3.5, range 23–84). Selection of plot locations was restricted by excluding plots that overlapped areas sampled in the current or previous five years. In most years (1988–1994 and 1997–2014) the plots measured 402 m by 805 m (32.4 ha). From 1985 to 1987 plots varied from 16 to 166 ha, and were 45 ha and 36 ha in 1995 and 1996, respectively. The total area sampled each year within the 716-km^2 core nesting area averaged 20.8 km^2 (SE = 1.1 km^2, range 7.4–27.1 km^2).

Two to four biologists searched for nests in each plot for up to 8 hours, the time varying with the available nesting habitat, nest density, and the crew's size and experience. Crews used aerial photographs (1985–2007) and IKONOS satellite imagery (2008–2014) as field maps (JBF unpubl. data). Access to plots was achieved by boat or float-equipped aircraft. We examined all nesting habitat within each plot for active and destroyed nests of waterfowl, cranes, loons, and gulls. We recorded nests of other species as encountered, but most nests of shorebirds and passerines were likely missed. We recorded each nest's status (active, destroyed, abandoned), site location (meadow, slough bank, shoreline, peninsula, island; see Kincheloe and Stehn 1991), stage of incubation (see below), clutch size, and geographic coordinates (2009–2014). We confirmed the species for each nest by either visual identification of an adult at the nest or by comparing the eggs, down, and contour feathers in the nest bowl with a photographic field guide (Bowman 2008).

We measured the stage of incubation (days following initiation of incubation) by the float angles (Westerkov 1950) of three eggs per nest (or fewer in clutches of one or two eggs). To measure float angle, we placed eggs into water and compared the angle of the resulting floating or sinking egg to a diagram defining nine stages from sinking to very buoyant that corresponded to number of days following start of incubation. We floated eggs from a total of 33,982 nests, comprising 19,637 of the Cackling Goose, 7269 of the Greater White-fronted Goose, 5657 of the Emperor Goose, and 1419 of the Spectacled Eider.

Data Analysis

Aerial Surveys

We calculated Indicated Breeding Bird (IBB) indices for these four species as the sum of twice the number of single birds observed and twice the number of pairs seen (USFWS and CWS 1987). The number of single geese and eiders is doubled under the assumption that these birds are accompanied by unobserved mates on nests. The Indicated Total Bird index (ITB) was IBB plus birds observed in flocks.

We analyzed the populations of the three species of geese with a customized Visual Basic program. We first combined data from left-front and right-front observers. Then we calculated the average densities, weighted by transect area, of each index (IBB and ITB) from transects within each stratum. We used a ratio-estimation procedure to estimate the variance of the average densities (Caughley 1977, Cochran 1977). To calculate the population index for each of the four density strata, we multiplied the average density by the total area of the stratum, then summed the results across all strata.

With but a few exceptions, we used similar analysis procedures to calculate indices for the Spectacled Eider from aerial surveys. Observations of this species were initiated in 1988 by a rear-seat observer, and they continued annually with the exception of 2011. For the Spectacled Eider as for the geese, we also used a ratio estimator (Cochran 1977) to calculate stratified population indices and variance. But rather than using strata based on density distributions of geese, we subdivided the study area into 18 strata better fitting variation in eider density and resulting in greater precision, i.e., a smaller coefficient of variation (CV).

We used log-linear least-squares regression to determine the average slope of annual population indices across years. By exponentiation, we converted the log-linear slope to the average rate of annual change (= the population growth rate). We calculated the estimated standard error of the growth rate by the residual mean square error in the log scale multiplied by the growth rate (Taylor series approximation; see Bart et al. 1998).

To estimate the population in fall and to determine the appropriate goose-harvest strategy for the current hunting season, the Pacific Flyway Council extrapolates indices from the breeding grounds. In the case of the Cackling and Greater White-fronted Geese, ITB indices from the aerial survey of the YKD are converted to fall population estimates on the basis of the relationship between breeding-ground counts and fall population estimates made during matching years (Pacific Flyway Council 2003, 2016a).

Nest Surveys

We estimated the total number of nests by first calculating the detection-corrected average density of nests within the core nesting area. To do this we divided the total number of nests on plots by the total area searched, then multiplied the density by the total area sampled (716 km^2). We calculated a density-correction rate for each nest from a mark–recapture logistic model (Chao and Huggins 2005), using data from 30 plots sampled by two independent crews from 1995 to 1999 (Bowman and Stehn 2003, www.fws.gov/alaska/mbsp/mbm/waterfowl/surveys/pdf/nest_vistation_impact.pdf). This provided regression coefficients for covariates relating nest-detection rate that included nest status, species, nest-site location, and crew experience. With respect to status, we considered a nest active if it contained at least one egg that was neither abandoned nor depredated. Nest-status coefficients for inactive and active nests were –1.57 and 0.00, respectively. Species coefficients for the Cackling Goose, Greater White-fronted Goose, Emperor Goose, and Spectacled Eider were 0.00, 0.49, 0.59, and –0.12, respectively. Coefficients for nest-site location for meadow, slough bank, shoreline, peninsula, and island were –1.84, –1.38, –1.25, –0.10 and 0.0, respectively. We categorized the crew's experience as high, medium, or low on the basis of the number of waterfowl nests each participant had previously recorded on the project. Coefficients for high (>400 prior nests), medium (150–400 prior nests), and low (<150 prior nests) crew experience were 0.00, –0.36, and –0.63, respectively. For example, if a destroyed Emperor Goose nest was found along a shoreline by a highly experienced crew member, the coefficients were constant = 3.04, *destroyed* nest-activity status = -1.57, *Emperor Goose* species = 0.59, s*horeline* nest-site location = -1.25, *high* crew-experience status = 0.0. These values summed to 0.81 with a resulting detection rate of 1/[1 + exp(–0.81)] = 0.69. Thus the discovered nest, corrected for detection rate, was estimated to represent 1/0.69 = 1.45 Emperor Goose nests. Coefficients remained constant across years, but the proportion of nests in each activity status, nest-site location, and the experience level of crews changed annually, causing detection rates to vary somewhat from year to year.

We then extrapolated the corrected nest estimates to the YKD's total coastal zone (12,832 km^2) on the basis of the inverse proportion of the aerial IBB index (see aerial-survey methods) within the ground-sampled area to the entire aerial-survey area (Stehn et al. 1993, Taylor et al. 1996). To do this, for each year we calculated the ratio of the IBB index outside the ground-sampled area (OUT) to the IBB index within the ground-sampled area (IN) for each species. To estimate the number and variance of nests and eggs outside of the core nesting area, we used the OUT:IN ratios for each year as expansion factors. This procedure assumed that the frequency of nests per aerially observed singles or pairs was the same in both the IN and OUT areas. We then summed the indirect estimate of nests (OUT) and the estimate based on direct sampling of plots (IN) as an estimate of the total number of nests in the coastal zone of the YKD. Where aerial-survey data were unavailable, we substituted the average OUT:IN ratio from the two nearest years available. For example, aerial-survey data for the eider were not recorded from 1985 to 1987, so for those years, we substituted the average of the OUT:IN ratios in 1988 and 1989. Similarly, aerial data for the Spectacled Eider were not collected in 2011, so we substituted the average of the OUT:IN ratios from 2010 and 2012 for that year. Standard errors of the OUT:IN ratios were based on the variance of the quotient of the OUT and IN population indices based on aerial surveys, with each considered an independent variable. Variance of the nest population in the OUT region included both the variance of nests and variance of the OUT:IN ratio.

We used egg-float angles to derive the incubation stage for geese and eiders. Nine stages of float angles equated to 2, 5, 8, 10, 13, 15, 18, 22, and 24 days, respectively, for the Cackling Goose

Table 1. Growth rates of aerial indices (indicated breeding birds and indicated total birds) and nests of the Cackling, Greater White-fronted, and Emperor Geese in the coastal zone of the Yukon–Kuskokwim Delta, Alaska, 1985–2014.

Species and measure	Growth rate	SE	Lower 95% CI	Upper 95% CI
Cackling Goose				
Indicated breeding birds	1.049	0.006	1.037	1.062
Indicated total birds	1.049	0.008	1.034	1.064
Nests	1.047	0.007	1.033	1.061
Greater White-fronted Goose				
Indicated breeding birds	1.097	0.005	1.087	1.107
Indicated total birds	1.073	0.005	1.064	1.082
Nests	1.089	0.008	1.074	1.104
Emperor Goose				
Indicated breeding birds	1.025	0.003	1.019	1.031
Indicated total birds	1.018	0.003	1.012	1.025
Nests	1.012	0.006	1.000	1.023

and Greater White-fronted Goose (U.S. Fish and Wildlife Service unpubl. data). For the Emperor Goose and Spectacled Eider, we adjusted the incubation stage proportionally on the basis of these species' average incubation period being slightly shorter (24 days) than that of the Cackling Goose (25 days; after Afton and Paulus 1992). Thus for the Emperor Goose and Spectacled Eider incubation stage 1 indicates 1.9 days of incubation (calculated as 2 × [24/25]), where 2 is the number of days estimated after initiation of incubation for Cackling Goose eggs indicated by stage 1, and 24/25 is the proportional adjustment for the incubation period of these two species relative to that of the Cackling Goose.

We calculated the expected mean hatch date for each nest as the date of the nest visit plus the total days of the average incubation period minus the average days of incubation from all eggs floated during that visit. The average hatch date for each species was the average hatch date from all aged nests. We determined nest-initiation date (day with first egg laid) as the date of the nest visit minus days of incubation at the time of the nest visit, minus observed clutch size minus 1, divided by the laying rate expressed as eggs per day (e.g., 0.77 eggs/day for the Cackling, Greater White-fronted, and Emperor Geese; 0.75 eggs/day for the Spectacled Eider, see table 2-2 in Alisauskas and Ankney 1992). For example, the date of initiation of a Spectacled Eider nest visited on 20 June (ordinal day 171) containing 5 eggs that had been incubated an average of 12.5 days was calculated as 171 – 12.5 – [(5 – 1)/0.75] = ordinal day 153 (2 June).

Results

Population Indices and Trend

From 1985 to 2014, the population indices (IBB and ITB) and nest abundance calculated from aerial surveys of the Cackling Goose, Greater White-fronted Goose, Emperor Goose, and Spectacled Eider all increased significantly (Tables 1 and 2, Figure 2). The rate of population growth was highest for the Greater White-fronted Goose, followed by the Spectacled Eider, Cackling Goose, and Emperor Goose. For the Spectacled Eider, the rates of growth based on indices from aerial surveys were higher than those from ground surveys of nest abundance from 1988 to 2014, but rates of these metrics began to converge after 1993 when the aerial observer was constant and species identification improved (Table 2). Aerial indices and nest abundance are reported in 5-year increments (Table 3).

Nesting Chronology

The average of the four species' annual mean dates of nest initiation and hatching were similar. Average nest-initiation dates were 26 May (range 16 May–4 June) for the Cackling Goose, 25 May (range 17 May–2 June) for the Greater White-fronted Goose, 24 May (range 15 May–4 June) for the Emperor Goose, and 28 May (range 18 May–7 June) for the Spectacled Eider. Average hatch dates were 23 June (range 14 June–3 July) for the Cackling Goose, 24 June (range 16 June–1 July) for the Greater White-fronted Goose, 22 June (range 13 June–1 July) for the Emperor Goose, and 26 June (range 16 June–6 July) for the Spectacled Eider. We found no trend from 1985 to 2014 in dates of either nest initiation or hatching.

Effects of Survey Timing

Each year, on the basis of communications with Yukon Delta National Wildlife Refuge research camps, we adjusted the date we started aerial surveys to coincide with early to mid-incubation of geese and eiders. The average start date of aerial surveys was 4 June; the surveys' average duration was nine days. On average we started the aerial survey nine days after estimated nest initiation

Table 2. Growth rates of aerial indices and nests of the Spectacled Eider in the coastal zone of the Yukon–Kuskokwim Delta, Alaska, 1988–2014 and 1993–2014.

Period and measure	Growth rate	SE	Lower 95% CI	Upper 95% CI
1988–2014				
Indicated breeding birds	1.065	0.005	1.055	1.075
Indicated total birds	1.065	0.005	1.055	1.075
Nests	1.016	0.007	1.002	1.030
1993–2014				
Indicated breeding birds	1.059	0.005	1.050	1.068
Indicated total birds	1.059	0.005	1.049	1.068
Nests	1.036	0.008	1.020	1.053

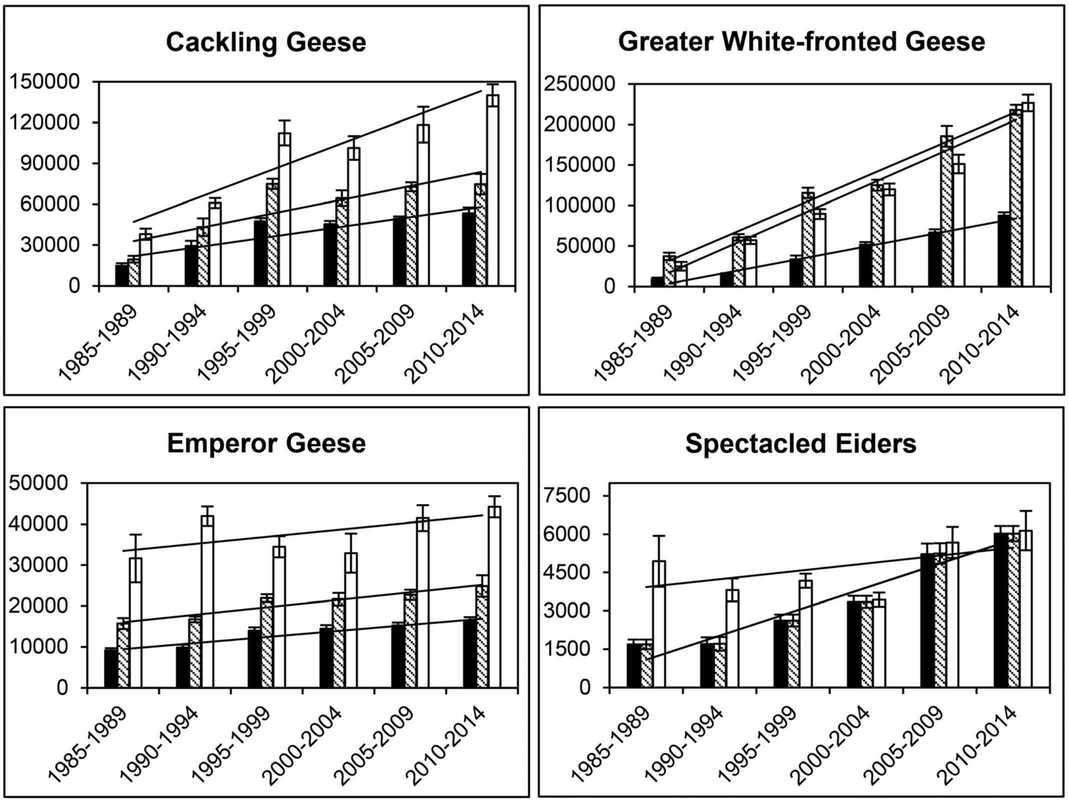

Figure 2. Average indices of indicated breeding birds (solid bars), indicated total birds (hatched bars), and nests (open bars) by five-year increments for three species of geese and one eider on the Yukon–Kuskokwim Delta, Alaska. Slopes of indicated breeding birds and indicated total birds for the Spectacled Eider appear as one line because values were nearly identical, a result of flocks not being detected on aerial surveys.

(range 2–17 days). The proportion of geese seen in pairs to total birds decreased as the interval between the survey's start date and nest initiation increased, presumably because of nest failures as the season progressed (Cackling Goose: $F_{1, 28} = 11.56$, $p = 0.002$, $r^2 = 0.29$; Greater White-fronted Goose: $F_{1, 28} = 20.04$, $p < 0.001$, $r^2 = 0.42$; Emperor Goose: $F_{1, 28} = 5.35$, $p = 0.03$, $r^2 = 0.16$), whereas calendar date was not correlated with this measure. For the Spectacled Eider there was no effect of survey timing relative to the proportion of pairs to total birds, given that virtually all aerial observations were of paired or indicated paired birds.

Nest-to-Pair Ratio as a Conversion Factor for Indices Based on Aerial Surveys

For all four species, numbers of nests exceeded numbers of indicated breeding pairs (IBB/2). Prior to 1993, ratios of nests to indicated pairs of all four focal species were highly variable. Since 1993, the ratio of nests to indicated pairs has been relatively stable. The 1993–2014 average ratio of nests to indicated breeding pairs was 4.8 for the Cackling Goose, 5.2 for the Greater White-fronted Goose, 5.4 for the Emperor Goose, and 2.4 for the Spectacled Eider. The nest-to-pair ratio is one tool that can be used to convert indices based on aerial surveys to an estimate of actual breeding pairs, although below we discuss limitations to this approach.

Discussion

Population Status and Trend

Population-management objectives for the Cackling and Greater White-fronted Geese are based on fall population indices (Pacific Flyway Council 2003, 2016a) that are derived from the aerial surveys of the Yukon-Kuskokwim Delta described here. The objective of 250,000 Cackling Geese was attained in 1997, after which time the population index has hovered just above or below

Table 3. Mean (SE) indices of indicated breeding birds (IBB) and indicated total birds (ITB) and nests of the Cackling Goose, Greater White-fronted Goose, Emperor Goose, and Spectacled Eider on the Yukon–Kuskokwim Delta, Alaska, 1985–2014. Indices of IBB and ITB for the Spectacled Eider based on data recorded 1988–2014.

Species and year range	IBB	SE	ITB	SE	Nests	SE
Cackling Goose						
1985–1989	14,582	1989	19,466	2522	37959	4221
1990–1994	29,232	3811	43,146	6407	60856	3620
1995–1999	47,516	2242	74,872	3780	112,293	9040
2000–2004	45,269	2505	64,411	5653	101,273	8728
2005–2009	49,490	1634	72,745	3359	118,429	13,084
2010–2014	53,477	4087	74,711	7503	140,011	8154
Greater White-fronted Goose						
1985–1989	9570	1067	37,126	4574	24,613	5292
1990–1994	14,706	1478	60,526	4028	57,009	4636
1995–1999	33,112	4909	115,458	6445	89,478	6166
2000–2004	51,418	3450	124,838	6763	119,745	7332
2005–2009	66,415	4198	185,501	12,966	151,140	11,386
2010–2014	87,506	3962	217,957	6041	226,624	10,266
Emperor Goose						
1985–1989	9140	544	15,703	1350	31,628	5867
1990–1994	9822	688	16,706	696	41,902	2359
1995–1999	14,008	800	21,922	958	34,483	2606
2000–2004	14,421	910	21,648	1509	32,924	4768
2005–2009	15,237	690	22,701	1235	41,496	3140
2010–2014	16,320	937	24,834	2638	44,227	2574
Spectacled Eider						
1985–1989	1682	192	1682	192	4941	1001
1990–1994	1699	265	1707	270	3816	450
1995–1999	2622	235	2622	235	4179	275
2000–2004	3352	234	3352	234	3433	276
2005–2009	5219	414	5244	405	5678	613
2010–2014	6029	304	6029	304	6135	765

the objective. The objective for the Pacific Flyway population of 300,000 Greater White-fronted Geese was attained in 1996, and the population index has continued to grow steadily since then. The objective for the Emperor Goose is based on the indicated total bird index derived from the aerial survey described here (Pacific Flyway Council 2016b); the objective of 34,000 was not attained during our study (USFWS 2017). Currently, the Spectacled Eider is still below, but approaching, the threshold at which delisting the western Alaska subpopulation from its status as threatened could be considered (USFWS 1996).

Recovery of these four species from the population lows in the 1980s is encouraging. The decline in the estimated fall Cackling Goose population from over 350,000 in the late 1960s to 26,000 by the early 1980s (O'Neill 1979, Raveling 1984) has largely been reversed, with the estimated fall population now slightly above the objective of 250,000 (Pacific Flyway Council 1999, USFWS 2017). More impressive, at least numerically, is the change in the fall estimate of the Pacific Greater White-fronted Goose population. This species' fall population, estimated at 480,000 in the mid-1960s, dropped by 1980 to 73,000 (O'Neill 1979, Timm and Dau 1979, Raveling 1984), but is now above 600,000 (USFWS 2017), more than double the objective for the Pacific Flyway (Pacific Flyway Council 2003). Emperor Geese also increased in abundance over the time of our study, recently attaining a level sufficient to allow a limited legal hunt (Pacific Flyway Council 2016b). Starting in 2016 the objective for the Emperor Goose is compared to the number of indicated total birds estimated from the aerial survey of the YKD; formerly the population was measured from surveys of birds staging in spring (Pacific Flyway Council 2016b). Average annual growth rates of indices based on aerial and nest surveys of the YKD (Table 1) closely match that of the spring counts during the same period (1.012, 1985–2014; USFWS 2017). Together, these independent sources of population data all indicate long-term growth, providing justification for the decision to open a limited legal hunt in 2017. The Spectacled Eider's population is believed to have declined by >79% from the late 1960s to the early 1990s (Stehn et al. 1993, Ely et al. 1994). Like the geese on the YKD, the Spectacled Eider has also increased in abundance since the mid-1980s when dedicated aerial and ground-based surveys began. Significant growth has prompted the U.S. Fish and Wildlife Service to review the population's status relative to recovery criteria in order to determine if some criteria for delisting the species have been satisfied.

The effect of past harvest on the abundance of the Emperor Goose and Spectacled Eider is not well understood (Stehn et al. 1993, Pacific Flyway Council 2016b), but the decline of the Cackling and Greater White-fronted Geese from the 1960s through 1980s has been widely attributed to hunting (Raveling 1984, King and Derksen 1986). Closure of subsistence and sport hunting of these two species was followed by population growth leading to their recovery. The Cackling Goose's response to suspension of hunting was prompt, with the population objective first achieved in 1997 (USFWS 2017). Following this, the population stabilized when hunting regulations were liberalized (Pacific Flyway Council 1999). The fall index for the Greater White-fronted Goose exceeded the population objective of 300,000 in 1996 and has continued to increase despite more liberal harvest regulations throughout the Pacific Flyway. Changes in agricultural practices and wetland-conservation programs in this species' winter range have reduced the distance the geese must commute between roosting and feeding and have provided alternative feeding areas when local foods are depleted (Ackerman et al. 2006). These changes likely increased overwinter survival, helping compensate for liberalized hunting regulations. The Emperor Goose population remained below the objective throughout this study (Pacific Flyway Council 2016b, USFWS 2017). Hunting of Emperor Geese, though closed in 1987, continued illegally through 2016 at a rate less than in the 1960s (Klein 1966, Naves 2015, www.fws.gov/alaska/ambcc/ambcc/Harvest/TP409.pdf), but even limited harvest has been implicated in impeding population growth (Hupp et al. 2008). The long-term effect on the abundance of Emperor Geese of renewed legal harvest starting in 2017 is unknown. Factors other than harvest that limited growth of the Emperor Goose population may have included poor recruitment resulting from depredation of goslings by avian predators (Bowman et al. 2004) or poor habitat conditions leading to low survival of juveniles (Schmutz 1993).

Nest depredation is a factor that could have exacerbated the Spectacled Eider's decline on the YKD prior to the species' listing as threatened in 1993. Disproportionate depredation of Spectacled Eider nests may have resulted from declines in sympatric nesting geese (Ely et al. 1994). As goose populations recovered, the effect may have moderated, so that by the early 2000s abundant alternative prey for nest predators reduced the toll on nesting Spectacled Eiders. Unfortunately, precise long-term data on nest success and fledging success are unavailable to test this hypothesis.

Outreach efforts in the villages of the YKD following the Spectacled Eider's listing as threatened may have served to reduce harvest and to limit contamination due to ingestion of lead shot. For example, the average reported subsistence harvest of the Spectacled Eider declined 75% from 1985–1995 to 1996–2005 (Wentworth 2007, www.fws.gov/alaska/ambcc/ambcc/Harvest/YKD_070730.pdf). The use of lead shot for hunting waterfowl has been illegal since 1991, and in 1998 the U.S. Fish and Wildlife Service intensified efforts to publicize and enforce prohibitions against the possession and use of lead shot for hunting migratory birds in Alaska. Furthermore, in 2007 the state of Alaska prohibited use of lead shot for hunting of upland game birds and small game on the YKD. Flint and Schamber (2010) showed that after 10 years, 90% of lead pellets were submerged >6 cm into pond sediment and 50% were submerged >10 cm into pond sediment. Hence, over the long term, regulatory changes and enforcement of the ban on lead shot likely benefitted all waterfowl, including the Spectacled Eider.

Marine conditions and food resources in winter also may regulate the Spectacled Eider's population. For example, extreme wind and cold in the Bering Sea, where Spectacled Eiders spend the winter, are associated with lower abundance on the breeding grounds in subsequent summers (Petersen and Douglas 2004). Additionally, changes in the abundance and distribution of marine resources on which Spectacled Eiders feed likely depress this species' overwinter survival (Richman and Lovvorn 2003, Lovvorn et al. 2009). Furthermore, oceanic regime shifts are correlated with trends in the eider's abundance, likely because of effects on its propensity to breed (Flint 2013).

Nesting Chronology

On the YKD, the timing of nest initiation and hatching varied from year to year by up to three weeks, geese and eiders varying similarly. Although spring conditions varied annually, the date of geese and eiders hatching did not advance significantly over the 30 years of our study (see also Ely et al. 2018). However, we recommend this finding be revisited with data collected after 2014, especially in light of warming predicted throughout and beyond the 21st century (IPCC 2014).

Effects of Survey Timing

Prior studies indicate that surveys not timed to coincide with the early nesting period may bias estimates of waterfowl population and trend (Naugle et al. 2000). Therefore, accounting for the timing of nesting when surveys are scheduled is important to obtaining an accurate estimate of indicated breeding pairs. We found the proportion of geese observed in pairs decreased as the interval between the survey's start date and nest initiation increased, whereas calendar date was not correlated with this measure. This finding emphasizes the importance of timing surveys according to meaningful biological signals. The timing of nest initiation prior to aerial surveys is not known, so correlates with nest initiation, such as spring temperatures and the accumulation of degrees above 0 °C, not just calendar date alone, should be considered when surveys are scheduled (Platte and Stehn 2015, www.fws.gov/alaska/mbsp/mbm/waterfowl/surveys/pdf/cod2015.pdf). A decline in the proportion of indicated pairs through the incubation period could be due to progressive failure of breeding attempts and subsequent clustering of previously paired birds into flocks. Alternatively, nonbreeding birds may arrive on the breeding grounds late in incubation as flocks to prospect breeding sites for the subsequent season. We detected no change in the proportion of Spectacled Eiders observed as pairs as incubation proceeded. This finding was due to virtually all observations during aerial surveys being of pairs or indicated pairs, suggesting nonbreeding birds remain off the breeding grounds during incubation.

Nest-to-Pair Ratio as a Conversion Factor for Indices Based on Aerial Surveys

One of the original objectives of the aerial survey of breeding pairs was to develop a visibility index for aerial observations because aerial detection is assumed to be incomplete (Caughley 1974, Malecki et al. 1981, Walter and Rusch 1997). Despite the stated objective, visibility indices have never been formally incorporated into the aerial survey. Nonetheless, because the aerial surveys of breeding pairs overlapped in space and time with the ground-based surveys of nests, the visibility bias of aerial observations can be measured. The ratio of nests calculated by ground crews to pairs estimated by aerial survey crews is not a true detection rate *per se* because birds observed as indicated pairs were not necessarily actively nesting. If detection of pairs and nests was 100%, and if all aerially observed pairs were actively nesting, the number of nests estimated by ground crews and pairs estimated by aerial crews would be equal. Thus the nest-to-pair index should be used as a correction factor for the results of aerial surveys, not a true detection rate. The resulting correction factor should adjust aerial indices closer to actual population sizes but cannot account for all undetected birds.

Correction of estimates from aerial surveys on the basis of the ratio of nests to breeding pairs is currently used for management of other geese in the Pacific Flyway. For example, regulations for annual harvest of the Dusky Canada Goose (*Branta canadensis occidentalis*) are based on indices corrected by a factor based on the ratio of nests to aerially observed pairs (Pacific Flyway Council 2015). The importance of developing such correction factors for the Cackling and Greater White-fronted Geese on the YKD has been reduced because the Pacific Flyway Council adopted alternative methods of converting ITB indices to fall population estimates (Pacific Flyway Council 1999, 2003).

While interest in using nest-to-pair correction factors for aerial estimates of geese on the YKD lessened, the approach is relevant for management of the Spectacled Eider. Currently, the Spectacled Eider Recovery Plan identifies nest abundance, adjusted for detection rate, as the best annual estimate of the absolute abundance of breeding pairs (USFWS 1996). The ratio of nests to indicated pairs can be used to convert indices from aerial surveys to estimates of nesting pairs. On average (1993–2014), we found 2.4 Spectacled Eider nests for every aerially observed pair or indicated pair.

For the Spectacled Eider, the use of the nest-to-pair index as a correction factor has application beyond the YKD. Paired air and ground surveys for Spectacled Eiders on the YKD are relatively inexpensive because the breeding distribution is concentrated in an area that is accessible to float planes and boats. In contrast, a ground-based survey of Spectacled Eiders in northern Alaska is impractical because the population there is distributed widely across the landscape at low densities; access to those habitats by ground crews would be prohibitively expensive. Application of the nest-to-pair ratio derived from the YKD to the northern Alaska population could be an efficient method to monitor population status relative to recovery criteria. However, the relationship between nests and pairs detected from the air may differ as a function of nest density, and the Spectacled Eider's population densities in the YKD and northern Alaska differ (USFWS 1996). Thus the nest-to-pair index from the YKD may be inappropriate to simply apply to northern Alaska. Instead, it is important to first assess the effects of nesting density and other factors on the nest-to-pair ratio. To address this need, continuing analyses by the U.S. Fish and Wildlife Service and U.S. Geological Survey are refining the estimates of nest-to-pair ratio on the YKD, and are evaluating density and other factors such as habitat, survey timing, and nest success, all of which may influence the relationship between aerial detections and the actual number of nests.

Conclusions

Waterfowl managers rely on estimates of abundance and trend in combination with information on demographic processes, such as annual productivity, to develop sound hunting regulations (Baldassarre and Bolen 2006). Effective harvest management often relies on indices based on aerial surveys, and when these indices reach certain thresholds, predetermined actions such as defined harvest strategies are either evaluated or implemented. In addition to measuring population status relative to specific management objectives, our surveys have also provided information on factors that may influence population change, including annual egg production, nest predation (JBF unpubl. data), and nesting phenology. Aerial and ground-based surveys also yield data from which broad-scale maps of waterfowl distribution on the YKD can be produced, with the species' distribution illustrated by interpolated polygons representing its density (Butler et al. 1995b). These can provide a baseline for detecting changes in distribution from factors such as habitat alteration or disturbance, as well as the basis for developing habitat-association models (Saalfeld et al. 2017) and vulnerability assessments. Geese and eiders may be vulnerable to an increase in the frequency or duration of coastal flooding or other predicted effects of climate change. For example, although the nesting habitat along the coast of the YKD floods regularly (Hansen 1961), flooding is likely to increase as sea levels rise and the intensity and frequency of storms increase (Jorgenson and Ely 2001). The effects of such changes on nesting birds will depend on many factors, but given the significant proportion of the North American populations of these four species nesting on the YKD, declines on the breeding grounds could have a measurable effect throughout the Pacific Flyway.

While this paper treats only three species of geese and the Spectacled Eider, our surveys on the YKD have yielded data on a suite of other species (JBF unpubl. data). Although originally justified and designed to monitor geese and eiders during the population lows of the mid-1980s, the aerial and ground-based surveys provide accurate data on the distribution, trend, and abundance of all species of large waterbirds. Data for species other than those treated here have been and will continue to be used for numerous applications. To our knowledge, the surveys of the YKD initiated in 1985 for geese have evolved to provide one of the longest-lasting multi-species, multi-scale datasets for nesting waterfowl and other waterbirds in North America.

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