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Increased abundance and range expansion of harlequin ducks *Histrionicus histrionicus* wintering in Eastern Canada

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ABSTRACT: The eastern population of harlequin duck *Histrionicus histrionicus* in Canada has been designated a species of special concern since 2001 and as endangered from 1991 to 2001, largely due to low and declining wintering numbers detected in the 1980s. Our objectives were to summarize the current state of knowledge of harlequin duck abundance and distribution in Eastern Canada, and assess trends in wintering abundance across regions over the past 30+ years. Abundance estimates were generated from targeted surveys with thorough spatial coverage of major wintering areas on insular Newfoundland (NL), Nova Scotia (NS), and New Brunswick (NB) between 2015 and 2018, complemented by regional trends estimated from Christmas Bird Count (CBC) data collected at 12 sites across the same wintering range between 1988 and 2021. Overall, targeted surveys indicated that numbers have increased and distributions have expanded beyond historically surveyed regions, particularly in NS. This was supported by trends from CBC data, with steep average increases (mean $\lambda > 1.05$) on most CBC circles in Eastern Canada since 1988 or later. Using localized annual rates of mean population change from CBC data to project counts from dedicated surveys, we suggest wintering areas in the provinces of NL, NS, and NB may currently be supporting a combined total of 5682 birds (95% CI 5065–6354) in 2022, well exceeding the recovery target of 3000 individuals listed in the 2007 management plan. Our findings indicate that the eastern population is in recovery, but also emphasize that a consistent, dedicated monitoring program would enable managers to confidently evaluate management actions, and to respond most effectively should regional trends slow or reverse.

KEY WORDS: Recovery · *Histrionicus histrionicus* · Species status assessment · Range expansion · Abundance · Distribution

1. INTRODUCTION

Understanding relative distributions and trends of waterfowl abundance is necessary to assess population status, evaluate drivers of population change, and determine requirements for management efforts (Bowman et al. 2015). The harlequin duck *Histrionicus histrionicus* winters along turbulent rocky coastlines and nearshore waters of both the Pacific and Atlantic coasts of North America (Robertson & Goudie 2020). The eastern population in Canada has been designated under the Federal Species at Risk Act as

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a species of special concern since 2001 and as endangered from 1991 to 2001, largely due to the small and declining wintering population size (Committee on the Status of Endangered Wildlife in Canada [COSEWIC] 2013). A management plan is in place for Eastern Canada, and recreational harvest has been prohibited since at least 1990 (Environment Canada 2007). The number of birds wintering in Eastern Canada has been increasing; however, formal estimates of abundance, distribution, and trends in Eastern Canada need to be updated and refined with the most recent information available (Bowman et al. 2015, Sea Duck Joint Venture [SDJV] 2015).

Due to low and patchy distributions within specific habitats while using riverine environments for nesting and foraging during the breeding period, range-wide breeding surveys of harlequin ducks require extensive resources and effort (Trimper et al. 2008). On the other hand, during the wintering period, harlequin ducks are highly gregarious, visible, and show high site fidelity and small home ranges, making them reasonably predictable in their exposed, nearshore, coastal environments (Robertson et al. 2000, Iverson et al. 2004, Mittelhauser 2008a). Surveys during the winter months have been used as the most suitable and cost-effective measure of population status and trends (Esler et al. 2002, Mittelhauser 2008b). Two types of winter harlequin duck survey data are generally available, each with unique limitations. First, targeted surveys have been conducted throughout Eastern Canada since the late 1980s in localized regions known historically to support wintering harlequin duck populations (Boyne 2008, Thomas 2008, Bowman et al. 2015). These surveys have varied over time in spatial coverage, timing, and survey platform type, but have been more consistent and frequent since 2013. The second source of winter survey data are from the Christmas Bird Count (CBC), a volunteer winter bird census conducted via protocols standardized since the 1960s. CBC observers tally the number of birds of each species encountered on a single day within a few weeks around Christmas within defined 12 km radius count circles (Dunn et al. 2005). The CBC, however, was not initially designed for population monitoring; CBC circle locations are not random and spatial coverage decreases with increasing latitude in Canada, surveys are not conducted in each circle in every year, and starting year for surveys varies across circles (Dunn et al. 2005). Regardless, in survey years, efforts are made for small parties of observers to cover all habitat types including nearshore areas for circles overlapping the coast. It follows that coastal CBC circles within range of wintering harlequin duck populations could be considered adequate indices of local numbers of this species. Indeed, CBC data were used in the initial status assessments of harlequin ducks (Goudie 1989).

Available data from both survey types in Maritime Canada up to 2003 (Boyne 2008) and the island of Newfoundland up to 2007 (Thomas 2008) suggested increasing abundance at wintering sites through the late 1990s and into the 2000s. Subsequent analysis for Atlantic Canada also suggested a general increase since the mid-1980s (CWS Waterfowl Committee 2020), as well as a more refined estimate for the rate of population change of 8.6% per year from 2001 to 2013 (Bowman et al. 2015). However, it was cautioned that these increases may be partially influenced by a lack of consistent coverage or methodology, and particularly by refined survey effort and observer experience over time (Bowman et al. 2015). At the same time, CBC data suggested an average annual increase for the entire eastern North America wintering population of 5% per year between 1981 and 2011 (COSEWIC 2013), supporting the notion that there had been an improvement in numbers in Atlantic Canada since declines were detected in the late 1980s.

Beginning in 2015, we conducted dedicated surveys for wintering harlequin ducks in Atlantic Canada with complete coverage of known wintering locations and exploratory surveys of potential areas of range expansion. Based on these surveys, we provide an updated assessment of regional and overall abundance and distribution in Nova Scotia (NS), New Brunswick (NB) and Newfoundland (NL), as well as a summary of all data collected to date. This is complemented by estimates of abundance and trends based on CBC data collected across the same wintering range over the 3 decades between 1988 and 2021, as well as CBC data from additional sites in Québec, Prince Edward Island (PE), and Ile St. Pierre of St. Pierre and Miquelon, France. Together these 2 data sources provide the best available information for assessing the status of the eastern population of harlequin duck in Eastern Canada.

2. MATERIALS AND METHODS

2.1. Winter surveys

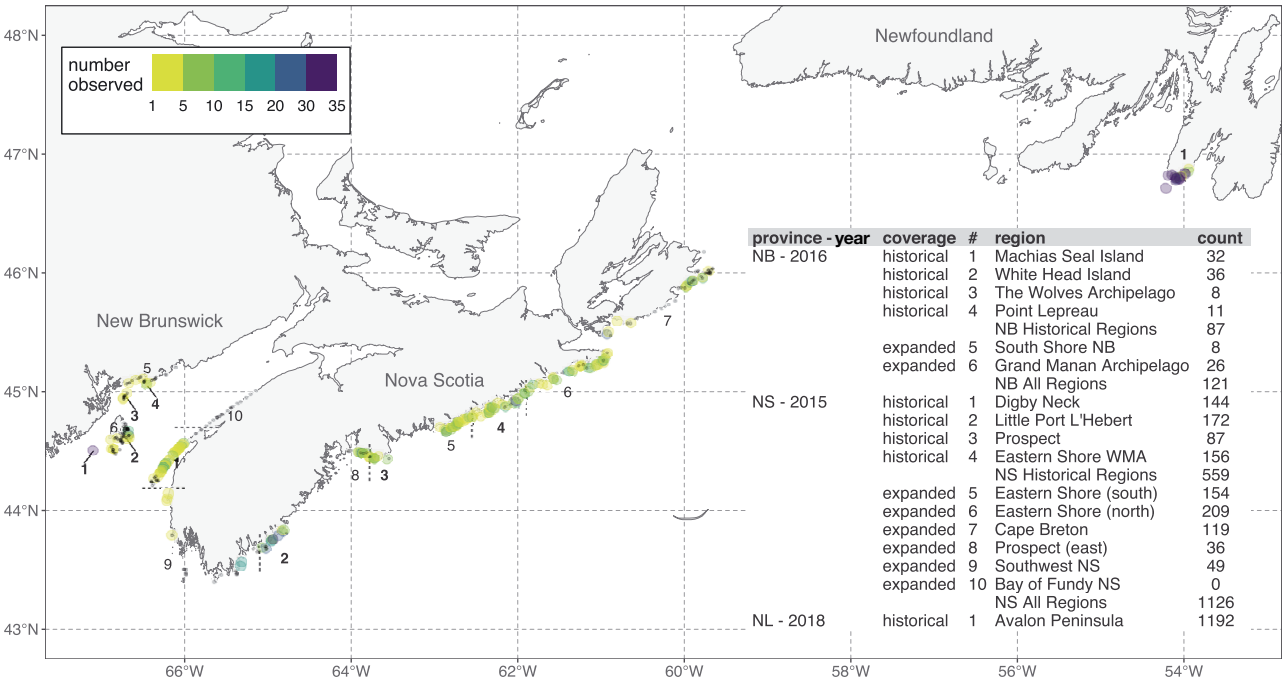
Harlequin duck wintering sites on insular NL, NS, and NB have been identified and surveyed at irregular intervals and from varying platform types over the period 1988 to 2021 (all survey data are provided in Tables S1–S3 in the Supplement at

www.int-res.com/articles/suppl/n049p187_supp.pdf). Surveys from helicopters or fixed-wing aircraft have included dedicated efforts to count harlequin ducks as well as general coastal waterfowl counts, while boat and land-based surveys have typically been used only to target known harlequin duck wintering sites (see Boyne 2008 and Thomas 2008 for more detailed accounts). Eight historically surveyed regions in NS and NB (4 each) and 1 in NL are considered the major wintering areas and have been used to generate winter abundance estimates for Atlantic Canada in the past (e.g. Boyne 2008 and Thomas 2008, respectively; Fig. 1). In NL, the Avalon Peninsula, particularly the Cape St. Mary's area, is the main region of concentration for wintering harlequin ducks (Thomas 2008, Gutowsky et al. 2019). Only surveys conducted between November and March were considered winter surveys for this study. Of 72 unique winter surveys, 94% took place in February (41 surveys) or March (23 surveys), which coincides generally with the over-wintering period before spring migration which initiates in late March or early April (Robertson & Goudie 2020). Survey years were defined as the year of January (i.e. surveys from November through April are designated as the year of January for that period and taken to represent the winter population for that 'year').

In winter 2015, between 24 February and 6 March, all 4 historically major wintering sites in NS were surveyed by helicopter, along with 6 additional regions where harlequin ducks were suspected to have expanded their range (Fig. 1). Similarly, in NB, on 15 February 2016, targeted helicopter surveys were conducted at 4 major historic wintering sites, along with 2 additional regions (Fig. 1). On 27 March 2018, Cape St. Mary's on the Avalon Peninsula in NL was thoroughly surveyed by boat (Fig. 1). We use data from these most recent dedicated survey years to produce updated provincial and total winter population estimates for the Atlantic Provinces, and to represent recent relative distributions.

2.2. Christmas Bird Counts

Harlequin duck count data was obtained from 12 CBC circles within the same range covered by dedicated winter surveys (NL, NS, and NB), as well as 4 CBC circles in Québec, Prince Edward Island, and Ile St. Pierre of St. Pierre and Miquelon (SPM), France.



province - year	coverage	#	region	count
NB - 2016	historical	1	Machias Seal Island	32
	historical	2	White Head Island	36
	historical	3	The Wolves Archipelago	8
	historical	4	Point Lepreau	11
			NB Historical Regions	87
	expanded	5	South Shore NB	8
	expanded	6	Grand Manan Archipelago	26
			NB All Regions	121
NS - 2015	historical	1	Digby Neck	144
	historical	2	Little Port L'Hebert	172
	historical	3	Prospect	87
	historical	4	Eastern Shore WMA	156
			NS Historical Regions	559
	expanded	5	Eastern Shore (south)	154
	expanded	6	Eastern Shore (north)	209
	expanded	7	Cape Breton	119
	expanded	8	Prospect (east)	36
	expanded	9	Southwest NS	49
	expanded	10	Bay of Fundy NS	0
			NS All Regions	1126
NL - 2018	historical	1	Avalon Peninsula	1192

Fig. 1. The most recent and complete dedicated surveys of harlequin duck *Histrionicus histrionicus* in New Brunswick (NB, 2016), Nova Scotia (NS, 2015), and insular Newfoundland (NL, 2018), Canada. Inset table shows total counts by province, year, and region for historically major wintering sites and newly surveyed areas of suspected range expansion. Map depicts regions by province and number with reference to the inset table (# column), with all locations of observations made in the associated year by province. Eastern Shore WMA: Eastern Shore Islands Wildlife Management Area; (•) reported 'zeros'. A more detailed view of the NL survey region is provided in Fig. S1, and all historical survey data are provided in Tables S1–S3

The majority of data were extracted from the CBC online database (National Audubon Society 2020), with the exception of 2 circles in NB. Data from these counts were not reported to the National Audubon Society in most years, but can be extracted from online archives of the 'NB Naturalist' (www.naturenb.ca/archives-nb-naturalist/). The year of a CBC is typically defined as the year of December, despite some counts taking place in the first week of January (survey window from 14 December to 5 January). In order to align survey years between the targeted surveys and CBCs to be representative of the same year's winter population, we adjusted CBC years to also be the year of January (i.e. surveys in December were taken as the following year). Data were filtered to include only circles reporting a minimum of 10 total individuals between 1981 and 2021, to eliminate circles with mostly zero counts, resulting in 9 to 34 years of count data from each of 16 CBC circles (Fig. 2).

It has been debated whether CBCs should be adjusted for observer effort, given that the number and skill level of volunteers participating in a count varies from year to year and could impact the number of birds counted (Dunn et al. 2005). However, for sea ducks, and especially harlequin ducks, the number of observers is not typically correlated to the count since this species is highly visible, concentrated in groups, and the areas where ducks are predictably found are well known to birders (COSEWIC 2013). Indeed, reported total counts of harlequin ducks from CBCs in Eastern Canada where effort metadata were available were not correlated with the number of field observers participating in a given count year (R^2 = 0.014, slope estimate = –0.08, 95% confidence interval [CI] –0.92 [lower confidence limit, LCL] – 0.78 [upper confidence limit, UCL]).

To formally evaluate the representativeness of CBC counts for local abundance, we calculated correlations between CBC counts and the sum of targeted survey observations within 12 km of a CBC circle center made in the same winter. Regression analysis indicated that CBC counts provide a reasonable representation of local abundance based on counts from dedicated surveys conducted in the same year in the same area (Fig. 3). This applies to the sum of observations across all survey types (R^2 = 0.64, slope estimate = 0.84, 95% CI 0.60–1.09, n = 30; Fig. 3), as well as only aerial surveys (helicopter and fixed-wing) taken together (R^2 = 0.56, slope estimate = 0.98, 95% CI 0.36–1.6, n = 11) or only boat surveys (R^2 = 0.71, slope estimate = 0.79, 95% CI 0.53–1.05, n = 19).

CBC counts generally underestimate the number of birds wintering in the area encompassed by the full radius of the circle and there is a high proportion of variance that remains unexplained, as CBC observers are limited in their access to all coastal areas and in visibility offshore. Despite these limitations, and given that targeted surveys and CBC counts were not conducted on the same day, or even the same month of the winter in most cases, the regression results lend further confidence to the use of CBC counts as an index of local wintering population size over time (Thomas 2008).

Most analyses of CBC data evaluate species-specific regional trends by summing annual counts within years across circles representing a geographic sub-unit of interest (e.g. Bowman et al. 2015, Soykan et al. 2016, Meehan et al. 2021). This necessitates re-expressing counts as means per circle because not all circles are surveyed each year (e.g. Bowman et al. 2015), and results in the dilution of trends and loss of circle-specific information, particularly when areas of relatively high and low abundance are lumped together. In this study, CBC count data and trends are presented and discussed independently for each circle, and counts are not adjusted for observer effort.

We employed standard techniques to analyze count data using generalized linear models (GLMs; Zuur et al. 2009) with the software R (v.3.6.1; R Core Team 2020). We limited our models to counts from 1988 to 2021 to capture the magnitude of regional population recovery, as historical lows are known to have occurred in the late 1980s, and CBC counts beginning in 1980 support this expectation (Fig. 2). We did not model circles with less than 15 years of counts (Cape Breton Highlands National Park, Sheet Harbour, St. Peters), or circles with zeros in more than 75% of counts (Lunenburg). The remaining 12 CBC circles had between 15 and 34 years of counts with the proportion of zeros ranging from 0 to 55% and no gaps in the time series >7 years (Fig. 2). We first considered GLMs with Poisson distributions and year (trend) effects to examine levels of overdispersion (R packages 'MASS' and 'performance'; Venables & Ripley 2002, Lüdecke et al. 2021), which was pervasive. We then fitted GLMs with negative binomial distributions to address the extra variance, and these models fit the data well (overdispersion ≤1.2), so we did not consider zero-inflation models further.

Trends for each CBC circle were derived as mean (with 95% CI) population change per year, or lambda (λ), from the year β coefficient on the response scale (i.e. exponentiated, where $\lambda = e^{\beta}$): values above 1 indicate the population is increasing (e.g. 1.02 would indicate a 2% increase in the population each year) and values below 1 indicate the population is declin-

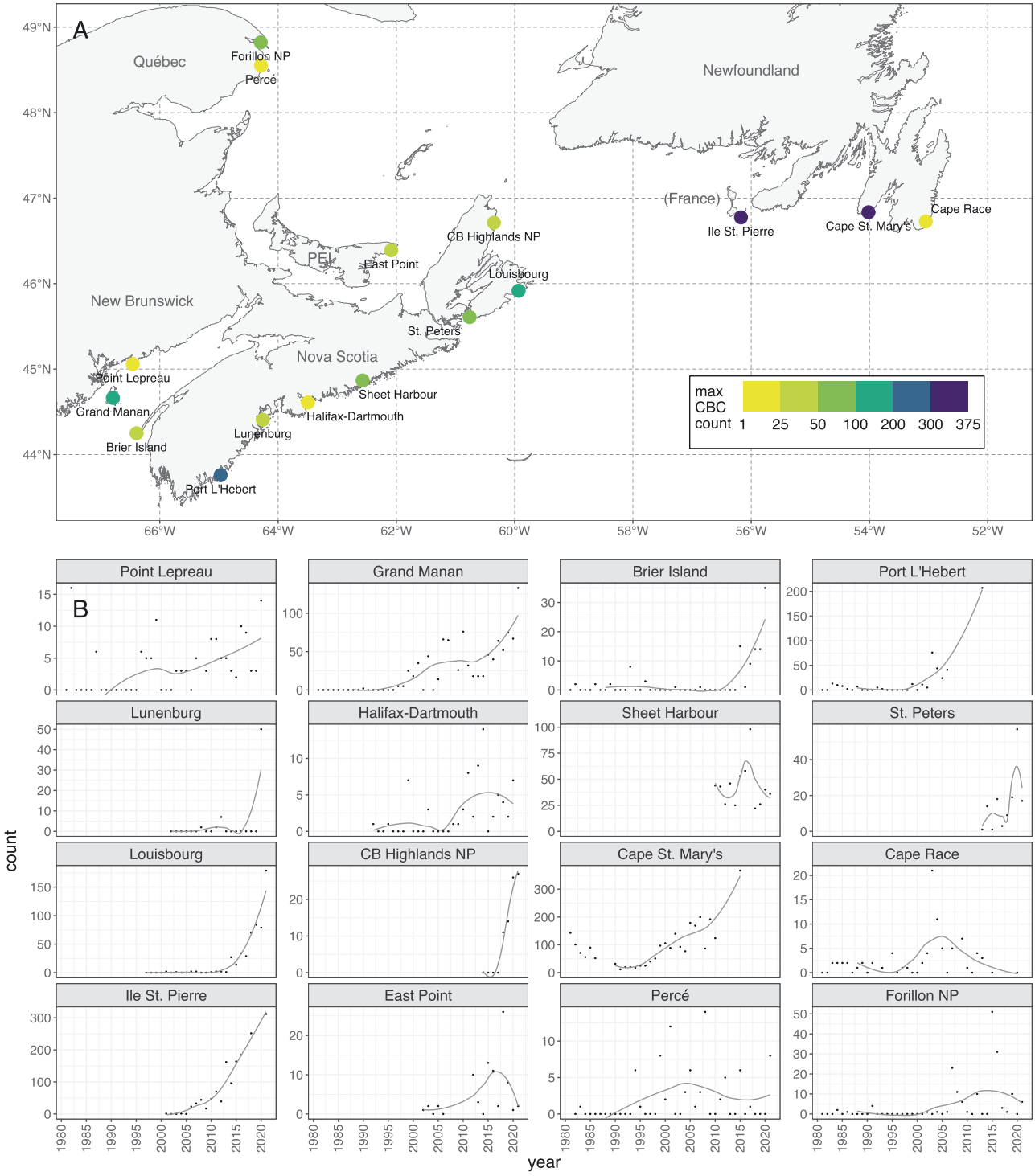


Fig. 2. Counts of harlequin duck *Histrionicus histrionicus* reported from Christmas Bird Count (CBC) circles within the Eastern Canada main wintering range. (A) Location and maximum reported count for each CBC circle. Year of maximum counts on each circle is readily determined from (B). (B) All raw total counts by CBC circle over the period 1981 to 2021 with a LOESS (locally estimated scatterplot smoothing) applied to data covering the period used for trend modelling (1988 to 2021). PEI: Prince Edward Island; CB: Cape Breton; NP: National Park

ing (e.g. 0.98 would indicate a 2% decrease in the population each year). We also considered generalized additive models (GAMs) for non-linear fits over time (R package 'mgcv'; Wood 2017), to address the

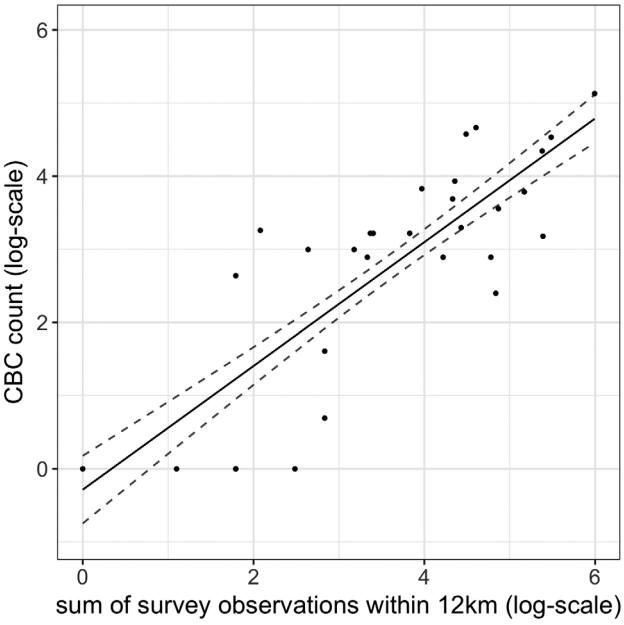


Fig. 3. Harlequin duck *Histrionicus histrionicus* Christmas Bird Count (CBC) data from Eastern Canada compared with total counts from targeted survey observations (by boat, helicopter or fixed-wing aircraft) within 12 km of CBC circle centers in the same winter (n = 30). Solid line shows a significant linear regression ± SE (dashed lines) between CBC counts and survey counts on the log-scale (R^2 = 0.64, slope estimate = 0.84, 95% CI 0.60–1.09)

possibility that trends may have slowed in more recent years toward saturation of local carrying capacities and thus mean linear growth rates may overestimate current population size. We found no evidence of slowing trends. In contrast, trends have generally accelerated in the most recent 10 years of most time series (Fig. 2), and our derived rates of mean population change per year thus provide conservative estimates of mean λ over the time series.

We conducted simulations to project abundance estimates from the most recent years of targeted surveys with complete spatial coverage out to 2022 using regional estimates of mean λ and associated error derived from CBCs. Projected abundance estimates were generated using the classical exponential growth model allowing for demographic stochasticity where the population size N in region i at time t is regarded as a Poisson random variable and λ_{it} at region i and future year t is sampled from a normal distribution with mean λ_i and SD from the CI ($(\lambda_{UCLi} - \lambda_i)/1.96$): $N_{i,t} \sim \text{Poisson}(N_{i,t-1} \times \text{Normal}(\lambda_i, \text{SD}_i))$. We ran 10 000 simulations for each region and present the means and 95% CIs from the output for N_{2022} at the provincial level and totals across the 3 Atlantic provinces. In general, we present all estimates (i.e. slopes, λ, N_{2022}) with 95% CI to consider confidence in the direction and magnitude of estimates.

3. RESULTS

3.1. Newfoundland and adjacent northern wintering sites

Cape Race showed no apparent trend and low numbers of harlequin duck reported over 25 CBCs during the period 1988 to 2020 (Figs. 2 & 4). In contrast, Cape St. Mary's, at the center of the historically surveyed region, showed a sharp positive rate of change in wintering numbers (λ = 1.13, 95% CI 1.10–1.16) over 22 CBCs during 1990 to 2015, where the maximum reported count of 367 birds occurred in the last reported CBC year in winter 2015 (Figs. 2 & 4). CBC data from Cape St. Mary's also clearly demonstrated that a decline in abundance occurred until historical lows were reached around 1990, followed by a trajectory suggesting the initiation of population recovery (Fig. 2). Targeted boat surveys of the Avalon Peninsula over the period 1998 to 2018 suggested that the increases detected in the Cape St. Mary's CBCs continued through 2018 (Table S1), and that CBC counts reasonably captured birds using the area (Fig. S1). The number observed in 2018 by boat in late February (1192) was a remarkable increase from the number observed in early March of 2013 (110) or mid-February in 2005 through 2008 (143–263; Table S1). The majority of birds counted on the 2018 boat survey in the Avalon Peninsula region were observed within the 12 km radius of the Cape St. Mary's CBC circle and within 500 m of the coast, with the exception of a large group (284 birds) at a shoal roughly 10 km offshore and an additional 2 groups (total 93 birds) farther offshore around islands (Fig. S1). Thus, if a CBC had been conducted in winter 2018 and a minimum of 50% of birds detected by boat in late February within 500 m of the coast had been counted from shore in late December or early January, the 2018 CBC may have been as high as 408 birds.

The number of harlequin ducks wintering at sites in Ile St. Pierre, France and Cape St. Mary's, NL has been increasing, at least from 2001 to 2015 when both circles were monitored concurrently (Figs. 2 & 4). To the northwest on the Gaspé Peninsula in Québec, counts of harlequin duck on CBCs have been conducted every year since 1988 (Fig. 2). Counts at Percé have been highly variable but generally low (<10 birds most years; Fig. 2) and with no apparent trend (λ = 1.02, 95% CI 0.94–1.12; Fig. 4). At Forillon

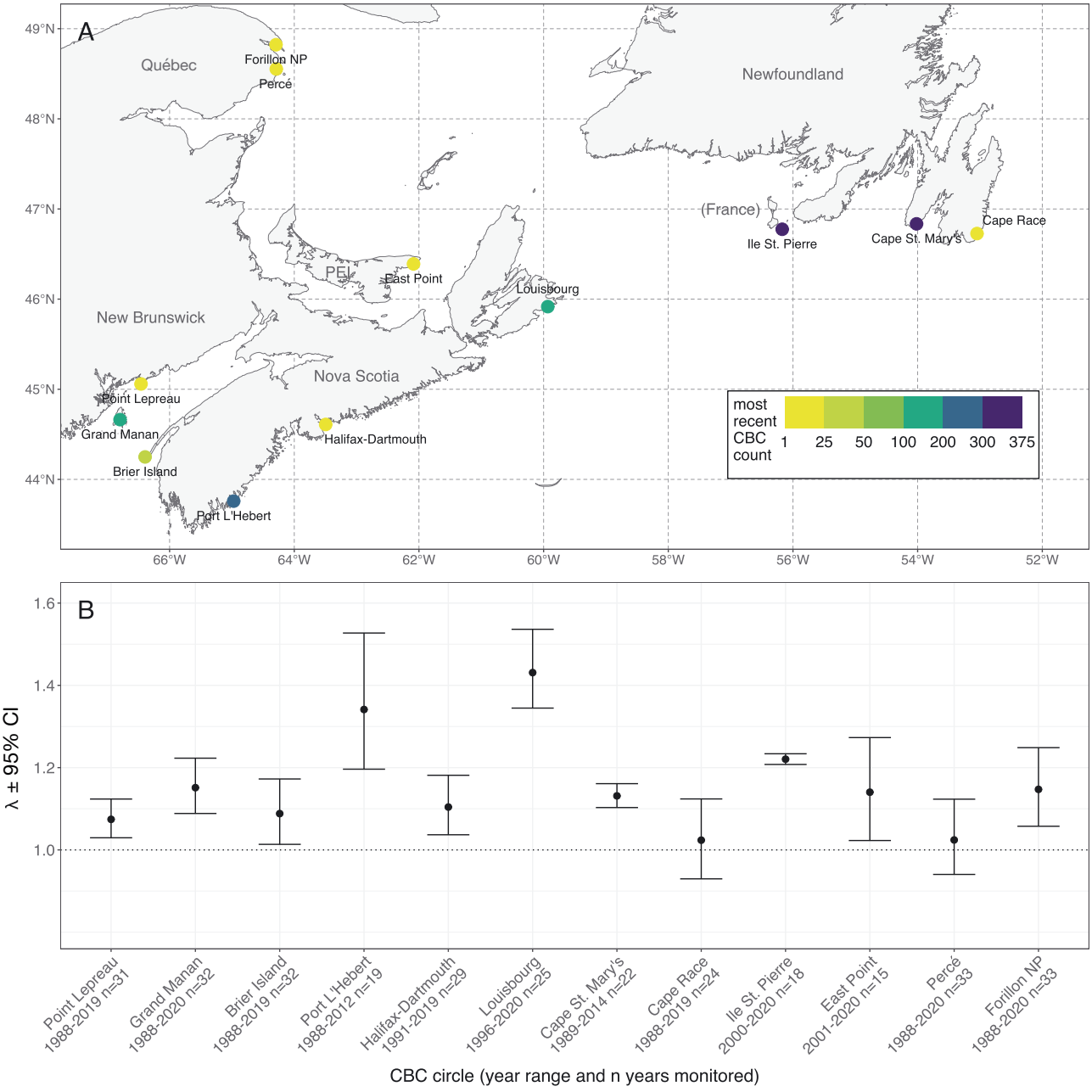


Fig. 4. Counts and trends of harlequin duck *Histrionicus histrionicus* on Christmas Bird Count (CBC) circles within the Eastern Canada main wintering range for the period 1988 to 2021. (A) Location and most recent reported count for each modeled CBC circle. Year of recent counts for each circle is readily determined from (B). (B) Mean rates of population change per year, or lambda (λ), derived from negative binomial models of counts by year fitted for each circle with sufficient data. Estimates of λ are presented with 95% CI. Year ranges of counts and total number of survey years are provided for each circle. PEI: Prince Edward Island; NP: National Park

National Park (NP), counts were generally low at zero or 1 bird from 1981 to 2006, after which counts became variable but generally greater than zero, with a high count of 51 birds in 2015 (Fig. 2). Overall, Forillon NP showed a positive mean rate of population change between 1988 and 2021 (λ = 1.15, 95% CI 1.06–1.25; Fig. 4).

Overall, the data indicated that numbers of harlequin ducks wintering at northern sites in NL, Québec, and SPM was recovering, and in recent years could be supporting a significant proportion of the current total eastern Canadian population, with a total count of nearly 1200 harlequin ducks on the Avalon Peninsula alone in 2018. We conducted simulations that

applied the mean annual growth rate estimate of 13% from the Cape St. Mary's CBC circle (as of 2014), and used those to project the 2018 total survey count (1192) forward in time. That process indicated that the number of wintering birds along the southern Avalon Peninsula in 2022 could be closer to 1952 birds (95% CI 1745–2170).

3.2. Nova Scotia

All 4 CBC trends for circles in NS indicated steep increases since 1988 (Figs. 2 & 4). Increases occurred in CBC count circles located within or near to historically surveyed regions (Brier Island at the southern end of Digby Neck and Port L'Hebert near Little Port L'Hebert) and count circles within the regions of survey expansion around the Eastern Shore Islands Wildlife Management Area (Halifax-Dartmouth) and on Cape Breton Island (Louisbourg; Fig. 4).

About half of birds counted on the 2015 helicopter survey were observed within the 4 historically surveyed regions (559/1126), with the other half observed in regions of survey expansion (Fig. 1). While CBCs at Port L'Hebert have also not been undertaken since 2013, the mean rate of population increase per year at this site was very high up until this time (λ = 1.34, 95% CI 1.20–1.53; Fig. 4), with positive growth beginning in the late 1990s (Fig. 2). There was a long time series of CBCs at Brier Island and over most of its history, counts averaged <5 birds (Fig. 2). Beginning in the early 2010s, there was an abrupt increase (Fig. 2), with the trend suggesting that the numbers of harlequin ducks wintering in this area has been increasing at a rate of 10% per year (λ = 1.10, 95% CI 1.03–1.17; Fig. 4).

Expanded areas of survey coverage in western NS included the Bay of Fundy region north of Digby Neck, where no birds were observed in 2015 but 47 birds were observed in 2013 (Table S2, Fig. 1). Similarly, relatively few birds were observed by helicopter within the southwest NS region in 2015 (49), while later boat surveys suggested higher numbers of birds were likely supported in this region (Table S2, Fig. 1). This region was surveyed by boat every year between 2018 and 2021, over which the number ranged from 111 to 134 (Table S2).

Farther north along the south coast of NS, 87 birds were counted within the historically surveyed area around Prospect in 2015, with an additional 36 counted to the east (Fig. 1). Counts from surveys of varying types conducted since 2000 suggested numbers in the general Prospect area could be increasing (Table S2, Fig. 1). Just north of Prospect, the Halifax-Dartmouth CBC circle also indicated a positive trend (λ = 1.10, 95% CI 1.04–1.18) over 29 CBCs between 1992 and 2020 (Fig. 4). South of Prospect, a reasonable trend could not be estimated for the Lunenburg CBC circle due to mostly zero counts since CBCs began for this circle in 2002, followed by a sudden increase to 50 birds in the most recent CBC in 2019 (Fig. 2). This increase may be due to the adoption of spotting scope optics in 2019 (J. Hirtle, Lunenburg CBC volunteer, pers. comm.), yet still provides further support for the interpretation that local numbers of wintering birds increased or were higher than initially appreciated around the area traditionally occupied in winter at Prospect, NS.

In 2015, the region around the Eastern Shore Islands Wildlife Management Area showed the lowest helicopter counts across 3 surveys of this area during the most recent 5 years of surveys (156 birds; Table S2). Meanwhile, large numbers of birds were counted in 2015 in areas of expanded survey coverage to the south (154) and north (209; Table S2, Fig. 1). Trends could not be estimated for the CBC circle at Sheet Harbour near the southern extent of the historic Eastern Shore Islands Wildlife Management Area survey region, as this circle has only been counted since 2010 (Fig. 2). Regardless, this general area along the Eastern Shore clearly continued to support relatively high numbers of harlequin duck in NS (Fig. 1).

On Cape Breton Island, helicopter surveys in 2015 observed considerable numbers of birds (119 vs. 12 in 2003 and 28 in 2013; Table S2), particularly around the northern and southern extent of the surveyed region (Fig. 1). It should be noted that 2015 was the first year the coastline had been searched in its entirety. CBC counts at Louisbourg, located within the northern survey extent, also suggested that the number of harlequin ducks wintering in this area had been increasing since the early 2000s (Fig. 2), with a very steep positive trend (λ = 1.43, 95% CI 1.34–1.54) over 25 CBCs during the period 1997 to 2021 (Fig. 4). CBCs at St. Peter's and Cape Breton Highlands National Park, located to the south and north of the survey extent, respectively, also suggested potential positive population growth. However, trends could not be estimated for these sites due to short time series beginning in 2013 or later (Fig. 2). Farther west, in PE, positive mean population growth (λ = 1.14, 95% CI 1.03–1.27) was also detected at the East Point CBC since monitoring began in 2001, although the relative abundance was low where the majority of counts reported less than 12 birds (Figs. 2 & 4).

Overall, these 2 data sources together suggested that the number of harlequin ducks wintering in NS has expanded in range and increased over the duration of our study, and likely represents nearly 50% of wintering harlequin ducks in Eastern Canada; however, estimating the total numbers in NS is complicated by relatively low counts in historically surveyed regions during the most recent year of complete survey coverage. At present, the highest concentrations of wintering harlequin duck in NS occur in northeastern Cape Breton Island, along nearly the entire length of the Eastern Shore, and in the area around Port L'Hebert on the South Shore, with significant numbers also occurring along Digby Neck and around the Tusket Islands in southwest NS (Fig. 1).

A conservative estimate of the number of harlequin ducks wintering in NS in 2022 was projected by simulating regional annual growth of dedicated survey counts in 2015 in the same general regions: Brier Island CBC 10% per year growth applied to Digby Neck, Bay of Fundy, southwest NS, Little Port L'Hebert; Halifax-Dartmouth CBC 10% per year growth applied to Prospect, Prospect east, Eastern Shore Islands Wildlife Management Area, Eastern Shore south and Eastern Shore north; Louisbourg CBC 43% per year applied to Cape Breton Island. Accordingly, the NS wintering population projected to 2022 is likely closer to a minimum estimate of 3435 (95% CI 2862–4072).

3.3. New Brunswick

Two CBC circles in NB reporting harlequin duck have been monitored consistently since 1988 and both showed moderate to steep increases over time (Fig. 4). The Point Lepreau circle indicated a positive trend (λ = 1.07, 95% CI 1.03–1.12) over 32 CBCs up to 2020 (Fig. 4). Numbers at Point Lepreau have always been relatively low on both CBC and dedicated surveys (≤16 total birds counted in any year; Table S3, Fig. 2); however, a low point of only zeros in the CBC data occurred during a period of 8 years between 1988 and 1995, after which population growth began (Fig. 2). The 2 highest reported counts occurred in 1983 and 2020 (16 and 14 birds, respectively). The Grand Manan circle indicated a steeper positive trend (λ = 1.15, 95% CI 1.09–1.22) over 33 CBCs up to 2021 (Fig. 4). CBC counts at Grand Manan were consistently near zero from 1988 until 1996, after which growth accelerated to a high count of 133 birds in 2021 (Fig. 2). Only 4 dedicated surveys have been conducted in the Grand Manan Archipelago beginning in 1997, but these also suggested that harlequin duck numbers increased over time (Table S3).

Roughly three-quarters of birds counted by dedicated helicopter surveys in NB in 2016 were observed within 4 historically surveyed regions (87/121). Two of these regions (White Head Island and the Wolves Archipelago) had historically low counts in 2016, while the others (Point Lepreau and Machias Seal Island) had counts more in line with previous surveys since 2000 (Table S3). Two additional regions were surveyed by helicopter in 2016, each with lower numbers counted compared with 2013 helicopter surveys in the same regions (Table S3). Five of 6 regions surveyed by helicopter in 2016 were surveyed in 2013 (all but Point Lepreau where numbers are known to be low regardless), with a total count in that year of 285 birds.

Collectively, these results suggest that the 2016 total estimate for NB is likely biased low, with the same caveat as NS in that dedicated winter surveys have not been conducted since. Simulating annual growth at a rate of 15% from the Grand Manan CBC circle to the 2016 total survey count (121), a highly conservative estimate for the NB wintering population projected to 2022 would be 295 (95% CI 197–410).

3.4. Eastern Canada

Totals from the most recent dedicated surveys with maximum coverage of potential wintering sites provide a minimum estimate of 2439 harlequin ducks wintering in NL, NS, and NB for the current survey years (2018, 2015, and 2016, respectively; Fig. 1). Of those birds counted in these 3 years, 75% (1838) were observed within historically surveyed wintering sites, with the remaining 25% observed within more recently expanded survey areas. These updated totals suggest the number of harlequin ducks wintering in Eastern Canada has increased and expanded in distribution, particularly in NS. This is supported by CBC data which indicated steep increases ($\lambda > 1.05$ where 95% CI do not bound 1) for most CBC circles in Eastern Canada since 1988 or later (10 of 12; Fig. 4). Using regional annual rates of population change derived from CBCs to project counts from the most recent dedicated surveys, we suggest the major wintering areas in the eastern Canadian provinces of NL, NS, and NB may currently be supporting a combined total projected estimate of 5682 (95% CI 5065–6354) wintering harlequin ducks in 2022.

4. DISCUSSION

Here we provide the current state of knowledge of harlequin duck wintering abundance, distribution, and trends in Eastern Canada. Our results indicate that numbers have continued to rapidly increase since the last reported positive trends (Boyne 2008, Thomas 2008, Bowman et al. 2015), and wintering birds are likely expanding into new areas. Based on analyses presented here for the Atlantic Provinces of NL, NS, and NB, combined with an additional ~200 birds estimated to winter along the south coast of the Gaspé Peninsula in Québec (CWS Waterfowl Committee 2020) and another ~500 birds wintering around Ile St. Pierre of SPM (L. Quénéé pers. comm.), we suggest that Eastern Canada currently supports an absolute minimum estimate of ~5500 wintering harlequin duck. This includes birds of all age-classes, thus assuming adults comprise ~85% of the wintering population (Caron & Paton 2007, Robertson 2008), the population may comprise a minimum of ~4670 mature individuals. Overall, our results indicate that the Canadian portion of the eastern population of harlequin duck has been on a positive recovery trajectory since historical lows were detected in the late 1980s.

The eastern population of harlequin duck was estimated to be between 3000 and 3500 birds in 2003 (Boyne 2008, Mittelhauser 2008b), with an average annual increase from CBC counts of about 5% per year over the period 1981 to 2011 (COSEWIC 2013), suggesting a total eastern wintering population estimate of ~5000 birds in 2011. Numbers in the USA were reported to be significantly increasing up to 2003, and birds in major wintering areas in eastern Maine (where more than half of the entire eastern North America population historically concentrated) were expanding their range into new areas (Mittelhauser 2008b). Similarly in the Canadian Maritime provinces, limited survey data up to 2003 combined with reports of birds in previously unknown locations indicated that an estimate of ~800 total birds wintering in traditional areas in NS and NB (about 600 and 200 birds, respectively) was likely an underestimate, and that the winter range was likely expanding and numbers had been increasing, especially in NS (Boyne 2008). Analyses of targeted survey data in NS and NB for the period 2001 to 2013 also indicated significant increases had occurred, with growth rates as high as 8.6% per year (Bowman et al. 2015). Our results joining trends from CBC data over the period 1988 to 2021 with the most recent and thorough targeted survey coverage suggest that these increases were not an artefact of poor survey design, or refined survey effort and observer experience (Bowman et al. 2015), and that the rate of increase has not slowed over time (COSEWIC 2013).

We confirm that record high numbers of harlequin duck in Eastern Canada have been observed in recent years on CBCs, and large numbers of birds have expanded into new areas that previously were not known to support significant wintering populations. Increases have been particularly steep since around 2010 in NS, while recovery has been comparatively steady since the early 1990s in NL and NB. These general patterns of recovery are mirrored by targeted surveys at Ile St. Pierre, SPM, where standardized counts have shown a steady increase from 11 birds in 2005 to >300 in every year since 2017, with 533 birds counted on 1 day in March 2021 (L. Quénéé pers. comm.). Patterns of recovery are also mirrored in CBC counts on Ile St. Pierre and to a lesser extent on PE and in some CBCs in Québec. The elimination of recreational harvests in Eastern Canada since 1990 was considered an important first step to give populations a chance to recover (CWS Waterfowl Committee 2020), as harlequin ducks have long been recognized as being particularly sensitive to harvest pressure (summarized by Goudie 1989). However, an unknown amount of incidental and subsistence hunting could still be limiting recovery (COSEWIC 2013), although this is thought to be a minor threat (SDJV 2015). Our results indicate that rapid growth is still occurring throughout Atlantic Canada. In NL alone, the wintering aggregation visible around Cape St. Mary's on a single day for the CBC was greater than 100 birds in 5 of 6 count years from 2005 to 2010, and reached a high of 367 birds in the last count year in 2015. Given historic levels at this site are thought to be around 100 or more birds (Robertson & Goudie 2020), these numbers are highly encouraging. Nevertheless, it is difficult to gauge the health of the current population without baseline information on population abundance before the initial detection of declines. Although it is debated (Vickery 1988, Goudie 1989), the historical population size on the east coast of North America was probably never large, remaining below 10 000 birds (Goudie 1989). If this is true, and reported growth rates have remained steady in both the Canadian and US portions of the wintering population, then the total eastern population may already be nearing historical levels.

Wintering habitat in Atlantic Canada is clearly supporting rapidly increasing numbers of harlequin

duck, and habitat protection is not yet extensive within the Canadian winter range (COSEWIC 2013, Gutowsky et al. 2019). Individual adult harlequin ducks exhibit high annual fidelity to molting and wintering locations, at least between 2 consecutive years (Robertson et al. 2000, Iverson et al. 2004). Given this high propensity to return to the same areas and to congregate, excessive disturbance, coastal development, and other types of habitat degradation are all considered potential threats (COSEWIC 2013), from both summer home development and an increasingly intense aquaculture industry in NS and NB (Boyne 2008, Gutowsky et al. 2021). Even more critical, some regional concentrations of birds are in areas near hydrocarbon refineries (Bay of Fundy, Chedabucto Bay, Placentia Bay), and are also near major national and international shipping routes, thus increasing vulnerability to oil contamination and pollution (COSEWIC 2013). In light of the gregarious nature, high site fidelity, increasing abundance, and expanding wintering range of harlequin ducks, further efforts should be made to identify, monitor and protect key Canadian wintering areas. Indeed, the Sea Duck Key Habitat Sites Atlas produced by the SDJV describes 85 distinct sites throughout North America that constitute important sea duck habitat, with the intention of increasing awareness of valuable habitats and aiding in prioritizing habitat conservation and protection efforts (Bowman et al. 2022). Criteria for inclusion in the atlas were strict, yet 5 of these sites were identified because they are continentally important sites for the eastern harlequin duck population, aligning with regions identified here as having the highest growth rates and wintering concentrations in NS (4 sites) and NB (1 site; Bowman et al. 2022).

Increases in abundance and range expansion reported here are based on the best information currently available. However, surveys may over- or under-estimate local abundance due to a number of contributing factors including interannual variation in local conditions or survey timing, and detectability. For example, some areas in NS (NS Bay of Fundy, Digby Neck, and Southwest NS) had considerable sea ice coverage in 2015 (R. Ronconi pers. obs.) which may have influenced harlequin duck distribution and counts, resulting in the low estimates in this region that year. In NL, the Avalon Peninsula survey in 2018 was conducted comparatively late in the season (Table S1), thus abundance may be over-estimated by the presence of early migrants from more southern wintering populations beginning their movement northward. On the other hand, our estimate does not include counts of birds from additional areas in southern NL outside of Cape St. Mary's that also support wintering harlequin ducks, although typically in smaller numbers (Gutowsky et al. 2019). More generally, the influence of observer bias or visibility on survey detection rates has not been quantified. Regardless, we are confident that the estimates we present here are reasonably representative of the current eastern population, which has increased significantly and expanded in range over the past 30 years since the initiation of management efforts to reverse the population declines.

The lack of consistent targeted monitoring data (i.e. collected at the same sites across the wintering range on the same dates in every survey year) necessitated the use of a non-targeted, citizen-science, bird census program to evaluate long-term trends from population indices and to project population estimates via simulation, which inevitably reduces the accuracy of estimates of current local or regional population abundance. The 2007 management plan for harlequin duck set a goal of 3000 wintering individuals counted or estimated in eastern North America in 3 of 5 consecutive years. Our assessment of current distribution and trends suggests this goal was met in the 2010s in Canada alone. Our work demonstrates the potential for CBC data to reasonably capture relative trends for nearshore waterbirds in the absence of targeted survey data. Given that the total number of harlequin ducks in Eastern Canada was relatively low when surveying began in earnest in the early 1990s, and that the majority of birds were believed to winter in discrete known locations, an ad-hoc approach to monitoring was sufficient in the past. The eastern population is clearly in recovery, and may have recovered depending on whether population targets developed in the 1990s remain appropriate, but only the development of a well designed monitoring program that can document changes in abundance and wintering range will enable managers to confidently evaluate the effects of current and future management actions, and to respond most effectively should regional trends slow or reverse.

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