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Declining population of Harlequin Duck (*Histrionicus histrionicus*) on the Bow River, Alberta, Canada: 25 years of monitoring

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Abstract
Harlequin Duck (*Histrionicus histrionicus*) is a small sea duck that winters in coastal waters and breeds on fast-moving mountain streams in western North America. Because of its dependency on streams and coastal near-shore habitat with healthy macroinvertebrate populations, population trends of this species can be used as an indication of healthy freshwater and marine ecosystems. From 1995 to 2020 we conducted roadside surveys for Harlequin Ducks on the Bow River in Banff National Park, Alberta. We calculated the population's trend by modelling maximum annual count, which showed a population decline over the 25 years of 3.3% per year. The trajectory varied over time: a relatively stable population from 1995 to 2005, a steep decline until 2011, then stabilising at a much lower level with a slight rebound in recent years. The predicted number of ducks from our state-space model closely tracked the maximum number of ducks observed in annual counts. During stable or slightly increasing population estimates the male:female (M:F) ratio fluctuated considerably but stayed high (1.4:1 and 1.3:1, respectively), and during the period of steep population decline the M:F ratio was at its lowest (1.1:1). This declining population trend is concerning because it is occurring in a protected area, but it is similar to data from other studies in the Rocky Mountains and at the coastal wintering area, suggesting that causes may not be solely due to issues on the breeding streams.

Key words: Harlequin Duck; *Histrionicus histrionicus*; Bow River; population trend; state-space model; sex ratio

Introduction
Harlequin Duck (*Histrionicus histrionicus*) is a small sea duck that winters in coastal waters and breeds along fast-moving mountain streams (Robertson and Goudie 2020). Harlequin Ducks exhibit delayed sexual maturity, low annual productivity, high annual adult survival (Goudie *et al.* 1994), and exhibit strong site fidelity to breeding (Smith *et al.* 2000) and wintering (Robertson *et al.* 2000) areas. Harlequin Ducks do not defend a stretch of river however males do guard their mates from other males, particularly on the breeding stream (Lazarus *et al.* 2004).

The welfare of Harlequin Ducks appears to be intimately related to the availability of fast-flowing, nonpolluted water (Soulliere and Thomas 2009; Robertson and Goudie 2020), and because of their tendency to locate their nests close to water, they also need streams where they can breed and nest away from human disturbance (Wiggins 2005; ASRD 2010). Because of the Harlequin Duck's dependency on streams and coastal near-shore habitat with healthy macroinvertebrate populations, population trends of this species can be used as an indication of healthy freshwater and marine ecosystems (Vaughan *et al.* 2007).

Understanding wildlife population trends is essential for effective species management and conservation (Mills 2013). Data on population size are important when setting limits on recreational activities such as sport harvest or commercial recreation or when considering impacts of industrial activities such as mining or logging. Accurate population data are also important when monitoring effectiveness of conservation actions such as habitat recovery or protection.

Sex ratios also have long been used as demographic tools for waterfowl management (e.g., Bellrose *et al.*

1961). Males are often hunted in higher numbers than females due to their attractiveness as trophy mounts, while the inexperience of juveniles of either sex leads to higher mortality of that age class for many species. While sex ratio at hatching is usually equal (Bellrose *et al.* 1961), subsequent male-biased ratios have been generally attributed to differential survival of male and female ducklings to recruitment (Lehikoinen *et al.* 2008) and to differential mortality between the sexes resulting from increased predation of females during incubation and brood rearing (reviewed in Donald 2007). While a male-biased sex ratio should not influence population trends, because females are not limited by male availability, more males may negatively affect female reproduction through energy loss and reduced foraging because of increased number of pursuit flights and attempted extra-pair copulations (Pöysä *et al.* 2019).

The eastern population of Harlequin Duck (*Histrionicus histrionicus pacificus*) in Canada is legally listed as a species of Special Concern under the federal *Species at Risk Act* (SARA; SARA Registry 2023). The Government of Alberta (2024) considers Harlequin Duck a Species of Special Concern due to specific breeding habitat requirements; threats to habitat integrity from logging, mining, grazing, and recreational activities; relatively small breeding population size; and sensitivity to disturbance during breeding. There is currently no reliable index of population size or trend for Harlequin Ducks in western North America.

Our 25 years of data, from 1995 to 2020, on the Bow River in Banff National Park, Alberta is one of the longest monitoring studies for a breeding population of Harlequin Ducks. Our objectives were to (1) calculate population indices and (2) document sex ratio in this population.

Methods

Study area

We observed Harlequin Ducks on the Bow River in Banff National Park, Alberta, Canada, during May and June, 1995–2020. The section of interest was a 25-km stretch of river starting ~4.5 km downstream of Lake Louise (51.4028°N, 116.1611°W) to Castle Junction (51.2633°N, 115.9219°W; Figure 1), along which the river decreases in elevation from 1545 m to 1440 m. The study area falls within the Lower Subalpine Ecoregion, predominantly forested with Lodgepole Pine (*Pinus contorta* Douglas ex Loudon) and Buffalo Berry (*Shepherdia canadensis* (L.) Nuttall; Holland and Coen 1983). The 30-year average (1991–2017) spring precipitation and temperature varied from 157.9 mm and 3.5°C near Lake Louise, to 152.4 mm and 4.0°C near Castle Junction (Clark and Kienzle 2022). The Bow River normal flow ranges from 2 to 4 m^3/s (lower quartile) on 1 May to 14 to 28 m^3/s (upper quartile) on 1 June, with a level of 1 to 1.45 m in height during the same period (Government of Alberta 2022).

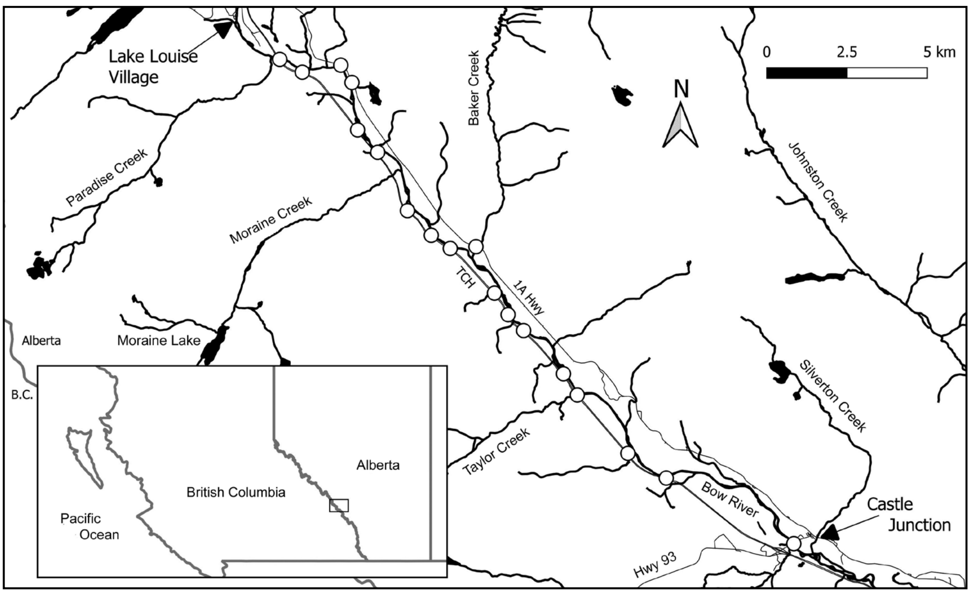

FIGURE 1. The 18 roadside survey stops (circles) for Harlequin Duck (*Histrionicus histrionicus*) covered 14 km of the 25 km along this section of the Bow River in Banff National Park, Alberta. Circles represent highway stopping locations and do not correlate with length of river observed at each stop.

Field surveys

We established a repeatable survey route along the Bow River in 1995, using 18 road-accessible locations along the Trans-Canada Highway (TCH; Highway #1) and Bow Valley Parkway (Highway #1A), between Castle Junction (the junction of the TCH and Highway #93 South) and the TCH bridge downstream of Lake Louise (a distance of 25 km; Figure 1). From the survey stops 14 km (56%) of the river could be observed. Most locations were within view of the road, but a few required walking a short distance through intervening tree cover. Not all segments of the river are equal, as there are local differences in ecologically relevant factors such as prey availability, and stream depth and velocity (Heath *et al.* 2006).

Confirmation that our chosen roadside survey stops adequately sampled the local Harlequin Duck population was provided by conducting boat surveys along the entire 25-km stretch of river described above, from 1996 to 2002, using expert canoeists who were also experienced wildlife observers. Ninety-one percent of the observations (CI 87–98%; range 71–100%) during 16 boat surveys (median 2/year, range 1–3) were at the same location as roadside survey stops.

The purposes of the roadside surveys were to: (1) obtain counts of ducks for population indices and (2) obtain sex ratios. Sex ratio data are presented as raw data and have not been statistically analysed but are included to better understand what may be driving population trends over time. At each survey stop we counted the total number of ducks and recorded the number of each sex. We do not report number of pairs because it can be difficult to distinguish pairs in a large group of birds and the time it would take to observe definitive pair behaviour would impact our ability to complete the survey in a practical length of time. While each survey was conducted in a single day, the amount of time we spent at each survey stop varied (minimum 5 min), depending on whether or not, and how many, ducks were present. Three to nine surveys (average six) were conducted each year. Surveys were spread out during the prescribed period as equally as possible depending on suitable weather conditions (no or little precipitation to ensure good visibility) and staff availability.

The colourful plumage of Harlequin Duck males increases their observability. Female Harlequin Ducks are more camouflaged, but at the time of year of our surveys, females are almost always accompanied by males, either their mate or single males. Observers are trained to scan the shorelines methodically with the spotting scope, which reduces the likelihood of missing loafing birds. Ducks in flight are easy to see as they fly very low to the water, following the river channel closely. There is a possibility of double counting individuals if birds fly or swim into another segment, as the survey can take several hours to complete. Because of the use of binoculars and spotting scopes, observers do not need to get particularly close to the birds, which reduces disturbance. While surveyors varied among years, new surveyors were always trained by an experienced surveyor.

Single males are the first to arrive on the river (median date 21 April), followed by pairs (median date 3 May; Smith 2000). We conducted surveys between 1 May (median start date 10 May) and 15 June; however, we truncated the early survey data before 7 May to eliminate surveys that may have had a higher proportion of early-arriving single males. We also truncated data after 2 June after plotting the ratio of male to female ducks during the full survey period. The mean male:female ratio (M:F) was significantly higher after 2 June than before 2 June (2.0:1.0 versus 1.3:1.0, respectively; $Z = -3.75$, $P < 0.001$), which suggested that the females were starting to leave the main river for smaller streams to lay eggs and then to incubate and would be less likely to be observed on the river. Smith (2000) estimated that the median date to initiate egg laying was 1 June for 11 female Harlequin Ducks that were radio tracked, and the median date for initiating incubation was 15 June. Including data after 2 June would bias the sex ratio towards males.

Analysis methods

Negative binomial generalized additive model (GAM)—To assess the effect of year and survey date, duck counts were modelled using generalized additive models (GAMs) using "mgcv" version 1.8.40 (Wood 2011). Negative binomial regression is a standard alternative to Poisson regression when modelling overdispersed count data (dispersion parameter = 1.9; Zuur *et al.* 2009). We used the maximum count of Harlequin Ducks for each year as an unadjusted number. The maximum count included all males and females observed, regardless of whether they were paired or not. Covariates were survey date (converted to ordinal date) and year. Data exploration was carried out following the protocol in Zuur *et al.* (2010). Visual inspection suggested non-linear relationships between counts and covariates, so we included linear and smoothed terms for day of survey and year in model selection. We applied a stepwise backward regression method to select the best model using AIC.

Generalized linear model (GLM)—To estimate a linear trend in the maximum count of Harlequin Ducks each year, we modelled the maximum count of ducks as a function of the covariates using a negative binomial GLM with a log link function using the "mass" package version 1.8.40 (Venables and

Ripley 2002) in R (R Core Team 2020). The GLM estimate of the trend was used because it provides a useful metric for understanding population status. We checked the model fit using standard residual plots and explained deviance. We checked the assumptions of the negative binomial GAM using gam.check in 'mgcv' and inspected the scatterplots of residuals plotted against fitted values and the explanatory variable and no obvious patterns were detected.

State-space exponential growth model (SSM)—Notably, some of the changes in maximum counts between years would be due to a change in the actual number of Harlequin Ducks, and some may have been due to differences in detectability or observer error. To address this, we used an additional method to detect trends in maximum counts. This method, called the 'state-space' exponential growth model (known hereafter as the state-space model or SSM) is a linear mixed model that treats the Observation Error Model and the Process Variation Model as special cases with corresponding variance parameters equalling zero, and uses maximum likelihood (and restricted maximum likelihood) to solve for the optimum parameter estimates. The SSM has been used to analyse ungulate population trends where population estimates are lacking (Flesch *et al.* 2016) and can also incorporate missing data in the time series (Humbert *et al.* 2009). The parameter of interest produced by the SSM is μ, which is the natural logarithm of lambda, or the expected change in numbers over time. The state-space modelling was conducted in the R programming language (version 3.24.3.2; R Core Team 2020), using a model from Humbert *et al.* (2009). We used Markov chain Monte Carlo modelling within package "nimble" (de Valpine *et al.* 2023) to fit parameters and credible intervals for the SSM population predictions. Convergence was assessed with the Gelman-Rubin test, and goodness of fit was assessed using Bayesian *P*-values (Royle *et al.* 2013) and Freeman–Tukey residuals. For each iteration, we simulated response data then summed observed and simulated Freeman–Tukey residuals. We calculated the percentage of iterations, where observed sums were larger than simulated sums. Values less than 0.05 or greater than 0.95 indicated poor fit. Five chains were run with 200 000 iterations with a 20 000 burn in. Package "ggplot2" (Wickham 2016) was used for graphing.

SSMs can operate at two levels (observation and process) by assuming that the process level is autocorrelated; i.e., a large population at time t will probably lead to a large population size at time t+1 (Auger-Méthé *et al.* 2016). There are two components to an SSM: process variation and observation error. The process variation model assumes that between time intervals there can be perturbations to the growth rate (due to environmental variation), and that these perturbations are random, distributed normally, and exhibit no serial autocorrelation (Humbert *et al.* 2009). So, the process is autocorrelated, but the perturbations should not be autocorrelated. It is difficult to know if this is precisely true for any population, however it is reasonable to think that a negative perturbation in one year (e.g., high water causing poor reproductive success) could be offset by a positive perturbation in another (e.g., high prey abundance causing increased survival). The observation error model assumes that the error term is normally distributed with a mean of zero, i.e., sampling error is independent across sampling periods. This is, we believe, a reasonable assumption for our population—poor detectability in one year (for example due to poor weather) would not necessarily be followed by poor detectability in the following year.

Results

An average of six roadside surveys (range 3–9) were conducted annually (1995–2020, except 2000) between 7 May and 2 June. The highest maximum annual count of Harlequin Ducks was in 1997 ($n = 64$) and the lowest count was in 2011 ($n = 17$). The M:F ratio (Figure 2), based on the roadside survey annual high count day, averaged 1.3:1.0 (range 0.9–1.9).

The optimal GAM predicting maximum annual counts (Table 1) included year as a smoothed term and survey date as a linear effect indicating early stability followed by a decade of declining counts, to recent stability at a lower level (Table 2, Figure 3a). Annual maximum counts were higher when they were recorded earlier in the season (Figure 3b). We plotted the relationship between the number of surveys conducted in a year and the maximum count, but there was no relationship. The model explains 76.9% of the null deviance.

We observed an annual decline of 3.3% in the maximum count of Harlequin Ducks from 1995 to 2020 on the Bow River (Table 3, Figure 4a,b). Validation plots of the negative binomial GLM, which included the linear effect of year indicated a non-linear pattern in duck counts over years which supported the use of a GAM to assess the effects of year and survey date. Explained null deviance was 57.5%.

The SSM, which accounts for observer error, mirrored maximum values of the other methods (Figure 5). The model appeared to converge based on a visual examination of the trace plots and because the Gelman-Rubin test statistics were <1.03 for all parameters. Fit was also good (proportion of observed greater than predicted Freeman–Tukey residuals was 0.60). The SSM trend was −0.0243, with a credible interval of −0.0748 to 0.0300. The observation variance

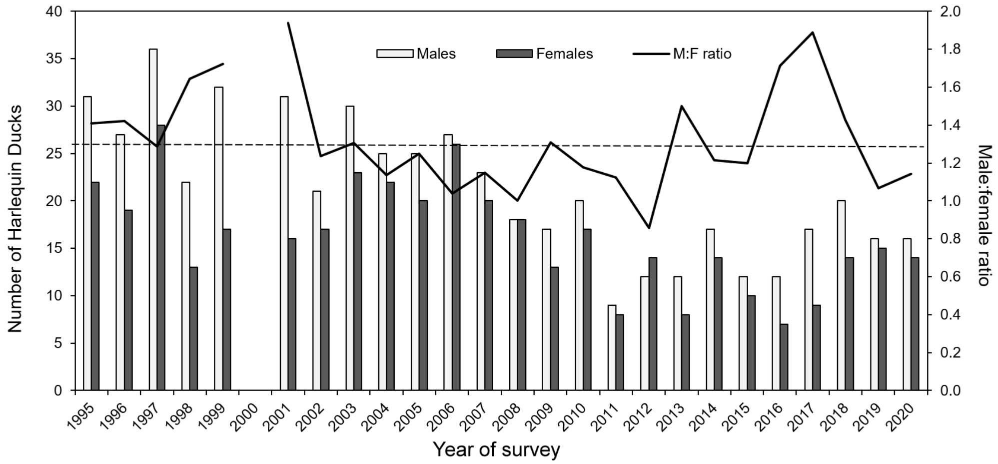

FIGURE 2. Number of male and female Harlequin Duck (*Histrionicus histrionicus*) and male:female ratios (M:F), observed from maximum annual counts during roadside surveys along the Bow River, Banff National Park, Alberta, 1995–2020. The horizontal dashed line is the median M:F ratio (1.3:1.0) during the 25 years.

TABLE 1. Akaike Information Criterion (AIC) table comparing generalized additive model fits for annual counts of Harlequin Duck (*Histrionicus histrionicus*) from roadside surveys, Banff National Park, Alberta, 1995–2020.

Model	df	AIC	ΔAIC
Survey date + s(Year)	7.9830	175.2133	0.0000
s(Survey date) + s(Year)	7.9838	175.2149	0.0020
s(Year)	6.9409	176.0891	0.8758
s(Survey date) + Year	4.0001	181.9957	6.7824

TABLE 2. Our negative binomial generalized additive model explaining maximum annual counts of Harlequin Duck (*Histrionicus histrionicus*) on roadside surveys, Banff National Park, Alberta, 1995–2020, and year and survey date. Edf = effective degrees of freedom; DE = deviance explained.

Predictors	Estimates	SE	*P*	DE (%)
(Intercept)	4.8052	0.8093	<0.0001	76.9
Survey date	−0.0087	0.0058	0.1300	
Smooth predictors	**Edf**	**χ^2**	***P***	
Year	4.084	58.07	<0.0001	

was 0.0706 and the process variance was 0.0339. Importantly, there was stability in the population until 2006, when the population declined sharply and then appears to have stabilized, but at a lower level.

Discussion

Our maximum annual count and the SSM both indicate a relatively stable population of Harlequin Ducks on the Bow River from 1995 to 2005, then a steep decline until 2011, with the population thereafter stabilising at a much lower level, and showing a slight rebound in the most recent years, although it may be too early to tell. A similar pattern has shown up on another breeding stream in Alberta, and one in Idaho. Maximum annual counts on the McLeod River in Alberta showed a slightly declining population from 1996 to 2005, then a steep decline to 2011, where it has since stabilised (B. MacCallum pers. comm. 16 November 2020). In Idaho, pair counts on the Lochsa River steeply declined from 30 in 1995 to four in 2011, then stabilised around the lower level (J. Sauder pers. comm. 20 April 2020). Our 1995–2020 trend of −3.3% is also similar to the overall trends observed for 1999–2019 at British Columbia wintering areas, where Harlequin Ducks aggregate from many breeding areas, including the Bow River (Smith and Smith 2003); trends varied from −0.70% per year (CI −1.98–0.70) in the Salish Sea (Strait of Georgia)

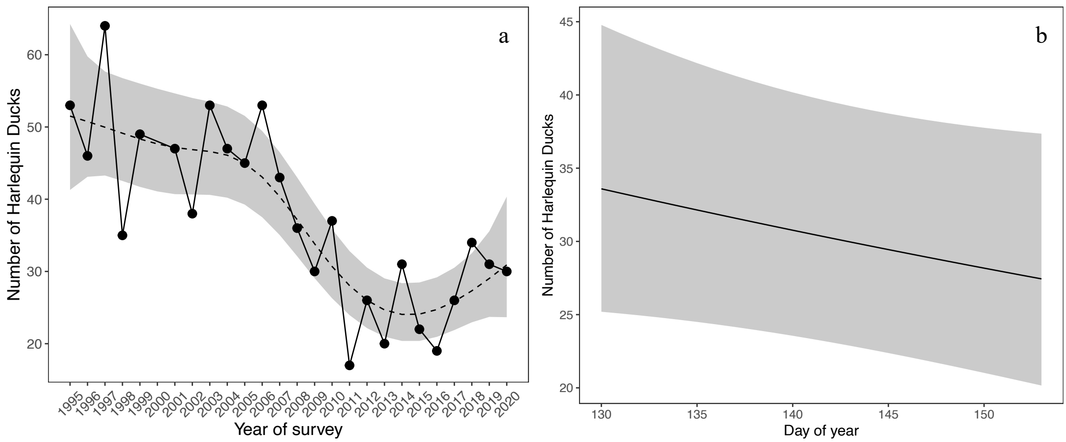

FIGURE 3. Fitted values (dotted line) and 95% confidence bands for the optimal negative binomial generalized additive model applied on the Harlequin Duck (*Histrionicus histrionicus*) count data, Banff National Park, 1995–2020. Plots were constructed using the range of values for year (a) and survey date (b) while holding the remaining predictor variable at the mean value. Black circles are the observed maximum counts.

TABLE 3. Our negative binomial generalized linear model explaining the linear relationship between the maximum annual counts of Harlequin Duck (*Histrionicus histrionicus*) on roadside surveys, Banff National Park, Alberta, 1995–2020, and year and survey date. DE = deviance explained.

Effects	Coefficient	SE	*P*	DE (%)
Intercept	71.8781	11.4499	<0.0001	57.51
Survey date	−0.0079	0.0063	0.2110	
Year	−0.0335	0.0057	<0.0001	

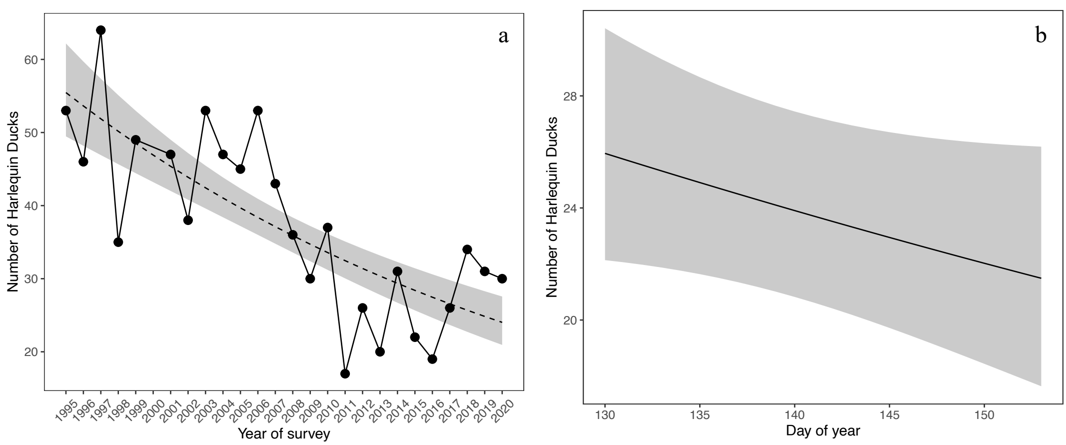

FIGURE 4. Fitted values (dotted line) and 95% confidence bands for the optimal negative binomial generalized linear model applied on the Harlequin Duck (*Histrionicus histrionicus*) count data on the Bow River, Banff National Park, 1995–2020. Plots were constructed using the range of values for year (a) and survey date (b) while holding the remaining predictor variable at the mean value. Black circles are the observed maximum counts.

to −4.97% per year (CI −11.4–2.22) on the outer Pacific Coast (Ethier *et al.* 2020).

Sex ratio averaged 1.3:1.0 (M:F) in the 25 years of our study, which is the same as that found in the Strait of Georgia, British Columbia wintering area (Rodway *et al.* 2015). Rodway *et al.* (2015) suggested that changes in sex ratios can function as early warning signals of population decline; an increasing

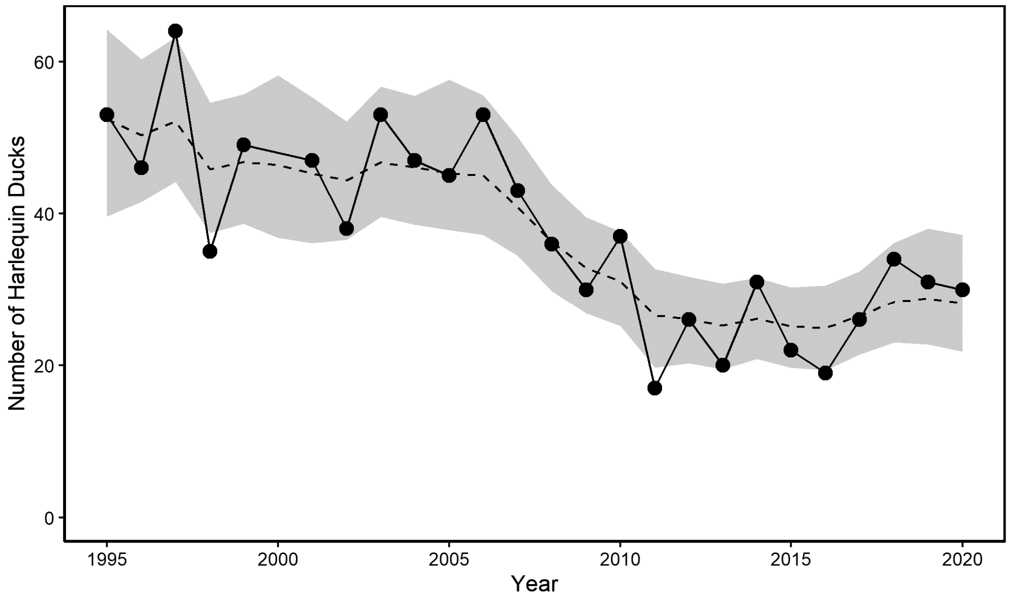

FIGURE 5. The predicted number of Harlequin Duck (*Histrionicus histrionicus*; dashed line) using a state-space model closely tracked the maximum number of ducks observed per year (black dots with black line), on the Bow River, Banff National Park, Alberta,1995–2020. The gray area represents 95% CI.

M:F ratio could signal declining female survival that would impact productivity and recruitment. In our study the lowest M:F ratio was during the period of steepest population decline, but it is difficult to determine if that was correlation with no obvious causation. A period of increased predation on males at the wintering area, because they are more colourful and perhaps easier to target, could reduce the number of males in the population. The recovery of some coastal Bald Eagle (*Haliaeetus leucocephalus*) populations in recent decades have influenced the distribution and abundance of sea birds and sea ducks (Middleton *et al.* 2018).

The similar trajectory of declining trends for Harlequin Ducks among various breeding and wintering populations suggest that the causes of the Bow River decline could be multifactoral, including threats outside the protected area. Harlequin Ducks may be impacted by numerous interacting threats: environmental pollution (Souillier and Thomas 2009), climate change affecting stream flows (Hansen *et al.* 2019) and invertebrate food sources (Souillier and Thomas 2009), habitat loss and alteration (MacCallum 2001; Souillier and Thomas 2009), increasing recreational activities (MacCallum 2001), increased numbers of predators in breeding and/or wintering habitat (Heath *et al.* 2006), and hunting mortality (Smith and Goudie 2021). More in-depth research into causes of the decline is warranted.

Our study proved that our roadside survey approach was effective and efficient for monitoring a Harlequin Duck population that is of Special Concern, and that this technique may be suitable for other species with similarly accessible breeding habitat.

Author Contributions

Writing — Original Draft: C.M.S.; Writing — Review & Editing: B.S., M.B., and S.H.; Conceptualization: C.M.S.; Investigation: C.M.S. and S.H.; Methodology: C.M.S.; Formal Analysis: B.S., and M.B.; Funding Acquisition: C.M.S. and S.H.

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Duck counts on the Lochsa River. Jesse Whittington helped with the MCMC analyses and provided valuable insight on interpretation of Bayesian results. Research was conducted under Parks Canada Agency Research and Collection Permits for Banff National Park, including Parks Canada Animal Care Committee Protocol Reviews. All applicable ethical guidelines for the use of birds in research have been followed, including those presented in the Ornithological Council's "Guidelines to the Use of Wild Birds in Research" (Fair *et al.* 2010) and the Canadian Council on Animal Care (2003). We thank two anonymous reviewers for their helpful comments on previous drafts of this manuscript.

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