

1 Wild bird mass mortalities in eastern Canada associated with the

2 Highly Pathogenic Avian Influenza A(H5N1) virus, 2022

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50 mortality assessment, Northwest Atlantic, seabirds, marine birds, sea ducks

51 **Data availability:** The complete mortality dataset (Data S1), the code to reproduce the double
52 count analysis, and colony survey information (Data S2, S3, S4) will be published upon
53 acceptance of the manuscript in a peer-reviewed journal. The following DOI has been reserved
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55

56 **Abstract**

57 In 2022, a severe outbreak of clade 2.3.4.4b Highly Pathogenic Avian Influenza (HPAI) H5N1
58 virus resulted in unprecedented mortality among wild birds in eastern Canada. Tens of thousands
59 of birds were reported sick or dead, prompting a comprehensive assessment of mortality
60 spanning the breeding season between April 1 and September 30, 2022. Mortality reports were
61 collated from federal, Indigenous, provincial, and municipal agencies, the Canadian Wildlife
62 Health Cooperative, non-governmental organizations, universities, and citizen science platforms.
63 A scenario analysis was conducted to refine mortality estimates, accounting for potential double
64 counts from multiple sources under a range of spatial and temporal overlap. Correcting for
65 double counting, an estimated 40,966 wild birds were reported sick or dead in eastern Canada
66 during the spring and summer of 2022. Seabirds and sea ducks, long-lived species that are slow
67 to recover from perturbations, accounted for 98.7% of reported mortalities. Mortalities were
68 greatest among Northern Gannets (*Morus bassanus*; 26,193), Common Murres (*Uria aalge*;
69 8,133), and American Common Eiders (*Somateria mollissima dresseri*; 1,945), however, these
70 figures underestimate total mortality as they exclude unreported deaths on land and at sea. In
71 addition to presenting mortality estimates, we compare mortalities with known population sizes
72 and trends and make an initial assessment of whether population-level impacts are possible for
73 the Northern Gannet, a species that has suffered significant global mortality, and two harvested
74 species, Common Murre and American Common Eider, to support management decisions. We
75 hypothesize that population-level impacts in eastern Canada are possible for Northern Gannets
76 and American Common Eiders but are unlikely for Common Murres. This study underscores the
77 urgent need for further research to understand the broader ecological ramifications of the HPAI
78 outbreak on wild bird populations.

79

80

81 **Introduction**

82 The Highly Pathogenic Avian Influenza A (HPAI) H5N1 virus of the A/Goose/Guandong/1/96
83 lineage emerged in Asia in 1996. Over the past 25 years, the virus has continued evolving and
84 been detected across Asia, Africa, and Europe. There has also been an increasing number of
85 mass mortality events involving wild birds (Verhagen et al. 2021), but until 2022, no unusual
86 mass mortalities caused by HPAIV have occurred in North America (Papp et al. 2017, Giacinti et
87 al. 2023). The current wave, clade 2.3.4.4b lineage H5NX HPAI with H5N1 as the dominant
88 subtype, has marked a drastic turning point with wild birds becoming not only a reservoir, but
89 also susceptible to morbidity and mortality associated with the virus. The HPAI virus is now
90 considered the cause of the largest avian panzootic to date, based on the number of dead birds
91 and species affected and the number and geographic spread of outbreaks (Klaassen and Wille
92 2023).

93 Globally, this new HPAI virus subtype has caused disease and unprecedented mass
94 mortality events among wild birds with disproportionate impacts on waterbirds, including cranes
95 (Lublin et al. 2023, Pawar et al. 2023), Great Skuas (*Stercorarius skua*; Banyard et al. 2022),
96 gulls and terns (Pohlmann et al. 2023, Roberts et al. 2023, Sobolev et al. 2023), gannets (Lane et
97 al. 2023, Pohlmann et al. 2023, Roberts et al. 2023), Peruvian pelicans (*Pelecanus thagus*;
98 Leguia et al. 2023), Cape Cormorants (*Phalacrocorax capensis*), and African Penguins
99 (*Spheniscus demersus*; Roberts et al. 2023). In North America, this virus was first detected in
100 wild birds in December 2021, following observation of several wild gulls with neurological
101 symptoms at a rehabilitation facility in St. John's, Newfoundland, Canada (K. Gosse, pers.
102 comm.). One of these, a Great Black-backed Gull (*Larus marinus*) was the index case for H5N1
103 2.3.4.4b in North America (Caliendo et al. 2022). During the following spring, mass mortalities
104 involving thousands of wild birds were reported across eastern Canada, with the HPAI virus
105 implicated as the cause.

106 Wildlife diseases that cause unusual levels of mortality or reduced fitness can exacerbate
107 population declines when they interact with the cumulative effects of other natural and
108 anthropogenic stressors which face marine birds (Phillips et al. 2023). Information on the scope
109 and scale of unusual mass mortality events are needed to facilitate the assessment of population-
110 level impacts, and support conservation and management decisions (e.g., species status

111 assessments, harvest management), as well as being an important complement to pathogen
112 surveillance programs that track the epidemiology of a disease and the evolution of the pathogen.
113 However, robust assessments of mortality can be challenging to conduct, especially over vast
114 areas. During large-scale mortality events, several types of surveys are employed to estimate the
115 number of affected birds, along with monitoring the temporal and geographic scope of the
116 emergency. For coastal species, beached bird surveys are typically conducted to estimate the
117 number of birds affected by oiling and disease (e.g., Camphuysen 1998, Haney et al. 2014).
118 Aerial (O’Hara et al. 2009) and boat-based surveys (Murphy et al. 1997) are also employed
119 during environmental emergencies to estimate wildlife mortality and population impacts.

120 In this study, we provide the first comprehensive collation and assessment of wild bird
121 mortality in eastern Canada during April - September 2022 following the fall 2021 incursion of
122 H5N1 2.3.4.4b into eastern North America. Due to the unprecedented magnitude and geographic
123 scale of the mortality, conducting systematic beached bird surveys to assess mortality was
124 logistically infeasible. Instead, we combined data from federal, Indigenous, provincial, and
125 municipal governments, the Canadian Wildlife Health Cooperative, non-governmental
126 organizations, universities, citizen science platforms, and reports from the public to estimate the
127 minimum number of birds of various species that died during this disease outbreak. In addition,
128 we present an analytical approach for dealing with double-counted birds to address observations
129 of mortalities which may have been reported by two or more different sources. With this
130 corrected data set, we describe the magnitude of the unusual mass mortality event in terms of its
131 spatial extent, duration, and the diversity and number of reported sick and dead birds. In addition
132 to presenting mortality estimates, by comparing mortality numbers to population sizes and trends
133 we make an initial assessment of whether population-level impacts are possible for three
134 prioritized species: Northern Gannet (*Morus bassanus*, which suffered significant mortality
135 globally (Lane et al. 2023), and two harvested species, American Common Eider (*Somateria*
136 *mollissima dresseri*) and Common Murre (*Uria aalge*), to support harvest management
137 decisions.

138

139 **Methods**

140 ***Study area and data sources***

141 We defined eastern Canada as the provinces of Québec (QC), New Brunswick (NB), Nova
142 Scotia (NS), Prince Edward Island (PEI), and Newfoundland and Labrador (NL), and we defined
143 our study period as 01-April-2022 to 30-September-2022 to capture the period of greatest
144 mortality. To generate the best available estimate of reported wild bird mortality linked with
145 HPAI during the study period, we collated reports of sick and dead birds on land, on the water,
146 and on breeding colonies. Information on recovery rates for wild birds is limited. We assume that
147 birds reported as sick (i.e., with clinical signs consistent with HPAI infection including tremors,
148 lack of coordination, or lack of energy or movement) succumb to infection (Roberts et al. 2023).
149 Hereafter, both sick and dead birds are referred to as mortalities.

150 Reports of mortalities on land and water were collated from numerous sources including
151 federal, provincial, Indigenous, and municipal government staff and databases, the Canadian
152 Wildlife Health Cooperative and other NGOs, academic researchers, and two citizen science
153 platforms (iNaturalist and eBird; see Appendix S1 for methods on extracting and processing
154 mortality data). Observations of wild bird mortalities on seabird colonies visited by government
155 biologists and academic researchers were obtained through direct solicitation. The reports
156 included incidental observations made on any seabird colony, and standardized surveys that were
157 conducted by boat, foot, or air. Unless reported mortalities were explicitly stated as having
158 occurred on a colony, they were not classified as colony mortalities. All mortality data are
159 provided in the online repository (Data S1).

160 Each record included the species, date, number of mortalities, location information (i.e.,
161 site name or coordinates), observer information (name and contact information), and information
162 source. We anonymized observer information in the published dataset. When species
163 assignments were not provided, less specific taxonomic assignments were used (e.g., unknown
164 gull, unknown bird). Taxonomic identification for iNaturalist reports was verified where the
165 quality of the species identification was rated as ‘needs_id’ by the submitter. When site names
166 were provided instead of coordinates, coordinates were obtained using the GoogleMaps API in R
167 version 4.2.2 (R Core Team 2023). A subset of coordinates and site names were reviewed by
168 regional experts to confirm the validity of this approach. To provide broad estimates for species

169 groups, we classified species as either: seabirds, waterfowl, waders, shorebirds, loons, landbirds,
170 or raptors. Age or breeding status was recorded when available. To assess how age class may be
171 differentially represented in the mortality events, photos of Northern Gannets submitted to
172 iNaturalist (557) were reviewed and the age class of birds was classified as adult, subadult, hatch
173 year (HY), or unidentifiable. Similarly, photos of Common Murres were reviewed (61) and birds
174 were classified as HY, after hatch year (AHY), or unidentifiable. We assumed that the age
175 structure of birds in these photos reflects the age structure of birds reported off colonies.
176 Mortalities of adult birds on colonies were assumed to be breeding adults unless there was
177 evidence to the contrary.

178

179 ***Prioritized species***

180 Environment and Climate Change Canada (ECCC), the federal wildlife management agency
181 responsible for the conservation of migratory birds, prioritized three species based on a need for
182 information to support conservation and harvest management decisions in 2022. Details about
183 colony surveys in 2022 for Common Eiders, Northern Gannets, and Common Murres are
184 summarized below and shared in the online data repository (Data S2, Data S3, Data S4,
185 respectively).

186

187 ***Common Eiders***

188 Eastern Canada is the core of the breeding range for American Common Eiders (Beuth et al.
189 2016, Lamb et al. 2019, Gutowsky et al. 2023), hosting 85% of the global breeding population in
190 three subpopulations: QC North Shore and NL (60% of breeding birds), QC St. Lawrence
191 Estuary (20% of breeding birds) and NB & NS (5% of breeding birds; C. Lepage, pers. comm.).
192 The cryptic brown females of this species are wholly responsible for raising chicks, and nest in
193 colonies on hundreds of islands across the region. In the St. Lawrence Estuary of QC, the largest
194 breeding colony (Île Bicquette) has been declining for the last two decades (Lepage 2019). Other
195 colonies in the St. Lawrence Estuary are stable or increasing (i.e., Île aux Pommes, Île Blanche,
196 Île aux Fraises, Île aux Oeufs, Îles du Pot, and Île Laval; Giroux et al. 2021), as are the eider
197 populations on the QC North Shore (Rail 2021b). Elsewhere in eastern Canada, populations have

198 been declining (Giroux et al. 2021, Noel et al. 2021). Colonies in the St. Lawrence Estuary
199 currently support recreational harvests in the USA and Canada (Rothe et al. 2015), and are the
200 subject of down collection (Joint Working Group on the Management of the Common Eider
201 2004). An assessment of mortality and potential population impacts for this species was
202 prioritized to support harvest management decisions.

203 To the extent possible, Common Eider colonies were surveyed by air or on foot
204 throughout eastern Canada (Data S2). In QC, this included surveys on foot of the three largest
205 colonies in the St. Lawrence Estuary, by down harvesters between May 29 and May 31 (Île
206 Bicquette, Île aux Pommes, Île Blanche). Twelve colonies along the North Shore of the Gulf of
207 St. Lawrence were surveyed on foot by ECCC, between May 29 and June 22, as part of the
208 quinquennial colonial seabird monitoring program, which includes nine migratory bird
209 sanctuaries. In NB, Machias Seal Island was partially surveyed weekly from mid-May to mid-
210 August, and only one dead juvenile Common Eider was found. An additional six colonies were
211 incidentally surveyed in the Wolves and the Grand Manan Archipelagos by ECCC staff between
212 May 31 and June 5, 2022. Six colonies along the northern peninsula of the island of
213 Newfoundland (NF) were partially or incidentally surveyed on foot and by boat by ECCC staff
214 between May 14 and June 7. In Labrador, nine colonies along the south coast were incidentally
215 surveyed by air (helicopter) and on foot between June 6 and July 12, 2022. For NS, two colonies
216 (John's Island and Grey's Island in southwest NS) were incidentally surveyed by boat and on
217 foot by ECCC staff between April 30 and May 1, 2022. Complete aerial (helicopter) surveys of
218 18 other NS colonies were conducted by the Nova Scotia Department of Natural Resources and
219 Renewables staff on June 21, 2022. No known colonies exist in PEI.

220

221 *Northern Gannets*

222 Canada hosts the entire North American breeding population of Northern Gannets (213,704
223 breeding birds; Data: Table S2), which represented 13% of the global population as of the latest
224 assessment (Mowbray 2020). Northern Gannets are long-lived seabird species that breed in
225 dense colonies at three colonies in QC (Île Bonaventure, Rochers aux Oiseaux, Île d'Anticosti)
226 and three colonies in NF (Funk Island, Baccalieu Island, Cape St. Mary's Data: Table S2).
227 Breeding populations at the five largest sites have increased dramatically since 1970 and are

228 currently considered to be stable or increasing (i.e., from 2010-2020; d'Entremont et al. 2022, S.
229 Wilhelm, pers. comm.).

230 In July and September 2022, ECCC flew aerial surveys of the two largest Northern
231 Gannet colonies in QC (Île Bonaventure and Rochers aux Oiseaux) and all three Northern
232 Gannet colonies in NF (Data S3). Aerial photographs were digitized following standardized
233 procedures (Chardine et al. 2013, Rail et al. 2014). The number of Apparently Occupied Sites
234 (AOS) and dead gannets were enumerated, in a complete survey of these colonies. Île d'Anticosti
235 in QC has a very small population (192 breeding birds in 2019) and was not surveyed (J.-F. Rail,
236 pers. comm.). In addition, complete surveys of 3 plots on Île Bonaventure were performed
237 between July 11 and September 30, 2022. Both the colony at Île Bonaventure, and at Cape St.
238 Mary's are within provincial protected areas that are staffed during the summer months.

239

240 *Common Murres*

241 There are approximately 1.75 million Common Murre breeding in eastern Canada (Ainley et al.
242 2021). The majority breed in NF (1.5 million breeding birds), with smaller breeding populations
243 in QC (191,500 breeding birds) and Labrador (76,228 breeding birds). The breeding population
244 in NF and QC represent 19% of the North American population and ~10% of the global
245 population (Ainley et al., 2021). Common Murre breed in colonies at 68 sites in eastern Canada,
246 including 39 sites in QC, 12 sites in NF, 15 in Labrador, and 2 sites in NB. Eight of these
247 colonies are considered large (>20,000 breeding birds): three are in QC (Île Bonaventure,
248 Rochers aux Oiseaux, Sainte-Marie Island), four are in NF (Funk Island, Green Island, Cape St
249 Mary's, South Cabot Island), and one is in Labrador (Gannet Islands). Common Murre are one of
250 only two regulated harvested non-waterfowl marine species in Canada, and this species was
251 prioritized for this assessment to support harvest management decisions.

252 In June 2022, the two small colonies at Machias Seal Island (NB) and Île à Calculot des
253 Betchouanes (QC) colonies were completely surveyed on foot. An additional nine colonies were
254 incidentally surveyed for evidence of mass mortality (Data S4). In July and September 2022, the
255 colonies on Île Bonaventure, Rochers aux Oiseaux, Baccalieu Island and Funk Island were
256 surveyed during aerial surveys of adjacent Northern Gannet colonies. Baccalieu Island was also
257 incidentally surveyed on foot in August. In July, Gull Island and South Cabot Island were

258 surveyed by boat and by helicopter, respectively. The colony at Cape St. Mary's was surveyed
259 by boat and helicopter in July and by boat in September. In July, Great Island and Gull Island in
260 Witless Bay Ecological Reserve (NL) were incidentally surveyed by boat.

261

262 ***Attributing mortality to HPAIV***

263 A subset of sick and dead wild birds was tested for the HPAI H5N1 clade 2.3.4.4b virus in
264 eastern Canada between April 1 and September 30, 2022, as part of Canada's Interagency
265 Surveillance Program for Avian Influenza Viruses in Wild Birds ($n = 96$ species; Giacinti et al.
266 2023). Given that our objective was to quantify mortality for the purpose of supporting
267 evaluations of population-level effects and that no other notable sources of mortality were
268 reported for this period (M. Jones, pers comm.), we assumed that HPAI was a likely cause of
269 mortality for any species that tested positive for HPAI virus in sick and dead birds within our
270 study region during our study period. For a description of the epidemiology of the HPAI
271 outbreak in wild birds in Canada, including spatiotemporal dynamics, host taxonomic
272 representation and viral genetic diversity see Giacinti et al., 2023.

273 For records where the species was unknown (e.g., unknown gulls), we presumed that
274 mortalities were caused by the HPAI virus if $\geq 50\%$ of the species within that group tested
275 positive for the virus. For example, a bird identified as an "Unknown Gull" was likely one of any
276 of the following species common in the study area: Herring Gull (*Larus argentatus*), Great
277 Black-backed Gull, Ring-billed Gull (*Larus delawarensis*), Glaucous Gull (*Larus hyperboreus*),
278 or Iceland Gull (*Larus glaucopterus*). We checked if most of these species had tested positive for
279 HPAI virus at some point within the study area and study period, and if yes, we presumed that
280 mortalities of unknown gulls were linked to HPAI (Giacinti et al. 2023). We did not presume
281 records identified only as 'Unknown Bird' were positive, and so mortalities for unknown birds
282 were excluded from the HPAI mortality dataset, along with individuals that had a cause of death
283 reported that could not be linked to HPAI and individual birds that tested negative for HPAI
284 virus.

285

286 **Scenario analysis to identify double counted mortalities**

287 Reported mortalities are subject to inflation when the same bird is reported by multiple
288 observers, to multiple sources, or both (i.e., double counts). We presumed that when our dataset
289 included records of a given species reported at similar times and places, this may indicate that an
290 observation was captured in our dataset more than once. To identify records in the HPAI
291 mortality dataset that could be considered observations of the same birds, we undertook a
292 comparative analysis to examine how the number of reported mortalities, that could be
293 considered double-counted, would change under six scenarios that explore a range of spatial and
294 temporal overlap (Table 1).

295 Specifically, the double count scenario analysis removes records from the complete
296 mortality dataset as a function of the number of days between observations (± 0 days, ± 1 day, ± 5
297 days), and the distance between observations (± 1 km, ± 5 km). The baseline scenario is the total
298 reported HPAI-linked mortality with no records excluded and assumes no double counting. More
299 precisely, each mortality record $a_{i,j}$ was coupled with another mortality record $a_{i \neq i,j}$, where i was
300 a unique identifier for the record and j was the species. The distances (km) and the number of
301 days between paired records were calculated and if the scenario conditions were met (e.g., for
302 Scenario A, record $a_{i,j}$ fell within 1 km and 0 days of record $a_{i \neq i,j}$), the records were considered
303 to be double counts. For each pair of records considered double counts, the record with the larger
304 number of total observed birds was retained, and the other record was excluded. All retained
305 records were iteratively re-submitted for consideration (i.e., coupled with another record within
306 the dataset) until all records that met the scenario conditions were considered, and only records
307 that did not meet the scenario conditions (i.e., non-double counts) and double counts with the
308 highest number of total observed birds remained. Both records in a pair were retained only if the
309 reports were made by the same observer to the same source. This exception reduced the mistake
310 of excluding reports made in close proximity, as is typical during beached bird surveys.

311 We assumed taxonomic identifications were accurate, and reports were only considered
312 as possible double counts if the species' name matched. However, we acknowledge that some
313 observers may have mistakenly identified one species as another (e.g., a Great Black-backed
314 Gull for a Herring Gull). To address this possibility in the double count analysis, we treated
315 reports of cormorants, gulls, and terns as interchangeable regardless of the species or taxonomic

316 resolution (Appendix S2: Table S1). For example, paired reports of Arctic Tern (*Sterna*
317 *paradisaea*), Common Tern (*Sterna hirundo*), and Unknown Tern were considered potential
318 double counts if they met the criteria. We did not perform the double count analysis on reports
319 that had other non-specific taxonomic assignments (e.g., unknown alcid) because it was not
320 reasonable to consider them to be interchangeable.

321 To arrive at a double-count corrected estimate of total reported HPAI-linked mortality for
322 each scenario, we discarded records identified as double counts and added all recorded
323 mortalities for species with less-specific taxonomic status (except for the cormorants, gulls, and
324 terns) if those unknown species were presumed to be positive for HPAI. We compared the total
325 reported HPAI-linked mortality from the various scenarios to the total reported HPAI-linked
326 mortality with no records excluded. To present spatiotemporal patterns and species-specific
327 information about mortality, we used a double-count corrected estimate. based on consultation
328 with experts who have experience with similar datasets and research questions. to choose the
329 scenario which best represented a reasonable compromise between excluding double counts and
330 retaining unique records.

331

332 *Species-specific mortality estimates*

333 We calculated species-specific mortality estimates after removing records unrelated to HPAI and
334 removing double counts based on the chosen scenario. Mortality estimates were calculated by
335 summing all records for a particular species. For the three prioritized species (Common Eider,
336 Northern Gannet, Common Murre), we present a more comprehensive spatiotemporal analysis of
337 mortality events in the study area, with specific dates and events highlighted. The summed
338 mortality numbers presented are minimum estimates, as we did not correct for birds that died that
339 went unrecorded (e.g., areas not surveyed, birds not detected, birds not reported, birds lost at
340 sea).

341

342 **Results**

343 ***Reported mortalities***

344 In total, 48,042 wild bird mortalities were reported in eastern Canada between April 1 and
345 September 30, 2022 (Data S1). This complete dataset of reported mortality includes 142 species,
346 as well as 23 less specific taxonomic assignments. Most of the mortality data were provided by
347 governmental bodies. Notably federal staff from ECCC (28.3%), the Provincial wildlife
348 management and natural resources departments of QC, NS, NB, PEI, and NL (18.6%), and
349 municipal governments (10.8%) contributed to a substantial number of the reported mortalities.
350 Mortality data were also reported by Parks Canada (2.0%), Fisheries and Oceans Canada (1.8%),
351 and Indigenous governments in Labrador (Nunatsiavut Government, NunatuKavut Community
352 Council) and the island of Newfoundland (Miawpukek First Nation and Qalipu First Nation)
353 (0.04%). Non-governmental organizations, including the Canadian Wildlife Health Cooperative,
354 contributed 7.7% of the reported mortalities, while academia provided 17.6%. The reports of
355 citizen scientists made to iNaturalist and eBird contributed 0.9% and 0.8% of reported
356 mortalities, respectively. The remaining 11.5% of reported mortalities were made by members of
357 the public directly to ECCC.

358

359 ***Scenario analysis***

360 After removing records for 3,321 mortalities that could not be attributed to HPAI, our baseline
361 HPAI mortality dataset includes 44,721 wild bird mortalities (Table 1). Across the scenarios,
362 5.4% to 12.4% of reported mortalities were identified as potential double counts (Table 1). In the
363 most restrictive scenario (Scenario A, ± 0 day, ± 1 km), 2,427 birds were identified as potential
364 double-counts, and 5,545 birds were identified in the least restrictive scenario (Scenario E, ± 5
365 day, ± 5 km; Table 1). A comparison of scenario results indicates that the closeness in time
366 criteria had a larger influence on the number of birds identified as double counts than the
367 distance criteria. The two scenarios that used the ± 5 day criteria (i.e., Scenarios C and E)
368 identified the highest percentage of birds as double counts (11.1%, and 12.4%, respectively). The
369 two scenarios that used the ± 0 day criteria (i.e., Scenario A and D) identified the smallest
370 percentage of birds as double counts (5.4% and 7.4%, respectively). Scenarios B (± 1 day, ± 1

371 km) and F (± 1 day, ± 5 km) were closest to the median percentage of records identified as double
372 counts.

373 We felt that Scenario B most likely represents the true reported mortality (Table 1)
374 because it balances accounting for introduced errors associated with our georeferencing of site
375 names and not excluding new birds that may come ashore each day. Values presented in the
376 remainder of the paper reflect Scenario B results. In Scenario B, most records identified as
377 double counts occurred in NL (51.4%), NS (28.1%), and QC (15.7%), with smaller double
378 counts occurring in the other provinces (Appendix S2: Figure S1). Most double counts were
379 reports of Northern Gannets (58.9% of reports, representing 2,213 birds) and Common Murres
380 (25.5% of reports, representing 959 birds).

381

382 *Spatial, temporal, and taxonomic patterns of mortality*

383 Accounting for double counts we estimate 40,966 individual birds of 45 species were reported in
384 eastern Canada between April 1 and September 30, 2022 (i.e., Scenario B; ± 1 km, ± 1 day, Table
385 1). The first large wave started in May when mass mortalities were first detected among
386 Common Eiders in the St. Lawrence Estuary, followed by mass mortalities of Northern Gannets
387 and other species (e.g., gulls, cormorants, alcids) in the southern Gulf of St. Lawrence. This
388 mortality event continued until mid-September. A second large wave of mortality began in June
389 in eastern Newfoundland, with reports of Northern Gannets, Common Murres and other species
390 starting in the southeast (e.g., Burin and Avalon Peninsulas) and later along the eastern and
391 northeastern Newfoundland coasts. Mortalities continued to be reported until mid-September.
392 The high numbers of colony mortalities for Northern Gannets reported the week of July 11 and
393 September 12 reflect a reporting lag, as periodic aerial surveys of colonies provide a snapshot of
394 mortalities during prior weeks. Reports of mortality along QC's North Shore, southwestern
395 Newfoundland, and in Labrador were limited.

396 Seabirds and sea ducks accounted for 98.7% (40,438) of reported mortality, with much
397 smaller numbers of waterfowl (282, 0.7%), landbirds (133, 0.3%), raptors (97, 0.2%), and
398 waders (16, 0.04%). Among seabirds, Northern Gannets accounted for 63.9% of all reported
399 mortality (26,193). A significant proportion of reported mortalities were Common Murres
400 (8,133, 19.9%), with smaller numbers of gulls (2,326, 5.7%), Common Eiders (1,945, 4.8%),

401 cormorants (981, 2.4%), Atlantic Puffins (*Fratercula arctica*, 282, 0.7%), Black-legged
402 Kittiwakes (*Rissa tridactyla*, 251, 0.6%), Razorbills (*Alca torda*, 119, 0.3%), and terns reported
403 (74, 0.2%). Among waterfowl, land birds, raptors and waders, the most reported species were
404 Canada Goose (*Branta canadensis*, 107, 0.3%), American Crow (*Corvus brachyrhynchos*, 99,
405 0.2%), Bald Eagle (*Haliaeetus leucocephalus*, 43, 0.1%), and Great Blue Heron (*Ardea herodias*,
406 15, 0.04%).

407 Approximately 45% of reported bird mortalities were observed on seabird colonies, and
408 the remaining 55% of mortalities were reported elsewhere, on land and water. On-colony
409 mortalities were dominated by Northern Gannets in QC (9,177) and the island of Newfoundland
410 (4,899), with smaller mortalities of other species being reported on colonies in NB (963) and NS
411 (643; Figure 1B). The largest numbers of bird mortalities were reported on land and water in NL
412 (8,738 birds, including 100 birds in Labrador), although significant mortalities were also
413 reported in QC (7,076), NB (4,461), and NS (1,522). Fewer than one thousand wild bird
414 mortalities were reported on PEI (915).

415

416 *Summaries for prioritized species*

417 Accounting for double counts (i.e., Scenarios B (± 1 day, ± 1 km) and F (± 1 day, ± 5 km)),
418 Northern Gannets, Common Murres, and Common Eiders suffered mass mortality during the
419 HPAI outbreak, and we provide an overview of the spatiotemporal distribution of the mortalities
420 for these species. Similar information for gulls, cormorants, Atlantic Puffins, Black-legged
421 Kittiwakes, Razorbills, and terns is provided in Appendix S3.

422

423 *Common Eiders*

424 In total, 1,945 Common Eider mortalities were reported in eastern Canada during our study
425 period (Figure 2A). Most were breeding females observed at three colonies in the St. Lawrence
426 Estuary: Île Bicquette (610), Île aux Pommes (503) and Île Blanche (222). These mortalities
427 were reported during regular down harvesting operations (when complete surveys of the colonies
428 are carried out) in May and beginning of June, and as result of follow-up partial surveys at the
429 end of June.

430 HPAI-linked mortality was also reported at several other smaller Common Eider colonies
431 in the St. Lawrence Estuary: Île aux Fraises (66), Île Le Gros Pot (44), and Île Le Pot du Phare
432 (3). Unusual mortality was also reported at Île La Razade d'en Bas (67), Île La Razade d'en Haut
433 (10), Île aux Lièvres (53), and Île aux Basques (30). Other known eider breeding colonies in QC,
434 NB, and NL were surveyed in May and June with no unusual mortality being detected. In June,
435 known breeding islands in NS were visited and no dead eiders were observed. Few HPAI-linked
436 mortalities of eiders were reported off-colonies in eastern Canada (139 in QC, 21 in NS, 13 in
437 NB, 5 in NL (of which 2 were on the island and 3 in Labrador) and none reported in PEI).

438

439 *Northern Gannets*

440 During our study period, 26,193 Northern Gannets mortalities were reported in eastern Canada
441 (Figure 2B). Approximately half the mortalities were reported on the five gannet colonies that
442 were surveyed (14,091), and half were reported on beaches and on the water (12,102). The
443 mortality occurred in two waves: the first was reported in the Gulf of St. Lawrence in QC in May
444 and involved at least 19,695 gannets. Approximately a month later, in June, mass mortality was
445 detected in eastern Newfoundland involving at least 6,498 gannets. Both mortality events lasted
446 until mid-September.

447 Out of 557 images of individual dead gannets submitted with iNaturalist reports, 92.8%
448 were identified as adults. Another 3.2% were categorized as subadults based on the presence of
449 black secondaries or tail feathers and it was not possible to identify the age of birds in the
450 remaining 4% of images. Consequently, we assume that 11,231 out of 12,102 dead gannets
451 reported off colonies were adults, and many would be expected to be breeding individuals.

452 The dominant source of the first wave of mortality is inferred to be the Rochers aux
453 Oiseaux colony north of Îles-de-la-Madeleine in QC, based on the large number of carcasses
454 observed on nearby beaches (4,065). Rochers aux Oiseaux is a remote colony in the middle of
455 the Gulf of St. Lawrence and hosts 25% of Canada's population of breeding gannets (~52,000
456 breeding birds; Mowbray 2020, Rail 2021a). The earliest documentation of an outbreak and mass
457 mortality at this colony was from Transport Canada's National Aerial Surveillance Program on
458 June 27, and subsequent aerial population surveys on July 11 detected a total of 5,119 dead

459 adults. Dead gannets were not counted during the September aerial survey to avoid double
460 counts, as it was difficult to distinguish between old and new carcasses.

461 To the west, at the Île Bonaventure colony, which hosts 50% of Canada's breeding
462 gannets (~104,000 breeding birds; Rail 2021a), mortality was also reported (3,609). Île
463 Bonaventure is closely monitored and the first on-colony report of mortality was made on May
464 24, 2022, by an employee of Parc National de l'Île-Bonaventure-et-du-Rocher-Percé (J.-L.
465 Legault, pers. comm.). A subset of these birds tested positive for HPAI virus (Giacinti et al.
466 2023). In addition to quantifying dead birds observed in the July 11 aerial population surveys,
467 dead birds in three study plots were enumerated weekly between June 18 and October 10. The
468 mortality rate in study plots peaked between July 29 and September 10, but continued until the
469 Park closed October 10, 2022 (Seyer et al., in prep.). Only mortalities reported in plots after July
470 11 are included in the mortality tally for this colony, to avoid double counting carcasses
471 enumerated from aerial photographs. Direct counting of dead gannets indicated a smaller
472 proportion of the Île Bonaventure breeding population died of HPAI (minimum of 3.5% colony
473 mortality) than at Rochers aux Oiseaux (minimum of 9.8% colony mortality), although effort
474 was unequal and the complete colony survey at Île Bonaventure preceded the peak of the
475 mortality event.

476 The second wave of mortalities reports started in southeastern Newfoundland in early
477 June and lasted until the second week of September. Outbreaks were detected at all three
478 colonies in this region, which together host 25% of Canada's population of breeding gannets
479 (Cape St. Mary's ~30,000 breeding birds; Funk Island ~22,000 breeding birds; Baccalieu Island
480 ~7,000 breeding birds; S. Wilhelm et al., in prep.). The first mortality to test positive for HPAI
481 near a colony was a subadult found by a fisherman within 1km of Cape St. Mary's on June 5,
482 2022 (E. White, pers. comm.). The first mortalities among breeding birds were first recorded by
483 employees at Cape St. Mary's Ecological Reserve on July 16th, 2022 (C. Mooney, pers. comm.).
484 Additional mortalities were observed at this site until the onset of fledging on September 9.
485 Population surveys at Cape St. Mary's colony detected 1,551 mortalities (at least 5.2% colony
486 mortality) and 1,050 dead birds reported on the southeastern coastline of Newfoundland likely
487 originated from this population.

488 The colonies at Funk and Baccalieu are remote, and the status of outbreaks was only
489 evaluated during aerial surveys. The first aerial surveys of the Funk and Baccalieu colonies on
490 July 27 and July 24, respectively found only a limited number (149, 13 respectively) of dead
491 individuals on these colonies; however later flights in September (September 15, Funk and
492 September 14, Baccalieu) revealed a much larger-scale die-off. This suggests an outbreak
493 occurred some time between late July and mid-September. At the Funk Island colony, 3,158
494 mortalities were observed (at least 14.4% colony mortality), while at the smaller Baccalieu
495 Island colony, 28 mortalities were observed (at least 0.4% colony mortality). The 545 birds
496 reported along the northeast and eastern shores of Newfoundland likely originated from these
497 colonies.

498

499 *Common Murres*

500 Across eastern Canada, 8,133 Common Murre mortalities were reported (Figure 2C). The
501 mortality event for Common Murres followed generally the same pattern as Northern Gannets,
502 with HPAI-linked mortality being reported first in the Gulf of St. Lawrence in QC (2,422),
503 followed by an outbreak in eastern Newfoundland (5,708). The larger mortality event on the
504 island of Newfoundland is consistent with the larger population (~1.5 million breeding birds)
505 compared to the Gulf of St. Lawrence (191,500 breeding birds; Ainley et al. 2021). Most of the
506 61 images of Common Murres associated with iNaturalist mortality reports were AHY (86.9%).
507 Only 3.3% were HY birds (i.e., post-fledge chicks), and 9.8% of images were unidentifiable.
508 Consequently, we assume that 7,049 of the 8,112 dead Common Murres reported off colonies
509 were adults (86.9%) and may have been breeding individuals at a minimum.

510 In the Gulf of St. Lawrence, mortalities started in late May and lasted until mid-August,
511 with most being reported between June 20 and July 20 on beaches of Îles-de-la-Madeleine.
512 These birds likely originated from colonies in Îles-de-la-Madeleine including Rochers aux
513 Oiseaux, which host ~54,000 breeding murres (Ainley et al. 2021). Smaller numbers were
514 reported on the Gaspé Peninsula and in northern NB, near a large murre colony at Île
515 Bonaventure (~80,000 breeding murres; Ainley et al. 2021). Although an estimated ~50,000
516 murres breed at colonies in this area, no mortalities were observed at either murre colony and
517 few murres were reported on the QC North Shore of the Gulf of St. Lawrence.

518 A second, larger wave of reported mortalities event started approximately a month later,
519 in late June, on the island of Newfoundland. Initial reports of mortalities came from the Burin
520 Peninsula and Avalon Peninsula in southeastern Newfoundland. These birds likely originated
521 from the colonies in the Cape St. Mary's and Witless Bay Ecological Reserves, which together
522 host ~540,000 breeding murres (Ainley et al. 2021). By August 2022, the outbreak progressed
523 northwards, with birds reported on the Bonavista Peninsula and Bonavista Bay. At least some of
524 these birds likely originated from South Cabot Island (~ 20,000 breeding birds), based on the
525 recovery of at least one bird off the northwest coast of Bonavista Bay that was banded as a chick
526 on South Cabot Island in 2018. This bird was recovered dead on Ship Island (49.0642, -53.5693)
527 on 4 August 2022, and subsequently tested positive for the HPAI virus (Giacinti et al. 2023).
528 Few murre mortalities were reported in southern Labrador (7).

529 No mass mortality was observed at any of the Common Murre colonies that were
530 surveyed. Only 0.3% of reported mortalities were in colonies (21). This includes small numbers
531 of mortalities (≤ 10) observed at Cape St Mary's, and the Great and Gull Island colonies in the
532 Witless Bay Seabird Ecological Reserve

533

534 **Discussion**

535 The HPAI H5N1 2.3.4.4b virus is now considered the cause of the largest avian panzootic to
536 date, based on the number of dead birds, species affected, and the number and geographic spread
537 of outbreaks (Klaassen and Wille 2023). Our study provides the first comprehensive assessment
538 of reported wild bird mortalities in eastern Canada during the mass mortality caused by the HPAI
539 H5N1 2.3.4.4b virus between April and September of 2022. To establish a minimum estimate,
540 we collated data from multiple sources in a comprehensive effort to understand regional
541 spatiotemporal and taxonomic patterns of mortality both on and off seabird colonies. We
542 presented a scenario-based method for identifying and excluding observations that were
543 potentially reported more than once by different observers or sources (i.e. double counted).

544 After the double-counts analysis, we conclude that the HPAI virus is linked to the deaths
545 of at least 40,966 wild birds between April 1 and September 30, 2022. Mass mortality was
546 restricted to the eastern Canadian provinces of QC, NB, PEI, NS, and insular NF. Limited
547 mortality was reported in Labrador. Experts indicated no wild bird mortalities on this scale (i.e.,

548 in the thousands) were reported during the study period on the eastern coast of the USA (Atlantic
549 Marine Bird Cooperative, Community Science and Marine Bird Health Working Group, pers.
550 comm.). To our knowledge, in North America, there has been no recorded infectious disease that
551 has caused a comparable level of mortality across such a diverse range of bird species. The
552 mortality reported here far exceeds mortalities associated with the 2014-15 outbreak of HPAI in
553 waterfowl in the prairies (Canadian Food Inspection Agency 2016a, 2016b), or avian cholera
554 outbreaks in prairie waterfowl (1977; Wobster et al. 1979), Arctic seaduck colonies (mid-2000s;
555 Iverson et al. 2016), or Alaskan seabirds (2013; Bodenstein et al. 2015), although larger
556 mortality events caused by marine heat waves have been reported (e.g., Piatt et al. 2020). In our
557 study, we found that between 5.4% and 12.4% of reported mortalities may have been reported by
558 more than one individual or source, highlighting the importance of accounting for double-counts
559 during large scale data collation exercises. Our approach for handling double-counted mortalities
560 could be applied to support the assessment of mortality in any case where information from
561 multiple sources are used.

562 In our study, Northern Gannets, Common Murres and Common Eiders suffered the
563 greatest mortalities, followed by gulls, cormorants, Atlantic Puffins, Black-Legged Kittiwakes,
564 Razorbills, and terns. Importantly, mortality estimates from scenarios that remove possible
565 double counts may be more accurate than the baseline scenario, but they still fall short of
566 capturing the complete picture because not all dead birds are reported. Below, we discuss the
567 potential for population-level impacts for the three prioritized species: Common Eiders, Northern
568 Gannets and Common Murres. Given the size of the breeding populations for these species in
569 eastern Canada relative to the number of mortalities reported, population-level impacts are
570 certainly possible and even likely for Northern Gannets throughout their whole Canadian range,
571 and for regional populations of Common Eiders, but are not likely for Common Murres.

572

573 *Common Eiders*

574 A notable event occurred in the St. Lawrence Estuary in QC, where mass mortalities were
575 observed, affecting the colonies at Île aux Pommes, Île Bicquette, and Île Blanche. These three
576 colonies represent 58% of the breeding population in the St. Lawrence Estuary and 11% of the
577 breeding population of Common Eiders in Canada, and the USA (Lepage 2019; C. Lepage, pers.

578 comm.). When compared their colony size in the previous summer (2021; 4619, 3263, and 3155,
579 breeding pairs (C. Lepage pers. comm.)), the HPAI outbreak resulted in 13.2%, 16.1%, and 6.8%
580 mortality, respectively. Cumulatively, the reported mortality at these three islands represents a
581 12.1% loss of breeding females from these three sites during early incubation. As a result of the
582 mortality event, we expected the number of young birds produced to have been particularly low
583 in 2022 and the population to be lower in the coming years.

584 Given that breeding colonies in the St. Lawrence Estuary support recreational harvests
585 and the collection of eider down, this species was prioritized to support harvest management
586 decisions. After considering the potential population level impacts of HPAI-linked mortality,
587 population trends, and harvest pressures, ECCC's Canadian Wildlife Service – the agency
588 responsible for hunting regulations in Canada under the Migratory Bird Act - recommended "*a
589 voluntary reduction in eider harvest for the 2022-2023 season and that hunters refrain from
590 harvesting female common eider or young*" (Environment and Climate Change Canada 2022).
591 Changes to the migratory bird hunting regulations, to reduce the impact of the harvest on the
592 Common Eider population in QC, was not possible given the short period of time between the
593 assessment of the mortalities on colonies and the date of the hunting season opening. Therefore,
594 awareness and cooperation of hunters was deemed likely sufficient to mitigate the risk of an
595 excessive decline in this population. ECCC also reached out to the different U.S. States agencies
596 that manage Common Eider hunting (e.g., Maine Department of Inland Fisheries & Wildlife,
597 Massachusetts Division of Fisheries & Wildlife) to relay this message about voluntary restriction
598 to local hunters (C. Lepage, pers. comm.). Ongoing annual nest monitoring at eider colonies in
599 the St. Lawrence Estuary will support the assessment of the long-term impacts of HPAI mortality
600 on these populations.

601 Outside of the St. Lawrence Estuary, no other major mortality events were reported in
602 colonies across the North Shore of QC, in NS, NB, and NL. Although these colonies were only
603 incidentally surveyed and fewer than 178 dead Common Eiders were reported off colonies across
604 eastern Canada, we are reasonably confident that no mass mortality events occurred outside the
605 St. Lawrence Estuary. This is fortunate because the NB and NS subpopulation is declining for
606 reasons that are not fully understood (Milton et al. 2016, Giroux et al. 2021, Noel et al. 2021). It
607 is worth noting that Common Eider mortalities were also reported in Maine (10), Massachusetts

608 (19), and New Hampshire (1), and subsequently tested positive, between June 24, 2022, and July
609 25, 2022, (USDA 2023) but no mass mortality events at colonies have been reported (C. Lepage,
610 pers. comm.).

611

612 *Northern Gannets*

613 HPAI-linked mortality was observed at all five of the surveyed colonies. The second and fourth
614 largest colonies, Rocher aux Oiseaux and Funk Island, appear to have suffered massive
615 outbreaks, while the outbreak at Île Bonaventure was less dramatic but may have lasted longer.
616 As large white birds with well-defined territories, gannets are among the easiest to enumerate
617 from aerial surveys (Chardine et al. 2013), and yet it was still challenging to differentiate
618 between old and new carcasses during the two aerial surveys of QC gannet colonies, where the
619 main mortality event occurred prior to the first aerial survey in July. For this reason, mortality at
620 the QC colonies was only estimated from the July photographs and should be viewed as
621 minimums. On NF, the main mortality event occurred after the first survey and before the second
622 survey, so mortalities were enumerated in aerial photographs from both surveys.

623 We can assume that the vast majority of Northern Gannets that were observed dead on
624 breeding colonies (14,091) were adults, and that 12,102 of the mortalities reported off colonies
625 were also adults (i.e., 92.8%). If those adults were breeding individuals, then the reported
626 mortality represents a minimum 11.6% loss of the North American breeding population.
627 However, this should be viewed as an absolute minimum. Many Northern Gannets were likely
628 lost at sea (e.g., Polhmann et al., 2023), particularly those that died in the waters off the
629 northeastern coast of Newfoundland (i.e., Funk Island, Baccalieu Island), where the dominant
630 currents (Wu and Tang, 2011) would tend to advect birds away from shore. Efforts to estimate at
631 sea losses and population surveys to detect changes in Apparently Occupied Territories (AOTs)
632 will help to resolve the complete picture of population impacts from the HPAI virus. For
633 example, while the number of mortalities enumerated at Rocher aux Oiseaux represents only
634 9.8% of the breeding population, a 58% decline in the number of Apparently Occupied
635 Territories was observed in 2022, compared to the previous survey in 2020 (J.-F. Rail, pers.
636 comm.).

637 Since monitoring of Northern Gannet colonies began in 1970, populations have increased
638 significantly (Chardine et al. 2013). Across all five main colonies, the North American
639 population is increasing or stable (Rail 2021a, d'Entremont et al. 2022, S. Wilhelm, pers.
640 comm.). A full assessment of the population-level impact of HPAI on the six Northern Gannet
641 populations in eastern Canada, and how long populations will take to recover, is beyond the
642 scope of this paper. Several factors will influence recovery, including the number of mature non-
643 breeding individuals available to recruit into the breeding population, breeding success in
644 subsequent years, acquired immunity to future infection, and the cumulative impacts of natural
645 and anthropogenic stressors that may have additive or synergistic effects with HPAI.
646 Epidemiology, including testing for active infections and serology in subsequent years, will be
647 important to understand exposure, survival, and immunity (Giacinti et al. 2023).

648 Globally, Northern Gannets are listed as Least Concern because they have a very large
649 range and a large population size (1,500,000 to 1,800,000 mature individuals; BirdLife
650 International 2023). However, Northern Gannets were impacted across their range, with an
651 estimated 75% of colonies experiencing unusual mortality events (Lane et al. 2023). This
652 includes marked declines in the number of breeding birds at key colonies in the UK (e.g., Bass
653 Rocks, over 71% decline in June 2022 compared to 2014; Lane et al. 2023). To fully appreciate
654 the population-level impact of HPAI on gannets throughout their range, an analysis of changes in
655 breeding populations before and after mortality events will be needed. Fortunately, breeding
656 Northern Gannets have well-defined territories and are methodologically easy to census via
657 aerial surveys, and innovative approaches to cost-effectively survey populations are in
658 development (Kuru et al. 2023 Walker et al., in prep).

659

660 *Common Murres*

661 In eastern Canada, Common Murres were the second most reported species, with 8,133 Common
662 Murre mortalities. We estimate that 7,049 of these were adults and may have been breeding. This
663 mortality represents less than 0.5% of the breeding populations, therefore clear population-level
664 impacts of HPAI-linked mortality in 2022 is not expected. However, the dominant currents near
665 the largest murre colonies on the eastern and northeastern coasts of NF likely advect birds away
666 from shore (Wu and Tang 2011). If at-sea losses are significant, the total number of murres

667 succumbing to HPAIV may be severaly underestimated based on reported mortalities. As with
668 gannets, efforts to estimate at-sea losses in 2022 and population surveys at key colonies (i.e.,
669 those with large populations) in the years post-outbreak will support a better understanding of
670 population level impacts for Common Murres.

671 Unlike Northern Gannets, no mass mortalities of Common Murre were observed directly
672 on breeding colonies in eastern Canada. The lack of mortalities seen on colonies themselves was
673 surprising given that thousand of adult murre mortalities were reported on nearby beaches.
674 Similar observations have been made in Europe (Germany, E. Ballstaedt pers. comm). Initially,
675 we reasoned that murre mortalities may not be readily observed at the colony because most
676 murres nest in packed colonies on rocky cliff ledges, and sick or dead birds had fallen into the
677 water. However, on Funk Island and Rocher aux Oiseaux, murre and gannets breed in adjacent
678 colonies on the plateau, but still no dead murres were observed. We speculate that murres leave
679 the colony when sick and recommend that characterizing the magnitude of outbreaks among
680 Common Murre based on mortality observed on the colony may not be the best approach.

681 Common Murre are harvested in Newfoundland and Labrador, a culturally important
682 practice in the province (Chardine et al. 2008). This species is numerous in eastern Canada and
683 populations have been increasing in QC, increasing or stable in the island of Newfoundland, and
684 declining in Labrador (Ainley et al. 2021). After reviewing abundance, population trends and the
685 mortality data presented here, ECCC chose “*not to change migratory bird hunting regulations to
686 reduce the harvest of Murres in Newfoundland and Labrador during the 2022 to 2023 hunting
687 season*” (Environment and Climate Change Canada 2022).

688

689 *Considerations for Interpreting Reported Mortalities on Beaches and at Sea*

690 It is important to acknowledge two simplifications that were made in arriving at these reported
691 mortality estimates. First, we attributed all mortalities to HPAI for species that tested positive for
692 the HPAI virus in the study area during the study period, removing only those records where
693 individual birds tested negative. Species specific HPAI virus prevalence rates are available from
694 Canada’s Interagency Surveillance Program for Avian Influenza (Giacinti et al. 2023), but using
695 these to adjust mortality estimates yielded unlikely results. For example, in eastern Canada,
696 prevalence of HPAI virus in Northern Gannets was 62.8%. If we attributed only 62.8% of

697 reported mortality to HPAI, this would suggest that 9,744 adult Northern gannets died of
698 unknown causes. This is far above background annual mortality rates for adults of this species in
699 North America (5% per annum; Chardine et al. 2013). Attributing all mortalities to the HPAI for
700 species that tested positive for the virus in the study area during the study period may be
701 simplistic, but in the absence of evidence that another large-scale mortality factor is operating at
702 the same time it seems a reasonable assumption. It is it is also consistent with other studies
703 assessing HPAI mortality (e.g., Rijks et al. 2022, Pohlmann et al. 2023).

704 The second simplification was the assumption that all sick birds die. This was necessary,
705 as the status of birds (sick or dead) was not consistently reported. While some birds may recover
706 from HPAI (Lane et al. 2023), even when they exhibit severe neurological symptoms (L. Taylor,
707 pers. comm.), most do not. The assumption that all sick birds died would only cause an
708 overestimate of reported mortality if a large proportion of sick birds recovered. To our
709 knowledge, recovery rates of seabirds' with HPAI are low (e.g., African Penguins; Roberts et al.
710 2023). Although these simplifications could lead to an over-attribution of reported mortalities to
711 HPAI, we are confident that our estimates still represent only a fraction of the total mortality
712 resulting from the HPAI virus outbreak in eastern Canada.

713 There are several reasons we view reported mortalities as a minimum estimate. Our
714 estimates are based on reported observations of sick and dead birds across an area spanning 5
715 Canadian provinces and Atlantic coastlines across 15 degrees of latitude. Although reporting
716 efforts were significant it is likely that many bird carcasses were not observed or reported, even
717 in areas of intensive effort. A considerable body of literature shows that detection rates and
718 persistence probabilities for seabird carcasses on beaches is higher for large birds and white birds
719 than it is for small birds and dark birds, and that beach type, weather, and degree of scavenging
720 all influence detection and persistence (e.g., Fowler and Flint 1997, Wiese and Robertson 2004).
721 It was beyond the scope of this study to generate an extrapolated number to estimate total
722 carcasses based on these factors (i.e., grounding probability, detection probability, persistence
723 rate) due to the sheer size and geographic scope of this outbreak.

724 Additionally, detection and reporting of mortalities is likely to be lower in areas with
725 lower human population density. Preliminary drift modelling suggests that large numbers of
726 gannet carcasses likely deposited on the North Shore of QC and on the shores of Île d'Anticosti

727 (Avery-Gomm et al. 2023), but very few mortalities were reported in these areas, which are very
728 remote from large population centers. Therefore, low reported mortalities in remote areas may
729 reflect low detection due to low human population density rather than low mortalities. Finally,
730 not all reported observations were captured due to capacity challenges of some jurisdictions to
731 receive and record large volumes of calls from the public during the summer months when other
732 urgent priorities arose (e.g., wildfires).

733 In eastern Canada, almost all reported mortalities were among seabird and seaduck
734 species that forage at sea. Among such species, sick individuals may have died at sea and at-sea
735 losses of these carcasses may comprise a significant fraction of total mortality. Experiments
736 designed to assess at-sea loss in the context of large oil spills and chronic oil pollution have
737 identified that temperature, scavenging activity, and body size are some factors that influence
738 how long a carcass will float (Burger 1991, Ford et al. 1996, Wiese 2003). Carcasses that float
739 for longer have a higher probability of washing ashore (i.e., grounding), but grounding
740 probabilities are strongly influenced by oceanographic conditions, wind (Bibby and Lloyd 1977,
741 Ford et al. 1987, Ford 2006), and distance the carcasses would need to drift to reach the shoreline
742 (Martin et al. 2020).

743 The proportion of mortalities that were lost at sea during this outbreak is unknown but is
744 likely to be significant and to have varied regionally in eastern Canada. As previously
745 mentioned, the dominant currents in eastern and northeastern Newfoundland (Wu and Tang
746 2011) likely act in concert to advect many carcasses floating in that region offshore. In future,
747 adaptation of operational drift modelling tools developed for oil spill response (e.g., (e.g., Paquin
748 et al. 2020, Sutherland et al. 2022) could be used to estimate the grounding probability of
749 simulated particles configured to drift like seabirds. Such information could be used to estimate
750 at-sea losses and thus improve mortality estimates for specific species.

751 Across eastern Canada, seabird and sea duck colonies were completely (66), partially
752 (29), and/or incidentally (46) surveyed by government and academic biologists. All information
753 about observed mortalities on colonies has been collated, however, there are important
754 considerations when interpreting our colony-related data. Specifically, the detectability of any
755 mortality at a colony depends on the magnitude of the outbreak, the timing, method and purpose
756 of the survey, and species-specific traits including nesting habitat and whether birds are likely to

757 return to the colony when sick. It is likely that mortality at the colony was easier to detect among
758 surface nesting species (e.g., gulls, terns, pelicans, cormorants, and gannets) than among burrow
759 nesting birds (e.g., puffins and storm-petrels) or among cliff nesting birds (e.g., murres and
760 kittiwakes) which may have difficulty remaining on ledges when sick or dead. Even with surface
761 nesting species like gannets, we experienced challenges in distinguishing between fresh dead
762 birds and decomposing dead birds when enumerating mortalities from aerial photographs when
763 colonies were visited multiple times. Ultimately, the absence of detections of sick or dead birds
764 at the colonies should not be taken as evidence of absence of mortality and population surveys in
765 subsequent years will provide the best measure of any population-level impacts.

766

767 *Reflections and recommendations*

768 During the HPAI outbreak, representatives from ECCC, the Canadian Wildlife Health
769 Cooperative, provincial/territorial government agencies, other federal departments (Canadian
770 Food Inspection Agency, Public Health Agency of Canada, Parks Canada, and Indigenous
771 Services Canada), and Indigenous and academic partners worked together to respond to the
772 HPAI outbreak in a One Health Approach (Giacinti et al. 2023). Similarly, communication and
773 collaboration were the cornerstone of the response to the mass mortality event in eastern Canada.
774 Significant efforts were made by all parties to support mortality data collation efforts, however
775 data quality varied across jurisdictions. The magnitude, duration, and geographic scope of the
776 HPAI outbreak and resulting mass mortality event in eastern Canada was unexpected and
777 unprecedented for this region. Similar large-scale events have occurred across the globe in recent
778 years, with seabirds being among the highly vulnerable to HPAI-related mortality. In all cases,
779 estimating total mortality is a logistical challenge.

780 Beached bird surveys have become an international practice for documenting and
781 monitoring the impacts of various sources of mortality (Camphuysen and Heubeck 2001,
782 Wilhelm et al. 2009, Jones et al. 2023). Given the apparent vulnerability of seabirds and sea
783 ducks to HPAI 2.3.4.4b, standardized beached bird surveys could provide valuable information if
784 implemented in areas of anticipated disease outbreaks or in areas when outbreaks are detected
785 early. They could improve the enumeration of large mortality events by providing information on
786 the onset, duration, and magnitude of HPAI mortality. Beached bird surveys could also provide

787 valuable information on species composition and age classes as well as improve access to fresh
788 carcasses for testing, necropsy, and early confirmation of HPAI. Where the resources to establish
789 beached bird surveys or collating mortality reports is limited, band recoveries (Johnston et al., in
790 prep) and or citizen science data from iNaturalist (e.g., Bartolotta et al. 2023) may provide an
791 inexpensive approach to collect information on mortality events.

792

793 **Conclusion**

794 Within months of the first positive detection of HPAI H5N1 2.3.4.4b virus in North America,
795 this virus sparked an outbreak that caused a mass mortality event of unprecedented magnitude
796 and duration and at least forty thousand wild birds across 45 species were reported as sick or
797 dead. Most of the mortalities were among Northern Gannets, Common Murres and Common
798 Eiders, although unusual levels of mortality were also reported in gulls, cormorants, Atlantic
799 Puffins, Black-legged Kittiwakes, Razorbills, and terns. Based on our assessment, it is probable
800 that Northern Gannets and Common Eiders will experience population-level impacts in eastern
801 Canada, whereas such impacts are not anticipated for Common Murres, due to their large
802 breeding populations. We recommend that the breeding populations of these three species in
803 eastern Canada be monitored closely in the years that follow to assess the long-term impacts of
804 HPAI mortality and support conservation decisions. Beached bird surveys could improve the
805 enumeration of large mortality events if implemented in areas where repeated outbreaks are
806 expected and/or ongoing.

807

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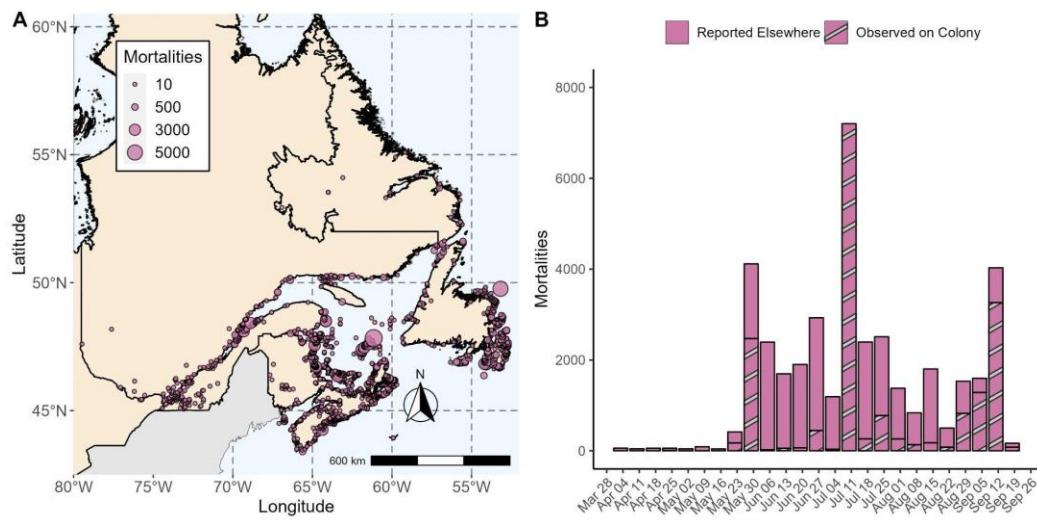
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1086 **Table 1.** Total number of HPAI-linked mortalities reported (i.e., baseline scenario) and the
1087 estimated number of mortalities with double counts removed according to a range of criteria.
1088 Reported mortalities for birds with less specific taxonomic identities that were presumed positive
1089 but that could not be included in the double count analysis have been added to totals. The values
1090 do not include birds that tested negative for HPAI virus and species that were presumed negative
1091 or the 2,762 Unknown Birds, because these mortalities could not be attributed to the HPAI virus.

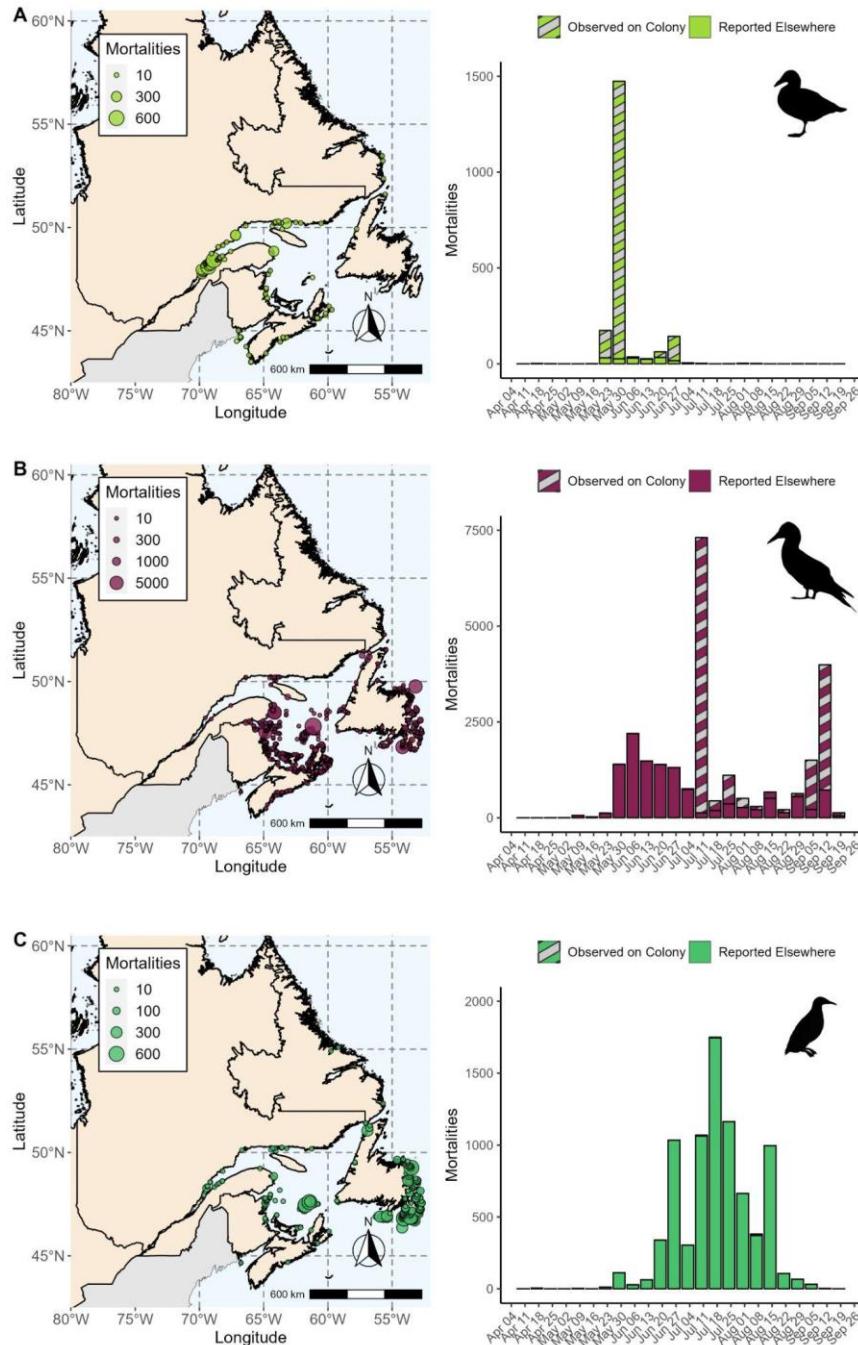
Criteria	Baseline	Scenario A	Scenario B*	Scenario C	Scenario D	Scenario E	Scenario F
Days	N/A	± 0 day	± 1 day	± 5 day	± 0 day	± 5 day	± 1 day
Distance	N/A	± 1 km	± 1 km	± 1 km	± 5 km	± 5 km	± 5 km
Total mortality	44,721	42,294	40,966	39,743	41,408	39,176	40,122
Δ from Baseline		2,427	3,755	4,978	3,313	5,545	4,599
%Δ from Baseline		5.4%	8.4%	11.1%	7.4%	12.4%	10.3%
Including:							
Common Eider	1,983	1,971	1,945	1,912	1,961	1,926	1,940
Northern Gannet	28,406	26,842	26,193	25,653	26,320	25,249	25,541
Common Murre	9,092	8,716	8,133	7,652	8,433	7,552	8,103
Gull	2,378	2,348	2,326	2,260	2,330	2,181	2,260
Cormorant	997	990	981	959	988	948	950
Atlantic Puffin	364	299	282	244	259	276	238
Black-legged Kittiwake	260	257	251	227	252	224	245
Razorbill	127	121	119	109	120	107	118
Tern	83	80	74	75	80	74	74

1092 *Scenario B (± 1 km, ± 1 day) was selected as the best compromise between removing multiple
1093 records of the same birds and but not removing records of new batches of birds arriving in an
1094 area.



1095

1096 **Figure 1.** Spatial (A) and temporal (B) distributions of HPAI-linked wild bird mortality in
1097 eastern Canada, April 1 – September 30, 2022. These values represent the estimates derived from
1098 the double count analysis (Scenario B: ± 1 km, ± 1 day).



1099 **Figure 2.** The spatial and temporal distribution of HPAI-linked mortalities across eastern Canada
1100 for (A) Common Eider, (B) Northern Gannet, and (C) Common Murre, reported between April 1
1101 and 30 September 2022, with double counted birds removed (Scenario B: ± 1 km, ± 1 day).
1102