Title: Spatial and Temporal Variation in Mortality from Avian Influenza in Greenland Barnacle Geese

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Summary

Capsule: Avian influenza caused a loss of more than 20% of the Greenland Barnacle Geese population but this impact varied between wintering areas and over time.

Aims: The primary objective was to investigate the spatial and temporal mortality patterns due to avian influenza (H5N1) in wintering Greenland Barnacle Geese.

Methods: We analysed a comprehensive dataset of marked individuals spanning six years, with observations from a network of observers across their wintering range. The study specifically compared the mortality rates of Greenland Barnacle Geese during the H5N1 outbreak years (2021/22 and 2022/23) with the three previous winters (2018/19-2020/21).

Results: The study found significant spatial and temporal variation in mortality within the Greenland Barnacle Goose population on their wintering grounds resulting from avian influenza outbreaks. Some sites (Islay, Tiree and Sligo) experienced 30-56% reductions in survival rates, while others (Uist and Mayo) showed little or no impact. The timing of the main outbreaks also differed between sites. Excess deaths (in comparison with the previous baseline) estimated using mark-resighting data indicated that mortality was considerably higher than suggested from direct field counts, reaching at least 20% of the global population in the peak outbreak winter (2022/23).

Conclusion: The results highlight the importance of spatial and temporal dynamics in avian influenza impacts. Disease dynamics should be integrated into population management models and set appropriate thresholds for minimum population levels to ensure resilience to disease outbreaks and long-term viability.

1. Introduction

Avian influenza is a viral infection that can cause severe illness in birds, including respiratory distress, internal haemorrhaging and neurological effects such as lack of coordination (FAO 2007). The H5N1 strain in particular has emerged as a global threat with significant potential to cause large-scale wild bird mortality, including waterfowl (Chen *et al.* 2005, Feare 2007). Vulnerability to avian influenza varies between goose species (Brown *et al.* 2008). Geese can be important reservoirs of the virus in nature (Webster *et al.* 1992; Olsen *et al.* 2006) and have a potential role in transmission, including to domestic poultry. Greenland Barnacle Geese *Branta leucopsis* represent a vulnerable group due to their congregatory nature, both on feeding fields and night roosts, which facilitates the spread of the virus. Understanding the spatial and temporal dynamics of avian influenza mortality is crucial for effective conservation management and disease control strategies.

The Greenland Barnacle Goose is listed under Annex 1 of the EU Birds Directive as a species requiring special conservation efforts, with most of its main wintering sites designated as Special Protection Areas to promote its long-term survival. Effective protection increased its population from 25,300 in 1982 to a peak of 80,670 in 2012 (Mitchell and Hall 2013). However, culling on its main wintering site on Islay to reduce agricultural damage and its subsequent economic costs (McKenzie 2014, McKenzie and Shaw 2017) reduced the population to 73,390 in March 2020 (Mitchell and Hall 2024) and, together with the initial impact of avian influenza, to 62,160 in February 2023 (Mitchell and Leitch *in prep*). A total of 11,300 were shot on Islay between 2015 and 2021 prior to the avian influenza outbreak (Percival and Bignal 2018, NatureScot in litt.).

The virus can cause population-scale impacts on geese. For example, 3,000 Bar-headed Geese, *Anser indicus* (5-10% of the global population) died in an H5N1 outbreak in central China in 2005 (Chen *et al.* 2005, Zhou *et al.* 2006, Bourouiba *et al.* 2010). Despite this, viral outbreaks are usually omitted from population models used to inform goose management. The recent Adaptive Flyway Management Programme for the Greenland Barnacle Goose (Nagy *et al*. 2021), and the Islay Goose

Management Scheme (McKenzie 2014, Mackenzie and Shaw 2017) both make no mention of the potential vulnerability of the population to avian influenza (or any other disease), and disease does not feature in a model recently developed to inform the management of this population (McIntosh *et al.* 2023).

This study investigates the impact of an H5N1 avian influenza outbreak on Greenland Barnacle Geese during 2021-23, focusing on spatial and temporal mortality patterns across their wintering range in western Scotland and Ireland. By comparing observed mortality during the recent outbreaks with baseline data, we aim to quantify the impact of the virus and evaluate its implications for population management strategies. We address the following questions:

1. How many Greenland barnacle geese have died as a result of the avian influenza outbreaks on their wintering grounds in 2021/22 and 2022/23?
2. How has that mortality changed over time?
3. How has that mortality varied across the birds' wintering range?
4. Can individually-ringed birds provide insight into how avian influenza affected this population?
5. How should future population management consider potential further outbreaks of avian influenza?

2. Materials and Methods

2.1 Study Population and Data Collection

This paper uses data from long-term studies of Greenland Barnacle Geese on Islay (Percival 1991, Percival *et al.* 2020) and Inishkea (Mayo) (Cabot and West 1973, Doyle *et al*. 2023), to investigate the impact of recent avian influenza outbreaks. Birds have been individually marked on Inishkea since 1963, on Islay since 1987, on the breeding grounds in southern Iceland since 1999 and since 2017 elsewhere within their winter range (including Sligo and Tiree, Mitchell et al. 2020). Currently, about 2% of the population is individually marked.

Resightings data from the three winters before the initial avian influenza outbreak (2018-19, 2019-20 and 2020-21) were compared with those from the two outbreak winters, 2021-22 and 2022-23. Data were collected by a network of observers across the wintering range from five main locations: Islay, Argyll (SP), Inishkea, Mayo (DC), Balygilgan, Sligo (ME), Tiree, Argyll (JB) and North Uist, Outer Hebrides (SD). The locations are shown in Figure 1. Islay was split further into two sites associated with the two main roosts on the island, Islay North (Loch Gruinart) and Islay South (Loch Indaal), which have been shown to have largely separate sub-populations during the winter (Percival 1991). Surveyors visited sites regularly through the winter period and recorded marked birds. Table S1 shows the number of resightings and the number of individually marked birds recorded at each site during each period. The only temporal gap in coverage was Islay in winter 2021, when it was not possible to visit because of COVID-19 restrictions (independent estimates of mortality could not be made for that period).

Information on goose numbers was collated from ongoing monitoring (including NatureScot surveys on Islay, RSPB surveys on Tiree, and whole range counts from Ireland (Kelly *et al.* 2023) and Scotland (Mitchell and Leitch *in prep*). Weekly carcass searches were carried out at Loch Gruinart, Islay (JH), in Sligo (ME) and on Tiree (JB), counting carcass numbers within the main feeding and, where accessible, roosting areas, to provide an index of mortality (rather than absolute counts which were

not feasible). Carcasses were not removed because of Health and Safety concerns (following government advice). Locations of carcasses in fields were mapped and the condition of each noted to reduce the risk of double-counting, whilst those on the strandline were sprayed with a waterproof dye when counted. Details of all ringed birds found were recorded, and further recoveries were reported through the BTO ringing scheme. Numbers of recoveries were compared between the baseline (the three winters before the avian influenza outbreak), and the two outbreak winters. Dead ringed birds found with other carcasses, no sign of predation, and not reported as shot, were considered likely avian influenza victims.

2.2 Data Analysis

Apparent Survival Rates

Survival rates were estimated using the Cormack-Jolly-Seber (CJS) model (Seber 1982) carried out using program MARK 10.0 (White and Burnham, 1999) and the RMark package 2.2.5 (Laake 2013). Two CJS parameters were estimated: apparent survival and encounter probability (Lebreton *et al*. 1992). These were estimated for each of the winters of the study (the three baseline winters of 2018/19, 2019/20 and 2020/21, and the two avian influenza outbreak winters, 2021/22 and 2022/23), and split into two periods each winter: autumn (October – December) and winter (January – April). The models were run separately for each location and time period, and were not age- or sex-dependent. Further details of the number of individuals in each analysis are given in Table S1. Spring migration (April) records were excluded from the Uist analysis as geese from other wintering sites often make a short-term stop-off on their northward migration (S. Duffield, unpublished data).

Excess Deaths

The apparent survival rates were used to estimate the number of excess deaths at each location during each outbreak winter. The number of excess deaths was calculated as the product of each location's population and the difference in survival rate between the baseline (from the three winters

prior to the avian influenza outbreak, including both natural and shooting mortality) and each outbreak year):

$$\textit{Excess Deaths} = \textit{Population} \times (\textit{Baseline Survival Rate} - \textit{Outbreak Survival Rate})$$

No large-scale changes in site fidelity (which is generally very high during winter, Percival 1991) or overall movement patterns were noted during the outbreak that would have affected this analysis (median distance between sightings was 740 m before and 1,060 m during the outbreak).

3. Results

Direct Field Evidence of Outbreak Timing and Severity

Islay: only small numbers of sick/dead birds were recorded in the winter of 2021/22. The first dead birds were recorded on 24 February 2022 (which subsequently tested positive for avian influenza). A total of 56 dead birds were counted on the RSPB Loch Gruinart reserve from then through to the end of March 2022, and it was estimated about 100 birds died on the reserve (JH). It was a different picture in the following 2022/23 winter, however. Weekly carcass counts made by RSPB (JH) on their Loch Gruinart reserve give the most detailed picture of what happened when. The first carcasses were recorded on 14 November 2022, totalling 34 by the end of that month and 263 more in the following month. Only 11 more were found in January 2023 and no more after that. Island counts undertaken by NatureScot indicated a fall from a mean of 33,400 birds for the three baseline winters and 37,400 in 2021/22, to 30,400 in 2022/23 and 27,100 in 2023/24. There was no evidence from resightings of marked birds that these reductions in numbers on Islay and at other sites were affected by any large-scale movements of geese between wintering sites.

Tiree: no evidence of bird flu was recorded during the 2021/22 winter. Dead/dying geese were first observed in late December 2022, with 20 carcasses logged on 22 December 2022 (JB). This was followed by another 43 dead in January 2023. By the end of February 2023, there were dozens of dead birds on both the fields and on the shore (though it was not possible to obtain a full count, with many carcasses being washed out to sea). A drop in the island count from 5,900 birds at the start of January 2023 to 5,200 in late February 2023 suggested the loss of at least 500 birds at that stage. The March 2023 count of 5,200 was 1,400 lower than the March 2022 count, whilst the November 2023 count of 4,700 was 1,100 lower than November 2022.

Sligo: ME recorded the first two sick geese in this area on 22 February 2022 and the first carcass was found on 27 February 2022 (which subsequently tested positive for H5N1). Thereafter, there was a rapid spread, with 50 dead geese recorded by 12 March 2022 and 70 by 17 March 2022. A further 7

carcasses found on 24 March 2022 were the last recorded on their mainland feeding sites. Many more dead birds were found on the main offshore island used as a night roost, Inishmurray, with the NPWS ranger recording a total of 604 carcasses in March 2022 (S. Kelly *in litt*.). As on Islay, new sick/dead birds were located over only a relatively short period (22 February – 24 March 2022). In contrast, no records of any sick or dead birds were found during the following winter. A large reduction in goose numbers in Sligo was apparent in spring 2022, falling from 6,000 in the previous spring to about 4,000, suggesting that as many as 2,000 geese may have been lost to bird flu.

In both **Uist, Outer Hebrides** and **Inishkea, County Mayo** there was no indication of any mortality, no sick birds were noted, and no major change in numbers present was recorded during the study period.

Winter 2023/24: there was no evidence of any mortality or sick geese observed at any of these sites during the winter of 2023/24. Survey efforts continued at a similar rate to the previous years across all areas, so this was not an effect of reduced surveillance.

Ring Recoveries

There were 31 winter recoveries of dead ringed barnacle geese during 2021/22 and 2022/23, 28 of which (90%) were considered likely victims of avian influenza. During the three previous baseline winters, there were only 11 dead recoveries in total (3.7 per year), so this represents a three-fold increase in 2021/22 and a five-fold increase in 2022/23. The recovery locations of the 28 likely avian influenza victims are shown in **Figure 1** (which also shows the winter range for comparison, from the most recent whole population census in February 2023, Kelly *et al*. 2023, Mitchell and Leitch *in prep*). This reflects the spatial variation noted above: high mortality on Islay, in Sligo and Tiree, and little or none at the northern (Orkney/Uist) and southern (Inishkea, Mayo) ends of the range.

Mark-resightings data – Survival Analysis

The assumptions of the CJS model were not met by the survival models. Goodness of fit tests of the survival data using program RELEASE (Burnham *et al.* 1987) showed an unequal probability of

recapture. Additionally, the populations are known not to be closed (Percival 1991, Percival *et al*. 2020), so the apparent survival includes a component of emigration. As a result, the absolute values of the apparent survival rates need to be treated with caution. However, this is not likely to affect the validity of the comparisons of survival rates before and during the avian influenza outbreaks that have been undertaken here.

Figure 2 shows the annual apparent survival rates for the geese at each of the six study locations over the 2018/19 – 2023/24 winters. Of particular note are the large reductions in apparent survival rate noted in Sligo in autumn 2022, and on Islay in 2021/22 and particularly 2022/23. In contrast, survival rates on Uist in 2021/22 and 2022/23 were similar to those recorded previously prior to the outbreak.

Excess Deaths

Table 1 shows the estimated change in apparent survival rate from the pre-outbreak baseline (2018/19 – 2020/21) and the number of excess deaths estimated in each of the two outbreak winters. Islay suffered excess deaths in 2021/22, when the outbreak was less apparent, but was much more affected in the 2022/23 winter. Mortality overall was considerably higher than suggested by the counts, and in 2022/23 likely reached 10,000 excess deaths across the island as a whole. Tiree had a relatively low level of additional deaths in 2021/22, but mortality in 2022/23 was high (proportionately higher than on Islay). Sligo, in contrast, suffered very high mortality in 2021/22 but much less in the following winter. Negligible excess deaths were apparent on Uist and on Inishkea in 2021/22, and only relatively small losses in both areas in 2022/23.

Furthermore, the excess death estimates likely underestimated avian influenza mortality as shooting mortality was reduced during the outbreaks. Shooting was reduced on Islay (where the geese are culled by NatureScot as part of the Islay Goose Management Scheme) in response to the avian influenza outbreak. An annual mean of 995 geese were shot there over the three baseline winters, 613 in 2021/22, and a further 58 were shot in 2022/23 (NatureScot *in litt*.). Bird flu deaths calculated

213 by comparison to the baseline with active culling (mostly in Islay South) underestimated the
214 mortality by about 400 birds in 2021/22 and 1,000 birds in 2022/23. There was reduced shooting in
215 Iceland in autumn 2022 (1,740 compared with a mean total shot of 3,260 in baseline years (Statistics
216 Iceland 2024), though this was also a result of very low breeding success in that year according to the
217 data from the Icelandic hunters' wing survey (AS, unpublished data). This reduction in the Icelandic
218 bag would, though, only minorly affect the results presented here as effects diluted across the winter
219 range.

4. Discussion

The study highlights the spatial and temporal variation in mortality resulting from avian influenza outbreaks within the Greenland Barnacle Goose population on their wintering grounds in western Scotland and Ireland. We have successfully used data on individually-ringed birds to show how avian influenza has affected this population. While some sites (Islay, Tiree and Sligo) experienced severe mortality (with survival rates reduced by 30-56%), others (Uist and Mayo) showed little or no impact. The timing of the main outbreaks also differed between sites, with Sligo being affected mainly in March 2022, whilst Islay and Tiree were hit mainly in November/December 2022 and February/March 2023, respectively.

Excess deaths estimated from ring resighting data indicated a higher level of avian influenza mortality than from direct field evidence (population counts and counts of dead geese). The number of dead birds was sufficient to cause population-level impacts, with an estimated 11,300 excess deaths on Islay during the peak outbreak, 2,200 in Sligo and 1,900 on Tiree (over 20% of the global population in total, and likely to be higher than this given our study did not cover all wintering areas).

This research highlights the critical need for dynamic population management strategies that account for the uneven spatial and temporal distribution of avian influenza mortality. The adaptive nature of the Islay Goose Management Scheme has enabled a rapid response to lessen the effects of avian influenza (halting the ongoing cull), but this has not been sufficient to prevent a major population decline. Ensuring the resilience of vulnerable waterfowl populations like the Greenland Barnacle Goose necessitates re-evaluating current practices to mitigate the impact of future viral outbreaks. Recent modelling to inform the Adaptive Flyway Management Programme for the Greenland Barnacle Goose (McIntosh, in Nagy *et al*. 2021) before the avian influenza outbreak had already noted that the population was declining and approaching the Favourable Reference Population (with the model showing that it was just below the 95% credible interval). The Adaptive

Flyway Management Plan does not provide targets for population sizes but does note that the flyway population should not fall below this Favourable Reference Population (54,000 individuals).

In conclusion, we make the following recommendations, relevant to this specific population and wider goose management:

1. Monitoring of individually-marked birds should be an important component of future surveillance to better understand the factors affecting the population and inform effective management.
2. The adaptive nature of the current Islay Goose Management Scheme has enabled a rapid response to the threat to the population from avian influenza, and should be continued in any future management scheme.
3. Existing population modelling should be extended to include catastrophic events such as this avian influenza outbreak.
4. Goose management thresholds need to be urgently reviewed. The Favourable Reference Population (FPA) level should be higher to increase population resilience for future outbreaks of avian influenza or other diseases. This updated FPA level should be accounted for in annual cull targets for Islay and hunting bag limits in Iceland.
5. For future disease outbreaks, an agreed monitoring and management protocol between all stakeholders (including quantifying mortality, checking for ringed birds, and safely disposing of carcasses) would facilitate a more systematic and effective response. This could be achieved as an addition to the current Flyway Management Plan.

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Table S1. Marked bird and resighting totals by location, year and season.

Site	Year	Season	Number of Ring Sightings [S]	Number of Ringed Individuals seen [I]	Sightings per Individual [S/I]
Islay North	2018	Autumn	1355	454	3.0
		Winter	1131	336	3.4
	2019	Autumn	1613	575	2.8
		Winter	858	289	3.0
	2020	Autumn	1377	502	2.7
		Winter	-	-	-
	2021	Autumn	1395	532	2.6
		Winter	699	265	2.6
	2022	Autumn	1163	444	2.6
		Winter	1026	312	3.3
	2023	Autumn	757	345	2.2
		Winter	731	273	2.7
Islay South	2018	Autumn	113	92	1.2
		Winter	550	264	2.1
	2019	Autumn	372	223	1.7
		Winter	445	193	2.3
	2020	Autumn	813	358	2.3
		Winter	-	-	-
	2021	Autumn	834	380	2.2

Site	Year	Season	Number of Ring Sightings [S]	Number of Ringed Individuals seen [I]	Sightings per Individual [S/I]
		Winter	999	366	2.7
	2022	Autumn	1199	441	2.7
		Winter	865	314	2.8
	2023	Autumn	687	326	2.1
		Winter	970	393	2.5
Tiree	2018	Autumn	81	49	1.7
		Winter	148	53	2.8
	2019	Autumn	135	66	2.0
		Winter	185	75	2.5
	2020	Autumn	242	97	2.5
		Winter	309	106	2.9
	2021	Autumn	221	107	2.1
		Winter	338	132	2.6
	2022	Autumn	99	70	1.4
		Winter	327	140	2.3
	2023	Autumn	308	119	2.6
		Winter	290	134	2.2
Uist	2018	Autumn	38	32	1.2
		Winter	169	73	2.3
	2019	Autumn	103	84	1.2
		Winter	142	80	1.8
	2020	Autumn	158	93	1.7
		Winter	373	141	2.6
	2021	Autumn	198	127	1.6
		Winter	197	109	1.8
	2022	Autumn	150	103	1.5
		Winter	265	151	1.8
	2023	Autumn	254	191	1.3
		Winter	303	175	1.7

Site	Year	Season	Number of Ring Sightings [S]	Number of Ringed Individuals seen [I]	Sightings per Individual [S/I]
Sligo	2018	Autumn	48	25	1.9
		Winter	412	113	3.6
	2019	Autumn	176	83	2.1
		Winter	555	106	5.2
	2020	Autumn	126	76	1.7
		Winter	723	115	6.3
	2021	Autumn	261	122	2.1
		Winter	608	135	4.5
	2022	Autumn	201	71	2.8
		Winter	304	72	4.2
	2023	Autumn	136	59	2.3
		Winter	220	75	2.9
Inishkea, Mayo	2018	Autumn	196	60	3.3
		Winter	241	86	2.8
	2019	Autumn	295	101	2.9
		Winter	141	52	2.7
	2020	Autumn	288	104	2.8
		Winter	278	69	4.0
	2021	Autumn	119	55	2.2
		Winter	107	48	2.2
	2022	Autumn	106	51	2.1
		Winter	274	115	2.4
	2023	Autumn	50	41	1.2
		Winter	309	102	3.0

Table 1. Change in apparent survival rates from baseline and estimated excess deaths at each study location, in 2021/22 and 2022/23.

Location	2021/22		2022/23	
	Change in Survival rate	Excess deaths	Change in Survival rate	Excess deaths
Islay North	-9%	1332	-35%	5503
Islay South	-18%	2780	-30%	4838
Tiree	-11%	440	-42%	1922
Uist	0%	60	-12%	731
Sligo	-56%	2179	-21%	285
Inishkea, Mayo	-7%	239	-23%	831

Figure 1. Greenland barnacle goose winter range and distribution of avian influenza ring recoveries. Counts are the most recent whole population census carried out in February 2023 (Kelly *et al.* 2023, Mitchell and Leitch in prep). Ringing recoveries plotted are dead birds likely to have been victims of avian influenza (total 27).

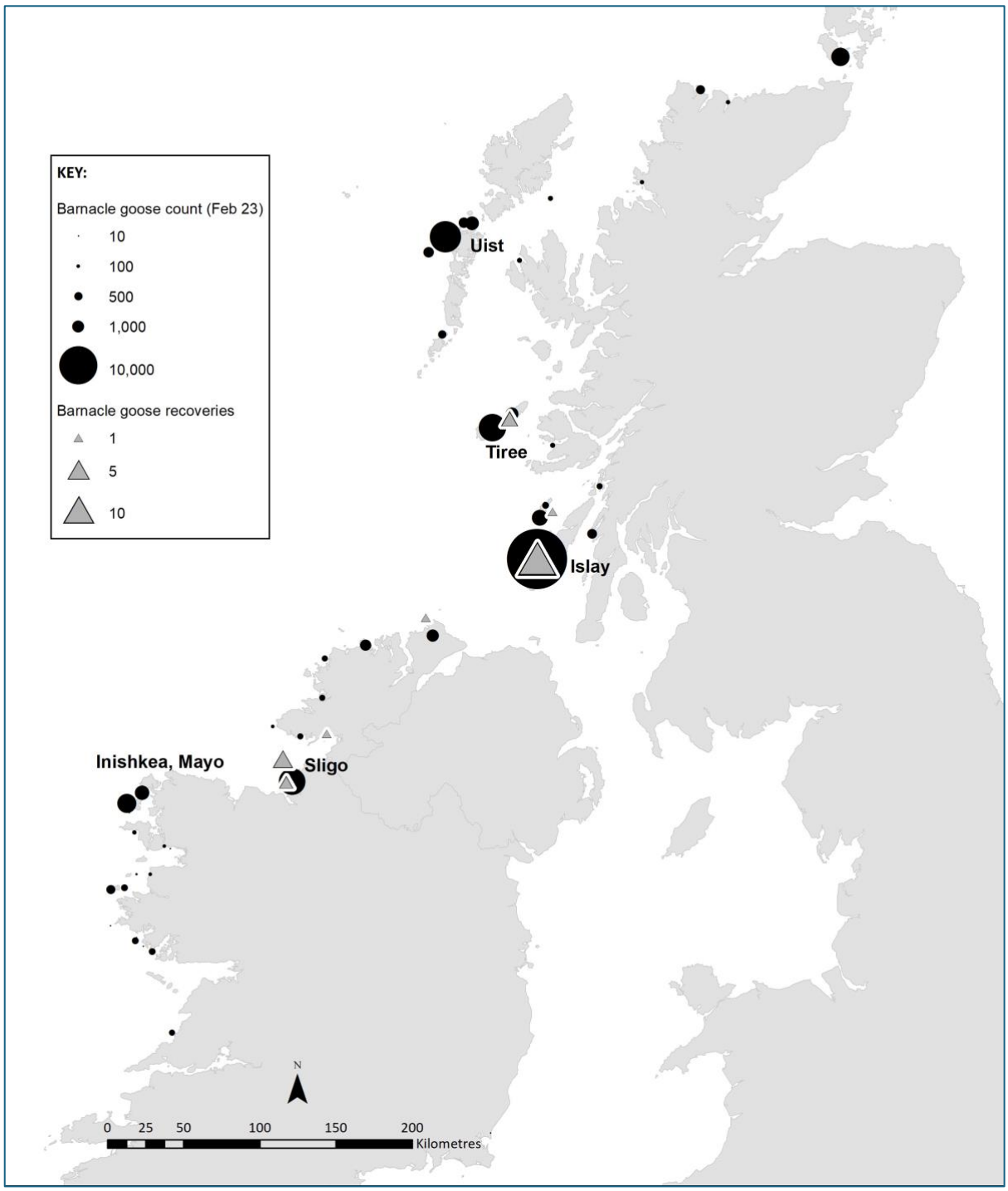

Figure 2. Apparent survival rates at each of the six study sites, with 95% confidence intervals. Grey bars show apparent survival rates between autumn and spring, and white bars between spring and autumn.