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Breeding Common Scoters in Scotland's Flow Country: a population in decline despite productivity being stable

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Abstract

Capsule: The breeding productivity of the Common Scoter population in Scotland's Flow Country remained relatively stable during a 44% population decline in Britain and Ireland.

Aim: To investigate breeding productivity changes in the eastern Flow Country's Common Scoter population over 22 years and identify possible threats and causes of change during a period of national population decline.

Methods: To investigate breeding productivity changes in the eastern Flow Country's Common Scoter population over 22 years and identify possible threats and causes of change during a period of national population decline.

Results: Between 2002 and 2023, whilst the Common Scoter population declined (approximately 44% from 27 to 15 breeding pairs) across the study area, breeding productivity (defined as large ducklings per female) remained stable, averaging 0.44 (range of annual means 0.00–1.06) large ducklings per female. The number of small ducklings per female also remained relatively stable. A year of higher breeding productivity did not result in an increase in the number of breeding females in the following years, suggesting that the cause of the population decline lies away from the breeding region.

Conclusion:

Breeding productivity needs to increase, and poor breeding seasons need to be prevented to help maintain this population. The causes of the Common Scoter's decline away from the breeding area need to be resolved to prevent local extinction. This could be assisted with the removal of non-native forestry plantations in the area, which has been observed to benefit other ground-nesting species by alleviating predation pressure, and by maintaining lake habitat quality, as reflected in shallow water and abundant large invertebrates.

Introduction

Populations of many species of sea ducks (Mergini) are declining (e.g. Bowman *et al.* 2015, Kilpi *et al.* 2015, Snoeken *et al.* 2016). Determining current population sizes and trends of sea-duck populations is imperative to develop effective management strategies (Roy *et al.* 2019). Scoters (*Melanitta* spp.) are the most species rich genus of sea ducks (Collinson *et al.* 2006) and spend the majority of their time at sea but breed in freshwater habitats (Žydelis & Richman 2015).

Breeding scoters occur widely in upland and northern freshwaters across the Holarctic, between the latitudes of 38°N and 74°N (Snow *et al.* 1997, Sibley 2000, Bowman *et al.* 2021). Five of the six recognized species of scoter have declining world populations (Birdlife International 2023a), but here we focus on Common Scoter *Melanitta nigra*, the only scoter species with an unknown global population trend (Birdlife International 2023b).

Common Scoters are highly gregarious in the winter, with flocks occasionally numbering over 100,000 individuals (Scott & Rose 1996), and birds gathering in the Baltic Sea, off the Atlantic coast of Europe and North Africa, and in the western Mediterranean (Snow *et al.*1997). Threats on these wintering grounds, exacerbated by the large flock sizes, include acute and chronic oil pollution (Larsen *et al.* 2007), eutrophication in the Baltic Sea affecting their prey (Skov *et al.* 2020), risk of bycatch in fisheries (Stempniewicz 1994, Žydelis *et al.* 2013), commercial exploitation of a key food resource (benthic shellfish, Kear 2005), windfarm interactions (Birdlife 2023b) and avian influenza (Jonassen & Handeland 2007).

In most European countries the national breeding population trends of the Common Scoter are poorly known (Kilpi *et al.* 2015) and, as with the closely related Black Scoter *Melanitta americana* (Collinson *et al.* 2006) in North America, demographic data are difficult to collect due to their breeding in remote locations and at low densities (Schamber *et al.* 2010). However, the detailed, complete surveys of Common Scoters in Britain and Ireland (in 1995 and 2007), and Ireland only (in 2012), have revealed a severe population decline (Underhill *et al.* 1998, Hunt *et al.* 2012, Musgrove *et al.* 2013), from 95 pairs in 1995 to 52 pairs in 2007 (Musgrove *et al.* 2013). To understand the drivers of this population decline it is important to have information on other demographic parameters, particularly breeding productivity (e.g. the number of fledglings per nesting attempt). The value of population and productivity monitoring in parallel is illustrated by the long-running study of breeding ducks at Lake Mývatn in Iceland (e.g. Gardarsson & Einarsson 2004). That study revealed a clear link for some species between population change and breeding productivity in previous years. For Common Scoters, there was a weak but significant positive relationship between the change in breeding numbers and breeding productivity three years earlier. Larger numbers of young birds can lead to higher recruitment into the population and, therefore, more breeding individuals. Unfortunately, no monitoring schemes of north-west European diving ducks have included such detailed studies, and few monitor breeding productivity despite the value in doing so for a suite of rapidly declining duck species (Kilpi *et al.* 2015).

Population and productivity trends may be affected by various factors. Identification and modelling of the factors affecting duck populations indicate the importance of loss in the quality of breeding habitats, loss in the quality and quantity of wintering habitats, and interactions with competitors (Conroy *et al.* 2002). These factors subsequently affect prey availability, lake condition, spring age ratios, bird condition, nesting success, and brood success (Johnson *et al.* 1987). The only area of Britain and Ireland with long running annual monitoring of breeding Common Scoters, which includes both population and productivity monitoring, is the Flow Country of northern Scotland. Detailed monitoring started there in the 1980s (Hancock 1991), and there was a national survey in 1995 led by the Wildfowl & Wetlands Trust (WWT), with a further round of surveying in 1996 (though this did not include productivity data). These data are available from the RSPB (2023). Monitoring resumed in 2002 following the establishment of Forsinard Flows National Nature Reserve (NNR) and has continued annually from 2002 until the present, on the reserve and in neighbouring areas. The Flow Country has tended to hold approximately half of the British population of breeding Common Scoters during the last 30 years, declining from 36 of 89 British breeding females in 1995, 26 of 52 in 2007, to 18 of 38 in 2018 (Underhill *et al.* 1998 and unpublished data). The other half of the British and Irish population is mostly found in the West Inverness-shire area, with isolated records elsewhere in Scotland. Earlier data imply a higher population in the Flow Country, estimated at 55 females in 1988– 1991 (Partridge 1993), based on detailed surveys in 1988 and 1991 (Hancock 1991) and other unpublished RSPB/WWT data. The importance of the Flow Country as a stronghold for breeding Common Scoters appears to have increased in recent decades, with the national breeding bird atlases (Sharrock 1976, indicating 5/19 of the 10 km breeding survey squares; Gibbons *et al.* 1993, 7/16 squares; Balmer *et al.* 2013, 7/18 squares), showing that the Flow Country held 26%, 44% and 39% of the British Common Scoter's range in 1968–1972, 1988–1991 and 2008–2011.

Over the past 30 years, various changes have taken place in the Flow Country that might have affected the Common Scoter's productivity. Widescale afforestation took place in the 1980s, transforming the character of this formerly largely treeless area (Stroud *et al.* 1987, Lindsay *et al.* 1988, Avery & Leslie 1990). Plantations of non-native conifer trees were established, using extensive drainage and fertilizer application. The establishment and maturation of these forest plantations have attracted increasing numbers of mammalian predators (Hancock *et al.* 2020) and may have increased nutrient levels in some lakes (Robson *et al.* 2019). Both of these factors have potentially reduced the Common Scoter's productivity.

Meanwhile, the traditional recreational angling for Brown Trout *Salmo trutta*, a significant feature of the area for at least 150 years, has declined in popularity and intensity during this period, particularly at the remoter lakes that scoters tend to use (authors' observations, local reports). There has been a growing tendency for trout anglers to favour catching and releasing fish rather than killing and removing them. Both factors may have allowed numbers of Brown Trout to rise in some lakes. This could have implications for Common Scoters, as their pattern of lake use suggests that they compete with Brown Trout for the same invertebrate food (Hancock *et al.* 2016). Furthermore, in the study area, beyond this correlative pattern, it has now been established that experimentally reducing Brown Trout biomass leads to increased biomass of some important invertebrate prey groups (e.g. gammarids) and increased lake use by invertebrate-feeding waterbirds, including Common Scoters (Hancock *et al.* 2023). There has also been a sharp increase in the number of onshore wind turbines in the Flow Country, with 256 already constructed, another 126 approved, with more planned (source: Highland Council Wind Turbine Mapping (NHZ5), January 2023). At sea, Common Scoters are highly vulnerable to population-level displacement by wind turbines (Furness *et al.* 2013), but it is not yet known how the onshore wind turbines in the Flow Country might affect them.

In this study, our aims were: (1) to determine whether the breeding productivity of Common Scoters declined during the study period within Flow County, and whether this may be a factor driving the local population decline; (2) to establish whether high breeding productivity in one year leads to a population increase in subsequent years (one, two or three years later), to allow us to estimate what level of productivity is associated with a stable population and, hence, better predict future population trajectories; and (3) we investigate lake-level habitat associations with breeding productivity to determine what makes a good lake for breeding Common Scoters, in the context of the Flow Country, to inform future management decisions to benefit the long-term breeding success of scoters.

Methods

Study area

The study took place in the Flow Country of northern Scotland (Figure 1), a 4000 km² peatland landscape holding Europe's largest blanket bog and thousands of nutrient-poor pools and lakes, ranging from a few m² to many km² (Stroud *et al.* 1987, Lindsay *et al.* 1988). Approximately 1300 km² of the area was specially protected under the European

Birds and Habitats Directives (Council Directive 92/43/EEC 1992, Lindsay & Andersen 2016). This protection continues to be upheld by the Scottish Government. These European designations include as important qualifying features the presence of breeding Common Scoters, and dystrophic (acidic water with low oxygen content) and oligotrophic (low nutrient) pools and lakes. Care has been taken not to identify specific breeding locations of Common Scoters in this study, as they have special legal protection (Wildlife and Countryside Act 1981), although the broad location is shown in Figure 1.

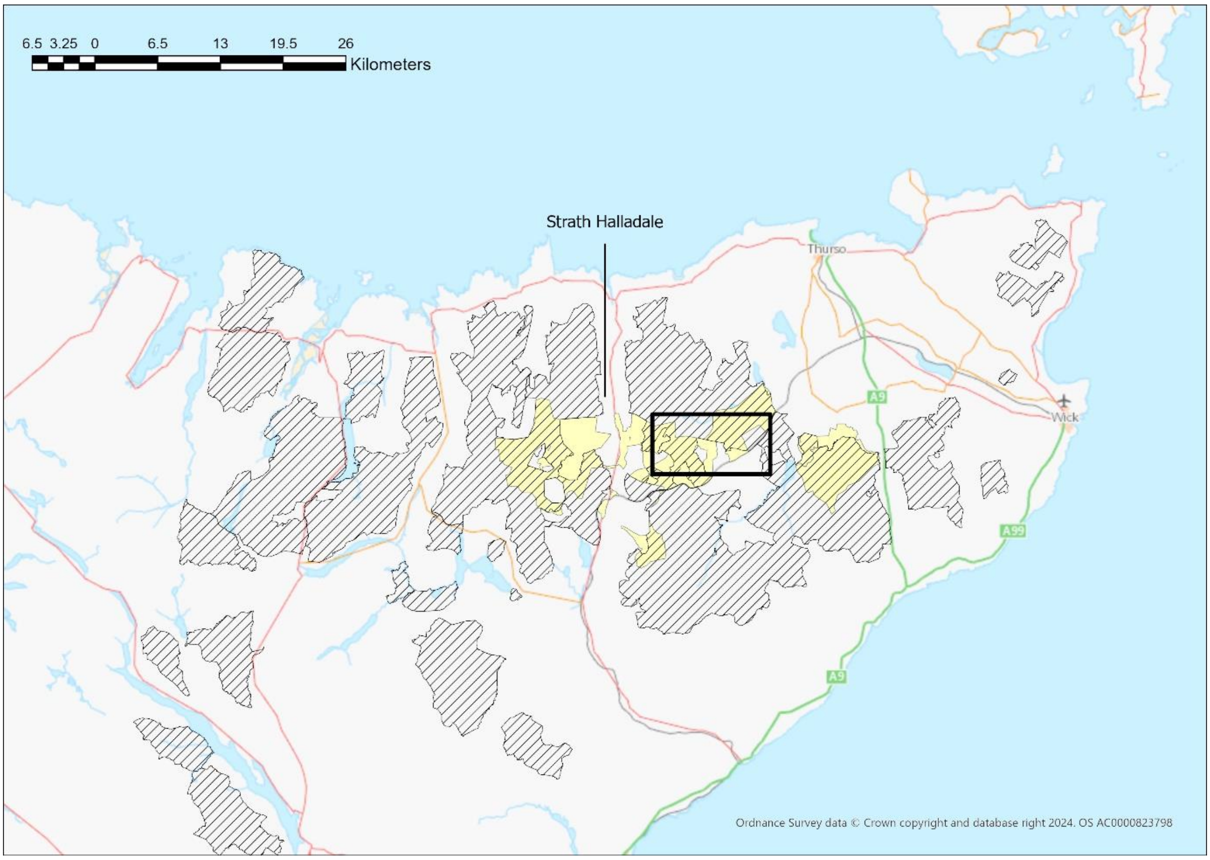

Figure 1. Map of north Scotland showing the location of the Flow Country (Scotland, UK), designated Caithness and Sutherland Peatlands Special Protected Area (diagonal lines), the boundary of Forsinard RSPB reserve (yellow fill), and the general study area (black bordered rectangle).

Our surveys covered the core breeding area for Common Scoters in the Flow Country. Within the wider survey area, we defined ‘sites’ as either an isolated lake or pool system or as a group of small lakes and pools that Common Scoters are known to readily move between during survey visits (Table 1). During the study period, the Common Scoters’ breeding range contracted, resulting in sites west of the Halladale River/Strath being almost completely abandoned, with very few brood records after 2008. Therefore, to maintain annual survey coverage of the breeding area in the face of increased pressure on resources, we excluded these sites after the 2014 breeding season. These excluded westerly sites were visited intermittently in more recent years but without any evidence of use by breeding Common Scoters. This study, therefore, analysed the data from the east side of the Halladale River/Strath, which runs through the centre of the Forsinard NNR, as well as adjacent areas to the south and east of the NNR. In total, our analyses focused on 32 sites where we observed at least one Common Scoter brood during the study period.

Field methods

The gently undulating terrain of the blanket peatland in the Flow Country, and the tendency of many waterbodies to be on broad watershed plateaus, make it challenging to survey lakes from a distance. However, the lack of human disturbance in this remote area means that breeding Common Scoters tend to respond to the arrival of a human observer by swimming out into the centre of the pool or lake and staying on the surface in an alert state, as opposed to flying away or not responding. Hence, we surveyed pools and lakes by walking through pool systems and along lake shores at a steady pace to minimize disturbance while ensuring that all areas of water were observed. The methods generally followed those of previous Common Scoter surveys (Hancock 1991, Underhill *et al.* 1998), where the number of females was taken to represent the number of breeding pairs.

Following earlier developments to the survey methodologies (Hancock 1991, Underhill *et al.* 1998), visits were focused on the main pre-nesting period (May, henceforth termed ‘early’ visits) and the post-hatch period (July and August, henceforth termed ‘late’ visits). The 22 survey years have some variation in effort due to variation in resources available for this work. Typically, all 32 sites were visited two to three times in both the early and the late visit periods. To account for variation in effort, visits outside this period were removed from the analysis. Each survey visit was conducted by multiple experienced observers as synchronously as possible over a morning to reduce the possibility of overcounting due to bird movements.

Data analysis

The following environmental variables that were expected to influence Common Scoters were included in the models exploring the correlates of productivity (summary in Table 1). Some wader species found at Forsinard are known to actively avoid areas near forest edges (Wilson *et al.* 2014); therefore, the distance (km) from the centroid of each site to a forest was included, calculated using ArcGIS Pro version 10 (ESRI 2023). To identify the forest boundaries, we used the 2018 National Forest Inventory Woodland Scotland dataset (Forestry Commission 2021), which describes the size, distribution, composition, and condition of forests and woodlands across Scotland. Forsinard RSPB reserve management data allowed us to determine when forest blocks were removed during the study period, which was incorporated into the distance to forest data. No new forest blocks were added to the area during the study.

Table 1. Environmental variables in the Common Scoter study area (see Figure 1). Distances are measured from focal site centroids to the nearest site centroids and forest edge.

Environmental variables	Value (with range)
Number of sites (grouped lakes)	32
Mean lake surface area (ha)	15.2 (1–40)
Mean distance to nearest survey site (m)	510 (93–1720)
Mean distance to forest (km)	0.83 (0.02–3.09)

Mean shoreline development index (SDI)	1.30 (1.05–1.75)

The Shoreline Development Index (SDI) was derived from the Standing Waters Dataset (UK Centre for Ecology & Hydrology 2023). The SDI indicates the complexity of a lake shoreline, accounting for lake size and the perimeter-to-area ratio, with a higher score indicating a more irregular shape or a greater number of bays and inlets. As such, it reflects the potential for development of littoral communities and sheltered water (Hutchinson 1957). A perfectly circular lake would have an SDI = 1.0. Shallow water (which is linked to higher SDI lakes), positively influences lake selection and foraging of Common Scoters in the Flow Country (Hancock *et al.* 2016, 2019). Other variables considered included relative fish abundance, underlying rock type, distance to the sea, and distance to the nearest lake. Variables with high Variance Inflation Factor (VIF) values (>3) were removed to reduce multicollinearity and improve the accuracy and stability of the models (water catchment area and distance to rivers and lakes were therefore removed). The effects of weather were not explicitly included in the models, but the influence of variables such as temperature and rainfall on Common Scoter productivity was accounted for by the inclusion of year as a random effect in the models.

The lakes and pools were grouped into 32 ‘sites’ to allow for small movements of adults and ducklings between waterbodies in close proximity. The number of ducklings/juveniles was recorded for each of four age classes (I = up to 25% of the size of an adult; II = 25–50%; III = 50–75%; IV = 75–100%; adapted from Southwick 1953). Ducklings were defined as ‘small’ if they were <50% of the size of an adult female and ‘large’ if they were >50% of the size of an adult female. Productivity was calculated as the number of large ducklings divided by the peak number of females counted within the same breeding season. Productivity was calculated at the level of the whole survey site and year, rather than at the lake level, due to different lake preferences in May arrival sites and breeding sites, and to account for the movement of ducklings between water bodies as they develop. White-winged Scoters

Melanitta deglandi, for example, have been recorded moving broods up to 1.5 km from nesting to brood-rearing lakes (Safine & Lindberg 2008). This has also been observed in the study area between different sites (authors' unpublished observations). We derived the peak count of females from the 'early' two and three counts (on or as near as possible to 20 May and 29 May) and derived the peak duckling count from the 'late' two and three (on or as near as possible to 9 July and 23– 24 July) counts, to standardize the dataset. 'Early' and 'late' one (initial) counts were removed as they were not done in all years.

While it is possible that females in breeding areas included some non-breeding individuals (e.g. first-year birds that look almost identical to adult females, or adult females that defer breeding), previous censuses assumed that all females recorded during the counts subsequently attempt to breed, with non-breeders remaining in coastal waters (Underhill *et al.* 1998). Hence, we have used the peak May count of females as the basis for breeding productivity; we used the number of ducklings greater than 50% of adult size, per breeding female, as our measure of productivity, roughly equivalent to the measure of survival for ducklings to 30 days old, as used for Black Scoters (Schamber *et al.* 2010). Whilst we recognize that some ducklings will die between being half-grown and the time of fledging, we needed a practical, repeatable measure of productivity that could be calculated from the available data.

All analyses were performed using R Stats version 4.1.1 (R Core Team 2021). For investigating the correlates of survey-site use by the females, from each site in each year we fitted a binomial logistic model (estimated using maximum likelihood) to predict peak May survey site use by females with the distance to forest plantations and SDI (see definition and rationale in the environmental variables section above). Models were standardized/offset by mean lake size to control for larger lakes potentially holding more females. We then used a multi-model interference tool in the MuMIn R package to run model selection based on model weights derived from AICc scores. Models with ΔAICc < 2 of the top model were considered, assuming this subset did not include the null model (in which case, there was assumed to be no significant evidence of any effects of explanatory variables).

We used the glmmTMB R package (Brooks *et al.* 2017) to run zero-inflated generalized linear models for the duckling productivity and environmental variables (distance to forest plantations and SDI). For investigating correlates of site use by the small and large ducklings, we ran univariate logistic models with absence/presence data for the two sizes of duckling and the same environmental variables. We used these simpler models due to the small sample sizes in the duckling datasets, which were insufficient for a multi model inference approach.

To investigate breeding productivity, we fitted the count of small (Model 1) or large (Model 2) ducklings against the peak number of females in each year, fitting negative-binomial mixed models (estimated using maximum likelihood and Nelder-Mead optimizer), with 95% confidence intervals (CIs) and P values computed using a Wald Z-distribution approximation. Nelder–Mead optimizer was used for multidimensional unconstrained optimization without derivatives (Nelder & Mead 1965). Following maximum likelihood, the Wald Z–distribution approximation was used to estimate the sampling distribution of a mean, assuming it follows normal distribution (Wald 1943). Both models included the study site and year as random effects.

To test whether high breeding productivity in a breeding season leads to an increase in the female population in subsequent years (one, two or three years later), we fitted linear models for each year, across all sites, with P values computed using a Wald t distribution approximation (due to the relatively small sample sizes). The population of females in a given year was the response variable with breeding productivity, and the number of females in the three lag years, the explanatory variables.

To investigate whether the Common Scoter’s local population mirrored the national trends, we fitted a log-linear trend model to evaluate the number of females’ during the period 2002–

2023 using TRIM (Trends and Indices for Monitoring data) models (Pannekoek & van Strien 2006a, 2006b), creating mean indices and associated standard errors in the R package rtrim (Bogaart *et al.* 2018). The overall slopes of these models were the results of linear regressions over time, plus site and year effects that measure deviation from the overall slope. TRIM uses a stepwise selection of change points in trends using Wald tests to assess the significance of change points. TRIM describes trends based on the mean annual rate of change and defines them as either a strong (>5% mean change per year) or moderate change (<5%). Trends were considered significantly divergent from stable when the 95% confidence interval of the slope does not contain zero.

Results

The Common Scoter population in the eastern Flow Country (measured from peak counts of females in May) declined by 40% over 22 years (Figures 2 and 3), consistent with national declines. Between 2002 and 2014, the Common Scoter's local population declined by 29.6%, but between 2015 and 2023 it remained relatively stable, demonstrating the importance of long-term studies. The mean breeding productivity at the study area level (n = 32 sites) was 0.44, with a year-wise range of 0.00–1.06 large ducklings raised per (2002–2023), as did the number of survey sites where scoters were recorded (Table 2). During the most recent year, 2023, 15 pairs of Common Scoters were estimated to have bred. There were no significant changes in the number of small and large ducklings per female over the same period.

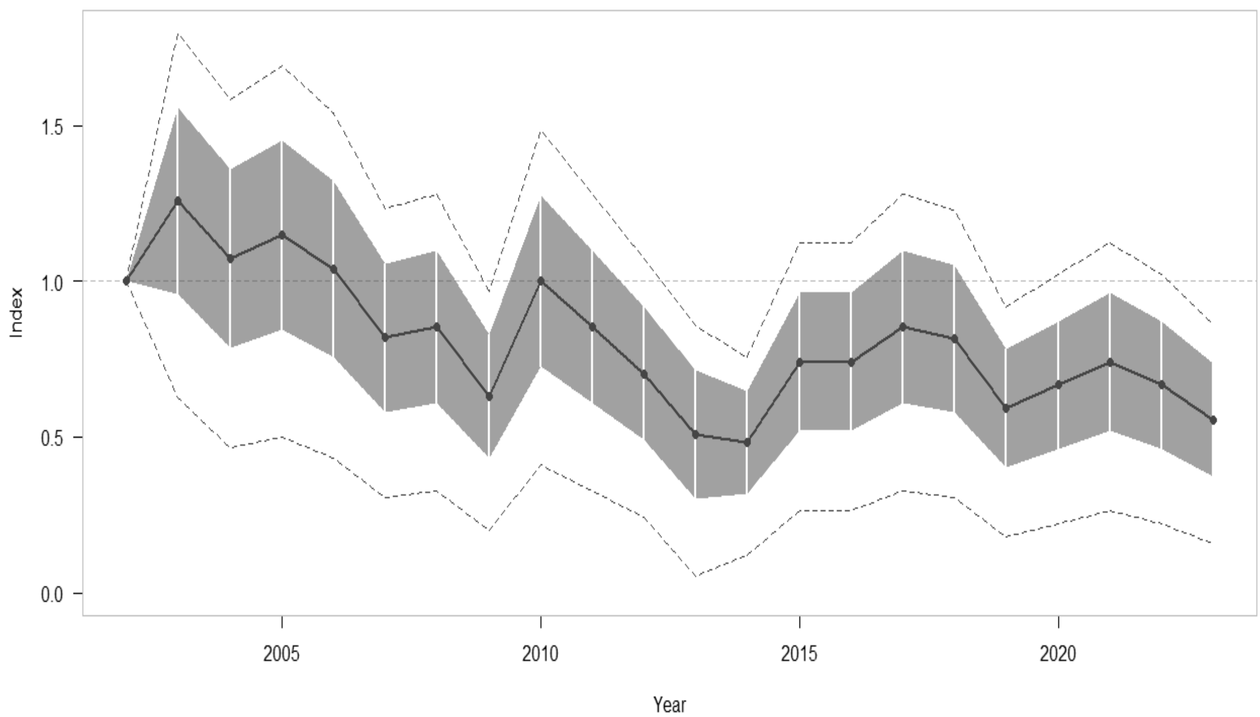

Figure 2. Change in annual index of breeding population for Common Scoter *Melanitta nigra*, in the Flow Country study area, with indices measured relative to the first survey year (2002) and standard error (grey shaded areas) and 95% confidence intervals (dotted line) shown. No surveys occurred in 2020 due to the coronavirus pandemic and associated lockdowns, therefore we used the mean of 2019 and 2021 to gap fill this index.

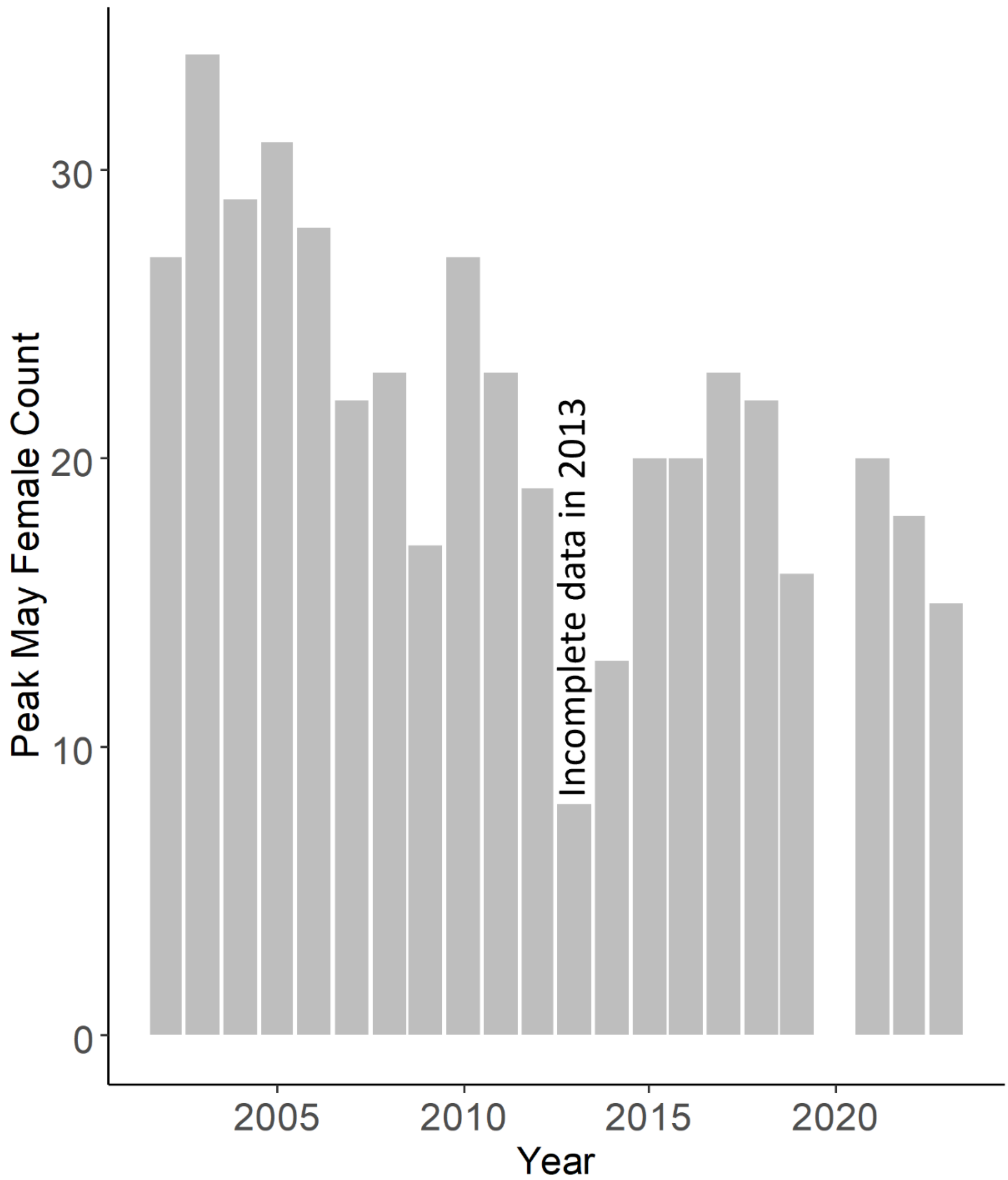

Figure 3. Peak count of female Common Scoter *Melanitta nigra* in May, at the Flow Country study area between 2002 – 2023. No data was collected during 2020 due to the coronavirus pandemic and associated lockdowns. Data is incomplete for 2013, due to a national census whereby fewer visits were made.

The peak count of females in May was lower in the year following a season of high breeding productivity ($t = -2.13$, $P = 0.050$). This was also true for breeding productivity two years previously (t = −2.76, P = 0.016). However, there was no significant change following breeding productivity three years previously (Table 3). There was also a significant positive relationship between the number of breeding females in consecutive years (Table 3).

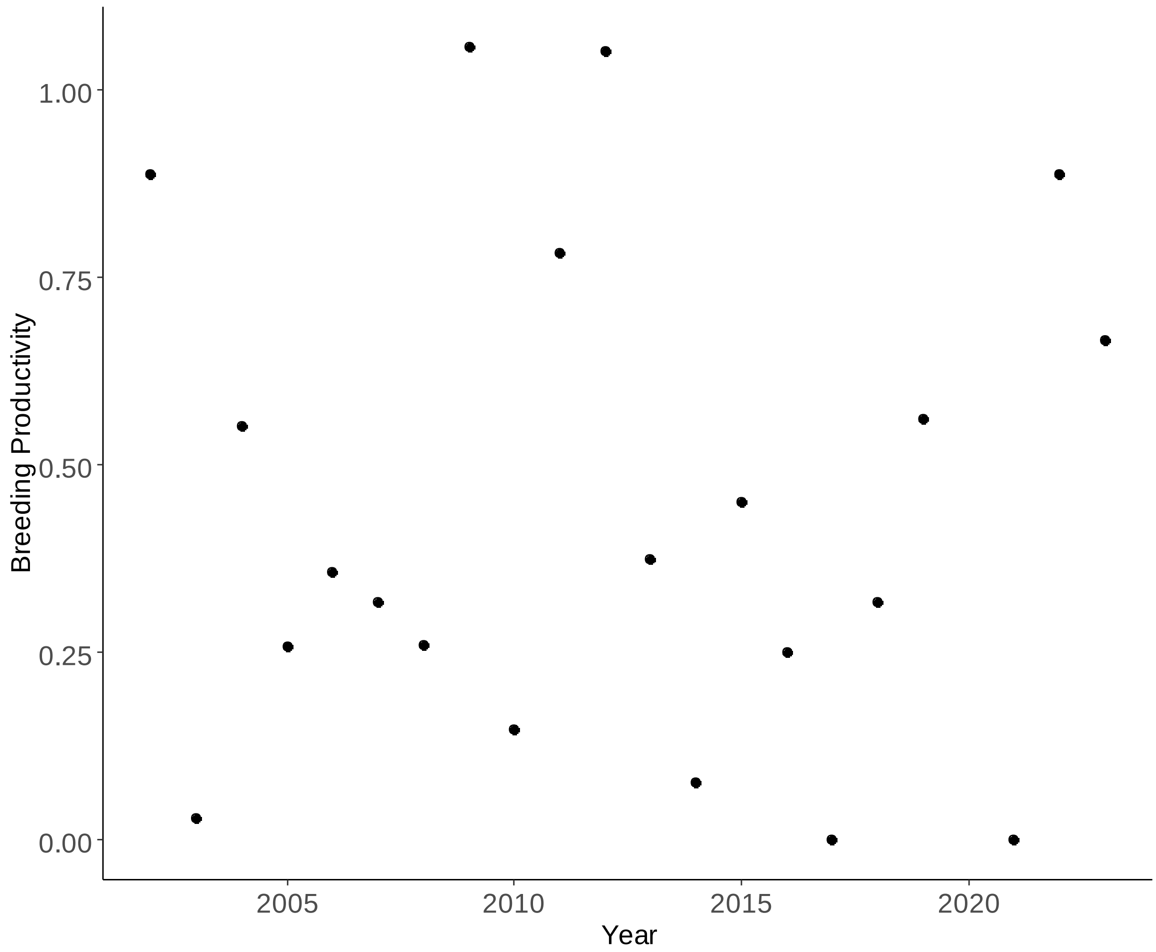

Figure 4. Breeding productivity (the number of large ducklings per peak count of May Females) of Common Scoter *Melanitta nigra* between 2002–2023.

For the lake-use correlate models, based on full model averaging (Table 4) the null hypothesis (ΔAIC 1.35) could not be rejected. However, the model with the lowest AIC showed that May females were encountered more often on lakes with a lower SDI, relating to more round lakes with fewer bays and peninsulas. For the second-lowest AIC the model with the May count of females also decreased with distance to forest plantations and SDI

(ΔAIC 1.16). Random effects were applied in these models, with the effect of survey site having a higher variance than the survey year. Essentially, different years at one survey site were more strongly positively correlated than different sites within one year.

Larger ducklings were encountered more frequently on lakes with a higher SDI, relating to lakes with more complex edges (β value = 0.37, $P < 0.01$). There were no significant interactions between large ducklings and distance to forest plantations, or small ducklings and distance to forest plantations or SDI.

Discussion

Despite the 40% decline in breeding numbers over the past 20 years, the 15 pairs of Common Scoters that bred in the Flow Country probably comprised about half of the UK breeding population in 2023. This study explored some potential reasons for the decline of this species in the Flow Country, and highlights areas that would benefit from future research. Common Scoters face many pressures and threats year-round, and migrate to reduce or avoid these risks (del Hoyo *et al.* 1992). Our results suggest that, whilst the number of breeding females in the study area had declined, the breeding productivity did not (at least over the previous 22 years), and the number of small and large ducklings per female remained relatively stable during the study, despite the reduced number of females. Overall, this work demonstrates the importance of long-term studies, as the female population appears to have been relatively stable between 2015 and 2023, following a decline between 2002 and 2014. A short-term study would have missed the initial decline.

A mean breeding productivity of 0.44 ducklings raised per female in the previous 22 years was relatively standard, compared to values of scoter breeding productivity reported elsewhere, although the available information was predominantly from declining populations (Supplementary Table 1). The mean estimate during 2002–2023 (0.44) was slightly higher than the estimates for 1988 and 1991 (0.37), implying no strong long-term decline in productivity over this period. By comparison, the breeding productivity of Black Scoters in

Alaska ranged from 0.09 to 0.35 over a three-year study (Schamber *et al.* 2010). In Ireland, at Lough Corrib, the productivity of Common Scoters in one study year was 0.80 (Hunt *et al.* 2012). This was considerably higher than the levels of productivity we report in this study, though it was lower than the highest annual values of productivity reported in the Flow Country, where a peak productivity of 1.06 was recorded, which is the highest known Common Scoter productivity. The productivity of other scoter populations worldwide ranged from 0.02 to 2.14 (Supplementary Table 1).

Table 2. Number of ducklings (small and large) and breeding female Common Scoter recorded between 2002–2023. For the number of lakes with large duckling broods, the number in the brackets represents the number of small duckling broods that were seen on the same lake in the same year. i.e., in 2002, eight lakes had large duckling broods, three of which had small duckling broods on the same lake earlier in the year. For the number of lakes with females, this was the number of lakes where female Common Scoter were observed, with the number of small and large ducklings seen on the same lake. I.e., in 2002 female Common Scoters were observed at 18 lakes, three of which had small duckling broods and five of which had large duckling broods. The number of lakes with scoter activity was the number of lakes with either had adult females, small or large duckling observations, with the percentage being that number of lakes / the total study lakes (32).

Year	No. of small ducklings	No. of large ducklings	Peak May Females count	No. of sites with small ducklings	No. of lakes with large duckling broods	No. of lakes with females	No. of lakes with scoter activity
2002	14	24	27	4	8 (3)	18 (3, 5)	21 (65.6%)
2003	20	1	34	2	1 (0)	16 (2, 0)	17 (53.1%)
2004	10	16	29	2	3 (2)	18 (1, 1)	20 (62.5%)
2005	8	8	31	3	3 (2)	13 (3, 3)	13 (40.6%)
2006	12	10	28	5	3 (0)	12 (3, 2)	15 (46.9%)
2007	12	7	22	3	5 (1)	13 (1, 1)	18 (56.3%)
2008	9	6	23	2	3 (1)	11 (1, 2)	12 (37.5%)
2009	23	18	17	5	6 (2)	10 (2, 2)	14 (43.8%)
2010	10	4	27	2	1 (0)	19 (1, 0)	21 (65.6%)
2011	2	18	23	1	3 (0)	10 (0, 2)	12 (37.5%)
2012	0	20	19	0	4 (0)	11 (–, 3)	10 (31.3%)
2013	12	3	8	3	1 (1)	3 (1, 0)	5 (15.6%)
2014	19	1	13	5	1 (0)	9 (3, 0)	10 (31.3%)
2015	1	9	20	1	2 (0)	11 (0, 1)	11 (34.4&)
2016	5	5	20	1	1 (1)	10 (1,1)	10 (31.3%)
2017	18	0	23	4	0 (0)	15 (2, –)	17 (53.1%)
2018	4	7	22	3	3 (2)	12 (0, 0)	12 (37.5%)
2019	10	9	16	3	3 (2)	12 (1, 1)	15 (46.9%)
2020	–	–	–	–	–	–	–
2021	10	0	20	2	0 (0)	11 (2, –)	11 (34.4%)
2022	13	16	18	4	2 (1)	11 (3, 2)	11 (34.4%)
2023	33	10	15	5	4 (0)	17(0, 0)	17 (53.1%)

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Given the relatively long life expectancy of Common Scoters, with an average of six years and adult annual survival of 0.783 (female: 0.783 ± 0.032, BTO 2023), the Common Scoter's population size may be driven by changes in adult survival as well as changes in productivity and recruitment (Gaillard *et al.* 2016). Applying perturbation analysis to the Common Scoter's matrix population model from Petersen *et al.* (2021) shows that the transition from adult survival accounts for 60% of the influence on population growth rate (data not shown). In Lesser Scaup *Aythya affinis*, a freshwater diving duck, an improvement in survival drove population recovery (Arnold *et al.* 2016, Koons *et al.* 2017). Therefore, adult survival could be one of the most important factors driving demographic rates in species like Common Scoter, meaning that a decline in adult survival could underlie the recent population decline in this species.

Table 3. Changes is the peak number of female Common Scoters in May at a period of one, two, and three years after breeding productivity, surveyed during 2002–2023.

	Estimate	**se**	**t**	***p***
(Intercept)	6.2733	4.2004	1.494	0.156038
ProductivityY+1	–10.9105	5.1122	–2.134	<0.05
FemY+1	0.7759	0.1482	5.234	<0.01
(Intercept)	16.0254	4.9794	3.218	<0.01
ProductivityY+2	–15.6515	5.6764	–2.757	<0.05
FemY+2	0.3614	0.1691	2.137	0.05218
(Intercept)	17.7214	5.8632	3.023	<0.05
ProductivityY+3	–12.1908	6.294	–1.937	0.0789
FemY3	0.2376	0.2196	1.082	0.3025

Table 4. Model results testing the effect of environmental variables on Common Scoter females and ducklings during 2002–2023. SDI is the Shoreline Development Index.

Intercept	Distance to forestry	Shoreline Development Index)	df	delta AIC
15.26		–24.86	5	0.00
20.08	–2.500	–26.93	6	1.16
–16.72			4	1.35

In European studies of Common Pochard *Aythya farina*, another freshwater diving duck, increased pressure on females during the breeding season (Fox *et al.* 2016, Brides *et al.* 2017) was not an underlying factor in adult survival, indicating that population changes were linked to factors outside the breeding season (Folliot *et al.* 2020), which may also need to be considered in Common Scoter. It could be expected that a year with high breeding productivity would result in an increase in the number of females in the following years, but the opposite was found in our study. Could the act of raising ducklings be reducing subsequent survival of the females? This would help to explain the negative correlation between productivity and subsequent female population size in the following two breeding seasons. The significant positive relationship between the change in breeding numbers and breeding productivity three years earlier (Gardarsson & Einarsson 2004) generally support this. In contrast, in our study, the lower return rates due to poor winter survival could mask changes in recruitment. Exhaustion from successfully raising ducklings may reduce a female's chance of winter survival or make them more likely to defer breeding, which has been recorded in other sea ducks (Steenweg *et al.* 2022).

Lake selection

During May, when Common Scoters engaged in courtship and display, there was a (non-significant) tendency for female occurrence to be negatively associated with lake SDI. It is not known whether the selection of these lakes for such activities are driven by the females, males or both. Rounded, open lakes might be preferred for better visibility during displays and for individual safety, as opposed to smaller, more obscured lakes. Larger, more open areas could also amplify display calls further, although observers may simply have found it easier to detect and count scoters on more open lakes.

Logically, it should be expected that small ducklings would be observed more frequently than (or at least as often as) large ducklings during our surveys, but this was not always the case. Large-size duckling broods were found on more lakes than broods of small ducklings in nine of the 21 observation years, suggesting small broods were being missed or had moved lakes. The greater detection rates for large ducklings on lakes with higher SDI's might be due to them spending more time on open water, making them more visible to observers. However, Hancock *et al.* (2019) found that all duck sizes had a very strong preference for shallow water when foraging. It might also be expected that lakes that had small broods present would also have large broods present in the same year, but this was not the case. Only 18 sites from 57 observations of large ducklings at various sites over 21 survey years recorded both small and large duckling broods in the same year.

This discrepancy could, at least in part, be due to observers having failed to detect small broods. However, this is also likely to be influenced by some female Common Scoters moving their small ducklings from where they hatched to different lakes as they develop, as described further below. Given that the ducklings were unable to fly at this stage, this movement would be through burns (small rivers), ditches and streams. King Eiders Somateria spectabilis, another diving sea duck, have been tracked moving broods ≥1 km overland during the breeding season (Mehl & Alisauskas 2007) and Common Scoter ducklings are thought to walk long distances in Ireland (Ferguson 1971). Our data also show that female Common Scoters were observed in many more sites in each year (means of 12.5 compared to the 2.9 for small and 2.7 for large ducklings) than were reported to hold ducklings later in the breeding season. This suggests that the females utilize a wide range of lakes early in the season compared to when they are rearing ducklings. Adult scoters were frequently seen flying between lakes during surveys, while inter-lake duckling movements were (understandably) rarely observed.

Later in the season, large ducklings were found to be associated with a higher SDI. Lakes with a higher SDI suggests that they have more bays and contours (Hutchinson 1957) that could offer hiding places from predators, as well as shallow water areas, which have also been shown to be highly preferred by foraging ducklings (Hancock *et al.* 2019), and likely have good prey availability. A higher SDI in lakes is thought to have a positive influence on invertebrate species richness (Friday 1987), including Coleoptera species (Angélibert *et al.*

2010), and the value of the shallow water and large invertebrates for Common Scoters breeding in Scotland was highlighted by Hancock *et al.* (2016, 2019). Lakes with a higher SDI may provide more hiding places from predators, although they could also offer ambushing sites for predators. Surf Scoters *Melanitta perspicillata* showed a strong preference for high SDI areas in Canada, where birds are thought to use the shoreline features as shelter from strong winds (Lesage *et al.* 2008), and where shallow water can facilitate foraging by ducklings. The susceptibility of small ducklings to energy loss (due to their size and plumage) could contribute to this association with sheltered bays. The open landscape and windy climate of the Flow Country could make these factors relevant for lake selection by breeding scoters in our study area.

Effects of afforestation

Earlier data imply a higher population of Common Scoters in the Flow Country, estimated as 55 females in 1988–1991 (Partridge 1993) based on detailed surveys in 1988 and 1991 (Hancock 1991) and other unpublished data. Declines coincided with the afforestation of large areas of the Flow Country with non-native trees (Stroud *et al.* 1987). Although Common Scoters were still breeding in the young forested area, further declines were predicted based on likely hydrological changes linked to this management (Underhill *et al.* 1998). The presence of forest cover before the population counts began limits the possibilities of fully explaining population changes, with 60% (18) of the Common Scoter lakes within the study located within 700 m of forest plantations. Whilst scoters can breed near or in woodland (e.g. at West Invernessshire Lakes, Scotland; NatureScot 2023), the effect of non-native forest plantations and associated predators are untested for this species.

Common Scoters also breed in forests outside of the UK, but these differ from non-native conifer plantations in aspects that could influence scoter breeding success, such as vegetation composition and structure, and mesopredator densities, which are especially high in UK forests (Roos *et al.* 2018). On a more global scale, Common Scoters select more open areas than other species in the Arctic (Snow *et al.* 1997), where trees are largely absent.

Recent camera-trap research in our study area (Forsinard) has shown that Red Foxes *Vulpes vulpes* and European Pine Martens *Martes martes* hunt much further out into the open bog, away from the forest edges, than was previously thought (Rob McHenry pers. comm). Pine Martens colonized the study area sometime between 2003 and 2016 (Hancock *et al.* 2020) and footprints were frequently observed on monitoring pads as early as 2009 (unpublished data). Pine Martens were more frequently observed in the study area than Red Foxes, perhaps due to their less secretive nature and greater activity during daylight hours, with the culling of foxes on neighbouring land possibly making them more elusive. Both species are known to predate bird eggs and ducklings (Seymour 2000, Weidinger 2009). Other mammalian predators present at lower densities than Pine Marten and Red Fox include five other mustelid species, as well as European Hedgehog *Erinaceus europaeus* and Feral Cat *Felis catus* (Hancock *et al.* 2020). Alongside these, Adders *Vipera berus* (another nest predator) are also present. Possible avian nest predators present include multiple corvid, raptor and gull species, whilst Great Skuas *Stercorarius skua* and Black-throated Divers *Gavia arctica* have been observed attacking Common Scoters in the study area (Hancock *et al.* 2019).

Self-seeding of non-native trees away from forest blocks poses a significant problem in the Flow Country, and while the dataset of the National Forest Inventory Woodland Scotland (Forestry Commission 2021) was useful for broadly identifying forest blocks, it does not include those self-seeded non-native trees at the edges of some important lakes used by Common Scoters in the study area (pers. obs). Although the trees may not be as dense as the.standing forest plantations, they may still provide enough cover for mammalian predators to access Common Scoters breeding on the lakes.

Common Scoters are known to move their broods through the pool systems and often used early ‘display lakes’ differently than brood lakes. Forest plantations could create physical barriers between lakes and water courses, affecting the connectivity between these pool systems and lakes. Other types of physical barrier could include fencing, which may pose a collision risk to waterfowl and aid predators by providing carcasses (e.g. grouse; Baines & Summers 1997). Deer fences are widespread in the Flow Country, where they are used for forest plantation conservation and management, road safety, and livestock protection, as well as preventing the movement of deer onto neighbouring land. Fences are also linear foraging routes (Boone & Hobbs 2004), providing perches for forest-nesting raptors such as Common Buzzard *Buteo buteo* (Cieśluk *et al.* 2023), which could increase predation risk of broods moving across the country. The effect of fences, through the provision of perches, is particularly relevant in open landscapes (Andersson *et al.* 2009).

Importance of long-term monitoring

In the 21 years of data collection, 19.8% of the recorded ducklings that had the potential to fledge came from the two most productive breeding years (18 in 2009 and 20 in 2012). With high-productivity years being quite rare, such events could easily be missed if monitoring was not done every year, demonstrating the importance of complete long-term datasets. It may be that these years of higher productivity can sustain the population when all conditions are favourable; while this might be a viable strategy under natural conditions, it could reduce population resilience in impacted ecosystems – there is less 'bet hedging' for a species if everything hinges on one or two years in every 20. This issue is relevant to the suitability of monitoring strategies for different species. For example, 10- to 20-year cycles of Statutory Conservation Agency/RSPB Annual Breeding Bird Scheme (SCARABBS) surveys or national seabird censuses make sense for populations of long-lived birds but are less well suited to generating information on productivity, especially in populations whose breeding output varies markedly from year to year.

Food availability for ducklings or adults on the breeding grounds could limit the breeding success of Common Scoters. Unfortunately, no diet data are available for the study area. Increases or range expansion may also be linked to other factors. Numbers of Tufted Ducks

Aythya fuligula, another dive-foraging species, increased in the Flow Country over the same period at similar lochs (Hughes *et al.* in prep.), and this may inflate interspecific competition for prey. Increased numbers of Tufted Ducks, as well as Mallards *Anas platyrhynchos* and Eurasian Wigeons *Mareca penelope*, may be related to the removal of non-native forest plantations and, consequently, reduced predation pressure. As Common Scoters are yet to respond in the same way as other duck species, this may also indicate that the scoters' problem lies away from the breeding area.

Challenges away from the study site

Whilst this paper explores the challenges faced by Common Scoters on their breeding grounds, it does not consider threats on migration or the wintering grounds. With breeding locations in the study area averaging 18 km from the sea, newly-fledged scoters need to negotiate another relatively new landscape feature, wind turbines, before they get to the sea. Common Scoters at sea are highly vulnerable to population-level displacement by wind turbines (Furness *et al.* 2013). It is not yet known whether onshore wind turbines in the area will affect Common Scoters, either through displacement, collision risk or barrier effects, with Common Scoters having been recorded flying at wind turbine height (summarized by Furness *et al.* 2013).

Conclusion

This study provides a comprehensive analysis of the Common Scoter population in Scotland's eastern Flow Country over a 22-year period, revealing a concerning 40% decline that was consistent with national trends. Despite this decline, the importance of the long-term study was highlighted, with the initial decrease in Common Scoters observed between 2002 and 2014, followed by a period of relative stability between 2015 and 2023. As far as we are aware, this population represents approximately half of the UK's breeding population of Common Scoters, and a national census planned for 2024 should verify this.

The study found that while the numbers of breeding females decreased, breeding productivity remained relatively stable, despite fluctuations. While this study indicates possible causes of decline on the breeding grounds, along migration routes and at their wintering grounds, it highlights a lack of knowledge for some basic aspects of the Common Scoter's ecology. For example, little is known about where Common Scoters migrate to and where they over-winter, partly due to the challenges of catching and deploying tracking devices on adult scoters.

The conservation of the Flow Country's Common Scoters could benefit from measures to increase or maintain duckling survival, such as trout management (Hancock *et al.* 2023) or restoration of afforested landscapes to open, peatland habitats. However, the long-term future of UK's Common Scoters hinges on the ability to improve annual (and particularly over-winter) survival, which is likely to require co-ordinated conservation action at an international level.

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Supplementary materials

Supplementary Table 1. Breeding productivity (number of chicks raised per scoter pair/female) from all known recording studies.

Species	Breeding area	Breeding productivity	Population trend	Year of study	Reference
Common Scoter	Flow County, Scotland	0.44 (0–1.06)	Declining	2002–2023	this study
Common Scoter	Lough Corrib, Ireland	0.55	Declining	2020	Heffernan & Hunt 2022
Common Scoter	Lough Corrib, Ireland	0.8	Declining	2012	Hunt *et al.* 2012
Common Scoter	Lough Ree	0.8	Declining	2012	Hunt *et al.* 2012
Common Scoter	Lough Arrow	1	Declining	2012	Hunt *et al.* 2012
Common Scoter	Lough Conn/Cullin	0	Declining	2012	Hunt *et al.* 2012
Black Scoter	Yukon–Kuskokwim Delta, Alaska	0.22 (0.09 – 0.35)	Declining	2001–2004	Schamber *et al.* 2010
White–winged Scoter	Central Saskatchewan, and east–central Alberta, Canada	≤ 0.5	Unknown	1977–1980	Brown 1982
White–winged Scoter	Redberry Lake, Saskatchewan	0.22 – 0.45	Unknown	1996	Brown & Fredrickson 1997
Velvet Scoter	Valassaaret, Finland	0.02 – 0.60	Unknown	1962	Hildén 1964
Surf Scoter	Lake Malbaie, Québec, Canada	0.84 & 2.14	Unknown	1994–1995	Lesage *et al.* 2007