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Reduced breeding success in Great Black-backed Gulls (*Larus marinus*) due to harness-mounted GPS device

SAMUEL LANGLOIS LOPEZ,*[1] GARY D. CLEWLEY,[2] DANIEL T. JOHNSTON,[2] FRANCIS DAUNT,[3] JARED M. WILSON,[4] NINA J. O'HANLON[2] & ELIZABETH MASDEN[1]
[1]*Environmental Research Institute, UHI North Highland, Ormlie Road, Thurso, KW14 7EE, UK*
[2]*BTO Scotland, Stirling University Innovation Park, Stirling, FK9 4NF, UK*
[3]*UK Centre for Ecology & Hydrology, Bush Estate, Penicuik, Midlothian, EH26 0QB, UK*
[4]*Marine Scotland Science, 375 Victoria Road, Aberdeen, AB11 9DB, UK*

Animal-borne bio-logging devices are routinely fitted to seabirds to learn about their behaviour and physiology, as well as their interactions with the marine environment. The assessment and reporting of deleterious impacts from such devices on the individuals carrying them is critical to inform future work and improve data quality and animal welfare. We assessed the impacts of thoracic-harness attachments on the breeding performance and inter-annual return rates of Great Black-backed Gulls. We found that tagged individuals hatched fewer eggs per nest (0.67) than two different control groups (handled but not tagged – 2.0, and not handled – 1.9) and had lower hatching success rates per nest (27% compared with 81% and 82% in control groups). Inter-annual return rates were similar between tagged and control groups, but the harness attachment potentially caused the death of an individual 5 days after deployment. Overall, the harness attachment was a lead driver of nest failure. We urge extreme caution for those wanting to use harness-mounted devices on Great Black-backed Gulls.

Keywords: animal welfare, device effects, seabird thoracic harness, seabird tracking.

Recent technological advances have revolutionized the field of bio-logging and animal movement ecology. There is now a plethora of animal-borne devices available (GPS, geolocators, accelerometers, cameras, time-depth recorders, etc.) that provide insights into the behaviour and physiology of species at the individual level, and data to inform the protection and conservation of habitats (Hussey *et al.* 2015). Birds are routinely fitted with bio-logging devices to learn about their ecology and physiology, and inform their conservation (Davies *et al.* 2021). Such devices, their attachment methods, and associated handling procedures, however, can have deleterious impacts on the behaviour, physiology and phenology of the individuals carrying them. These impacts may appear as higher energy expenditure, increased foraging times and changes in time budgets (Barron *et al.* 2010, Vandenabeele *et al.* 2012) that may ultimately reduce breeding success or survival. The effects may differ markedly between species even when they are ecologically and physically similar (Thaxter *et al.* 2016) and they may also vary according to the device characteristics, device placement, attachment duration, and handling invasiveness and duration (Thaxter *et al.* 2014, Vandenabeele *et al.* 2014, Bodey *et al.* 2017). This means that subtle changes in the deployment technique may result in different outcomes in terms of negative impacts, which consequently may lead to non-representative data being collected if individuals are not behaving normally and raise welfare concerns. Due to the wide range of deleterious impacts reported in the literature and their potential causes, it is not possible to make generalizations about device effects across species groups or

*Corresponding author.
Email: samuel.lopez@uhi.ac.uk
Twitter ID: @Naturalist_Sam

even between populations (Kelly *et al.* 2015). The assessment of device effects, efforts to mitigate them and their accurate reporting should be an integral part of bio-logging studies to validate the data and inform future tagging work.

GPS devices are fitted to seabirds using a variety of techniques depending on the required attachment duration and device characteristics. Short-term deployments (days to weeks) are typically achieved using glue, tape or zip ties to attach the device to tail or back feathers (e.g. Votier *et al.* 2011, Ponchon *et al.* 2017, Bonnet-Lebrun *et al.* 2022). Obtaining year-round or multi-year data relies on the use of more permanent attachment methods such as implants, leg rings or harnesses (Hatch *et al.* 2000, Daunt *et al.* 2006, Mallory & Gilbert 2008, Pérez-García *et al.* 2013, Weston *et al.* 2013). GPS implants are not frequently used, probably because they are highly invasive and can cause higher mortality rates, particularly in diving seabirds (Hatch *et al.* 2000). Leg rings impose several restrictions in terms of device capabilities; they need to be smaller and lighter, and are exposed to more wear and less sunlight. Thus, harnesses are the predominant method that allows multi-year, high–resolution movement data to be collected.

Harnesses carry higher risks to the birds due to the possibility of entanglement, constriction, or abrasion of skin or feathers from the materials, and also because of the high level of skill required to fit them properly (Geen *et al.* 2019, Clewley *et al.* 2021a). There have been several trials across seabird species with mixed findings on deleterious impacts. For example, leg-loop harnesses did not appear to impact the short-term survival or breeding success of South Polar Skuas *Catharacta maccormicki*, whereas they led to nest failure and probably higher overwinter mortality in Northern Fulmars *Fulmarus glacialis* (Mallory & Gilbert 2008). In large *Larus* gulls, both leg-loop and thoracic harnesses have been extensively used, particularly in Herring Gulls *Larus argentatus* and Lesser Black-backed Gulls *Larus fuscus*, and recent studies reported no detectable short- and longer-term effects on breeding success or overwinter survival (Thaxter *et al.* 2014, Clewley *et al.* 2021b, O'Hanlon *et al.* 2022), suggesting that perhaps other large gull species are appropriate subjects for harness-mounted devices.

The Great Black-backed Gull *Larus marinus* is a species of increasing conservation concern. It has declined by approximately 48% globally between 1985 and 2021 (Langlois Lopez *et al.* 2022) and there is interest in understanding its movements throughout the annual cycle and potential interactions with offshore windfarms because large gulls could be impacted by these developments (Furness 2019). As harness-mounted devices have been successfully used on ecologically and physically similar species with no detectable impacts over a relatively long periods (1–2 years; Thaxter *et al.* 2016, Clewley *et al.* 2021b, O'Hanlon *et al.* 2022), Great Black-backed Gulls would *a priori* be good candidates for harness-mounted devices. However, they have been the subject of few published harness-based tracking studies and device effects have not been investigated and reported, although previous observations by Maynard *et al.* (2022) showed a high level of breeding failure during incubation (six of eight tagged birds) after Great Black-backed Gulls were fitted with leg-loop harnesses. As a species of interest for future tracking work, further research is needed to understand its susceptibility to harness attachments. In this study we assessed whether there were any negative impacts on breeding performance and inter-annual return rate of Great Black-backed Gulls in the year following the deployment of GPS loggers with weak-link thoracic harnesses on 11 breeding individuals.

METHODS

Study site

Data collection took place on the Isle of May National Nature Reserve, Firth of Forth, Scotland (56°11′09.5″N; 2°33′21.3″W), in 2021 and 2022. Great Black-backed Gulls first colonized the island in the 1980s and have steadily increased since then, with approximately 120 breeding pairs in 2021 (Outram & Steel 2019, S. Langlois Lopez unpubl. data). The collection of data was carried out during the breeding season, commencing just before the first Great Black-backed Gull egg was found on 17 April, and finishing on 1 August once all chicks had fledged.

Bird capture and harness attachment

In 2021, 34 adult Great Black-backed Gulls were trapped at the nest using a combination of walk-in traps (three birds) and a leg-noose (31 birds;

Table 1. Details of Great Black-backed Gulls captured on the Isle of May in 2021.

Capture date	Nest type	Bird ID	Sex	Mass (g)	Device mass (%)	Days to hatching	Clutch size	Days to failure	Eggs hatched	Chicks fledged
14/05/2021	Tagged	HT74213	M	1620	1.96	6	2	< 6	NO	NO
16/05/2021	Tagged	HW99176	M	1660	1.98	< 20	2	< 1	NO	NO
11/05/2021	Tagged	MA43182	F	1600	2.04	12	3	–	YES	YES
11/05/2021	Tagged	MA43183	F	1550	2.13	< 14	2	5–8	NO	NO
11/05/2021	Tagged	MA43184	F	1440	2.26	9	2	8	NO	NO
14/05/2021	Tagged	MA43185	M	1900	1.68	14	2	–	YES	YES
15/05/2021	Tagged	MA43186	F	1460	2.23	11	1	4	NO	NO
15/05/2021	Tagged	MA43187	M	2100	1.58	12	3	–	YES	YES
15/05/2021	Tagged	MA43188	F	1690	1.94	< 17	2	< 4	NO	NO
15/05/2021	Tagged	MA43189	M	1960	1.69	16	3	Unknown	NO	NO
18/05/2021	Tagged	MA43194	M	1880	1.76	Unknown	2	Unknown	NO	NO
20/05/2021	Handled	HT74299	M	1900	–	Unknown	3	–	YES	YES
29/05/2021	Handled	HT93167	M	1880	–	Unknown	2	< 6	NO	NO
29/05/2021	Handled	MA32560	M	1760	–	10	3	–	YES	NO
01/05/2021	Handled	MA43179	M	1895	–	17	3	–	YES	YES
05/05/2021	Handled	MA43180	M	1795	–	Unknown	3	2	NO	NO
09/05/2021	Handled	MA43181	F	1485	–	Unknown	2	–	YES	YES
16/05/2021	Handled	MA43190	F	1410	–	Unknown	3	–	YES	NO
17/05/2021	Handled	MA43191	M	1550	–	Unknown	3	–	YES	YES
17/05/2021	Handled	MA43192	M	1590	–	Unknown	3	< 13	NO	NO
17/05/2021	Handled	MA43193	M	1820	–	20	3	–	YES	NO
18/05/2021	Handled	MA43195	F	1550	–	18	3	–	YES	YES
19/05/2021	Handled	MA43196	F	1490	–	17	3	–	YES	YES
20/05/2021	Handled	MA43197	M	2110	–	Unknown	2	–	YES	NO
23/05/2021	Handled	MA43198	F	1450	–	Unknown	3	< 4	NO	NO
25/05/2021	Handled	MA43199	F	1655	–	1	2	–	YES	YES
26/05/2021	Handled	MA43200	F	1560	–	4	3	–	YES	NO
26/05/2021	Handled	MA43201	F	1490	–	1	3	–	YES	NO
26/05/2021	Handled	MA43202	M	1890	–	10	3	–	YES	YES
27/05/2021	Handled	MA43203	M	2060	–	2	3	–	YES	NO
27/05/2021	Handled	MA43204	F	1590	–	Unknown	3	–	YES	NO
02/06/2021	Handled	MA43207	F	1540	–	6	3	–	YES	YES
02/06/2021	Handled	MA43208	F	1600	–	6	3	–	YES	NO
20/06/2021	Handled	MA43239	M	1720	–	Unknown	1	–	YES	NO

Nest type reflects whether the bird was captured but not fitted with a GPS device (handled) or fitted with a GPS device (tagged). Sex (F = female; M = male). 'Device mass' reflects the summed mass of the harness plus tag relative to bird body mass. 'Days to hatching' reflects how many days of incubation were left after capture. 'Days until failure' refers to the number of days the clutch was still present and being incubated after bird capture before failure.

Table 1). Where possible, nests with known laying dates were targeted and trapping was undertaken during the second half of incubation. This was done to allow birds to become strongly bonded to their nests prior to capture and reduce the risk of post-capture abandonment. Only one adult was targeted per nest to avoid potential handling/tagging impacts on both adults. During capture, the clutch was replaced with dummy eggs when traps were set, to reduce the risk of predation during handling and was switched back upon release. Feather samples (approximately 10 barbs from one primary, one secondary and nape feathers) were clipped from all birds for a separate study, and biometrics (head and bill, bill length to feather, bill depth at gonys, minimum tarsus, wing length (to the nearest mm); and mass (to the nearest gram)) were taken for sexing purposes. All birds were fitted with a metal British Trust for Ornithology (BTO) ring and an individually marked colour-ring to allow for post-capture monitoring. Birds were sexed using morphometrics following Mawhinney and Diamond (1999). Eleven birds (five females and six males) were fitted with long-term, solar-powered GPS/GSM loggers with a three-point attachment design (25 g Flyway-25; Movetech Telemetry, Thetford, UK; Table 1). The attachment method was a thoracic cross strap harness with a weak-link, described in detail in Clewley *et al.* (2021b). Briefly, the harness is made of four straps of Teflon tubular ribbon (Bally Ribbon Mills, Bally, PA, USA) that fit around both wings and neck of the bird, all joined together at a central loop made of cotton, which acts as a weak-link and causes the harness to fall off after the weak-link breaks. Because Great Black-backed Gulls are larger than Herring and Lesser-black Backed Gulls, the diameters of the Teflon used was 8.38 mm rather than 6.35 mm. The expected attachment period for this study was 1–3 years. The mass of the harness and tag was < 3% of the birds' mass in all cases (Table 1; range 1.58–2.26%; Phillips *et al.* 2003). Average handling time (time from capture to release) per bird was 43 min (range 35–60 min) for those that received GPS tags, and 13 min (range 5–23 min) for the remaining birds.

Nest monitoring and control groups

A total of 82 nesting attempts (at least one egg laid) by 82 pairs of Great Black-backed Gulls were followed throughout the 2021 breeding season. These were divided into 11 'Tagged' nests (one adult of the pair was caught for ringing and feather sampling, and received a GPS logger), 23 'Handled' nests (one adult was caught for ringing and feather sampling) and 48 'Control' nests (no adult was caught). Throughout the rest of this paper these are referred to as tagged, handled and control, respectively. Having these three groups allowed us to compare handled and tagged nests against controls, as well as discriminate between the effects of handling only and tagging on the birds' breeding performance, although such discrimination was potentially confounded due to birds from handled and tagged nests being handled for different amounts of time (see 'Data analysis'). Nests were monitored via observations from a vantage point or walks through the colony typically every 3–5 days, when individual nest status and contents were recorded. The distribution of nests on the Isle of May was heterogeneous, with an area of high density in the north of the island containing most breeding pairs (approximately 100) and the rest of the island to the south holding approximately 20 breeding pairs. We tried to keep a similar ratio of each nest type in the low-density area to minimize potential biases because of location and lower nesting density (Fig. 1).

From all 82 nests, we obtained four breeding metrics to measure overall breeding performance. These were: number of eggs hatched per nest, binary hatching success per nest (success or failure), binary fledging success per nest (success or failure from nests that successfully reached hatching) and overall productivity (number of chicks fledged per nesting attempt). We selected these metrics because handling or tag effects could be reflected by binary variables (success or failure of hatching and fledging), but could also be reflected as a reduction in the number of eggs and chicks produced per nest without necessarily leading to complete failure, which may be missed if only using binary variables. Furthermore, we selected both incubation and chick-rearing metrics, as tagging or handling effects may be more apparent in one than the other.

Overwinter return rates

In 2022, resighting of adult individuals that had been colour-ringed in 2021 (birds from tagged and handled nests) was undertaken on the Isle of May between 1 May and 25 July 2022. We used this information to understand whether return rates were similar between tagged and handled birds, assuming a relatively similar observation effort, and to rule out any obvious tag-induced impacts on adult survival as previously described in Great Skuas *Stercorarius skua* (Thaxter *et al.* 2016). Had all GPS tags worked throughout the 2022 winter and breeding season, absolute estimates of return rates of tagged individuals would have been obtained. However, only two of 10 GPS loggers were still transmitting locations in 2022 due to malfunction of the GPS devices (all birds resighted in 2022 were still carrying their tags). Thus, we had to rely on observations to ascertain whether tagged birds were still alive and had returned to the colony.

Data analysis

All analyses were carried out in R version 4.0.4 (R Core Team 2021).

To identify differences in breeding performance between nest groups (control, handled and tagged), we used separate Poisson generalized linear models (GLMs) for response variables of the number of eggs hatched per nest, and productivity (number of chicks fledged per nesting attempt).

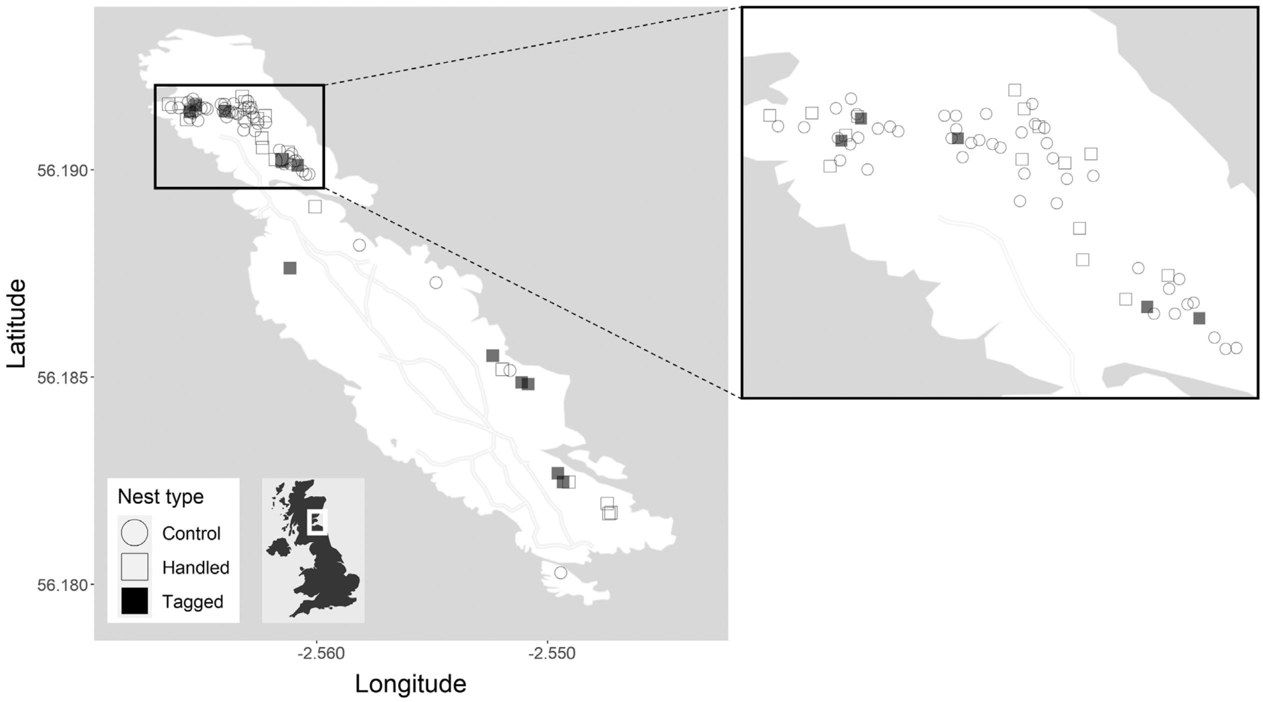

Figure 1. Location of 82 Great Black-backed Gull nests monitored in 2021 on the Isle of May. These were divided into 'Controls' (no adult birds caught), 'Handled' (one adult bird caught for colour ringing and feather sampling) and 'Tagged' (one adult bird caught for colour-ringing, feather sampling and GPS deployment). The small white box shows the location of the isle of May within the UK.

Additionally, we used separate binomial GLMs for response variables of hatching success per nest (success = 1, failure = 0) and fledging success per nest (success = 1, failure = 0). In all cases, nest type was the explanatory variable, and analysis of deviance was used to determine whether nest type was a significant model term. For models in which nest type was a significant term, further post-hoc Tukey pairwise comparisons were carried out with the R package *emmeans* (Lenth *et al.* 2018) to show differences between nest types.

To assess whether harness-mounted GPS devices could affect individuals of varying sizes differently, we ran GLMs using only data from the handled and tagged groups where we included the additional variable of bird mass. In these models, nest type and bird mass and their interaction were the explanatory variables, as heavier birds could potentially be less affected by the tag attachment (Phillips *et al.* 2003). Bird mass was chosen because it is a measure of body size that is correlated with other biometric measurements and sex in Great Black-backed Gulls (Mawhinney & Diamond 1999), and that is important in determining tag effects (Phillips *et al.* 2003). We used analysis of deviance to determine whether the models with bird mass and its interaction with nest type significantly improved the simplest model with only nest type as a term.

A limitation of our analysis was that bird handling time was collinear with nest type (Kruskal–Wallis $\chi^2 = 68.18$, $df = 2$, $P < 0.001$) because tagged birds were handled for longer than handled birds; this meant we could not consider handling time as an explanatory variable and posed a limitation in terms of discriminating device effects from handling effects. However, to lessen this limitation and provide insights into the potential effects of handling time alone, we ran separate Poisson and binomial GLMs using the handled group data only, where the number of hatched eggs and hatching success per nest were the response variables and handling time was the explanatory variable. Handling time within the handled group ranged from 5 to 23 min; this did not overlap with the handling range of the tagged group (35–60 min) but could give an indication of whether longer handling times led to nest failure. We did not model the effects of handling time on fledging success or productivity because we expected any handling impacts to be manifested shortly after capture and thus primarily impact incubation metrics.

Similarly, nest type was correlated with capture date, with handled individuals being captured over a more extended period across May and June, in contrast to tagged individuals, which were captured over a shorter 7-day period in May (Kruskal–Wallis $\chi^2 = 10.09$, df = 1, $P < 0.001$). To assess whether capture date could be a significant factor in the breeding performance discrepancies observed between groups, we ran Poisson and binomial GLMs using the handled group data only where the number of hatched eggs and hatching success were the response variables, and Julian date was the explanatory variable. Lastly, binomial GLMs were used to compare overwinter return rates between tagged and handled birds where the probability of resighting (1 = resighted, 0 = not sighted) was explained by nest type (handled or tagged).

RESULTS

Histories of trapped individuals

Great Black-backed Gulls were captured between 1 May and 20 June 2021. Of the 11 tagged individuals, three successfully hatched and fledged chicks; the remaining eight failed during incubation, typically 4–8 days post-capture, where accurate nest monitoring data were available (Table 1). Capture date was not a significant predictor of hatching success (Δdev = 0.66, df = 1, $P = 0.416$) or the number of eggs hatched per nest (Δdev = 0.01, df = 1, $P = 0.938$) within the handled group; this meant we could compare the breeding performance of handled and tagged individuals despite handled individuals being captured over a wider range of dates (Table 1).

Breeding performance

The number of eggs hatched per nest was significantly different between nest groups (Δdev = −12.01, df = 2, $P = 0.002$). Post-hoc pairwise comparisons showed no significant differences between control and handled nests, but tagged nests hatched a significantly smaller number of eggs than controls and handled nests (Tables 2 and 3). Similarly, hatching success was significantly different between nest groups (Δdev = −12.83, df = 2, $P = 0.002$). Post-hoc comparisons showed no differences in hatching success between control and handled nests, but the hatching success of tagged nests was significantly lower than control and handled nests (Tables 2 and 3).

Approximately 47% of nests from the handled and control groups fledged chicks successfully, a figure much lower than the 100% fledging success rate from the tagged group (Table 2). However, the sample size of the tagged group used in the fledging success model was only three, as only three nests from the tagged group successfully reached hatching. There were no significant differences in fledging success between any of the groups (Δdev = −4.22, df = 2, $P = 0.121$). Lastly, overall productivity was highest in controls, followed by handled and tagged groups (Table 2); however, no significant differences were found between them (Δdev = −0.65, df = 2, $P = 0.722$).

When modelling data from handled and tagged groups only, the addition of bird mass and its interaction with nest type significantly improved

Table 2. Great Black-backed Gull breeding performance on the Isle of May in 2021 across control (no adults trapped), handled (one adult trapped for ringing and feather sampling) and tagged nests (one adult trapped for ringing, feather sampling and GPS tagging), measured as eggs hatched (number of eggs hatched per nest), hatching success (percentage of nests that reached hatching), fledging success (percentage of nests that fledged chicks from nests that reached hatching) and overall productivity (number of chicks fledged per nesting attempt).

	Eggs hatched			Hatching success		Fledging success		Productivity		
Group	Mean	sd	*n*	*n*	%	*n*	%	Mean	sd	*n*
Control	1.94	1.16	48	48	81	39	48	0.73	0.98	48
Handled	2.00	1.09	23	23	82	19	47	0.61	0.84	23
Tagged	0.67	1.07	11	11	27	3	100	0.50	1.00	11

'*n*' denotes the sample size.

Table 3. Post-hoc pairwise comparisons between three different nest groups (control, handled and tagged) in terms of the number of eggs hatched per nest and hatching success per nest.

Response variable	Model type	Pairwise comparison	Estimate	Estimate 95% CI	*Z*	*P*
Eggs hatched	Poisson GLM	Control – Handled	−0.03	−0.45, 0.39	−0.18	0.983
		Control – Tagged	**1.11**	**0.20, 2.03**	**2.84**	**0.012**
		Handled – Tagged	**1.14**	**0.19, 2.10**	**2.82**	**0.013**
Hatching success	Binomial GLM	Control – Handled	−0.09	−1.65, 1.46	−0.14	0.990
		Control – Tagged	**2.45**	**0.63, 4.26**	**3.17**	**0.004**
		Handled – Tagged	**2.54**	**0.49, 4.58**	**2.91**	**0.010**

Significant differences between nest groups are highlighted in bold.

the model where the number of hatched eggs was the response variable (Table 4). In such a model, bird mass was not a significant predictor of the number of eggs hatched per nest in the handled group (estimate = 0.0001, 95% confidence interval (CI) –0.0015 to 0.0016; Z = 0.14, P = 0.893), but it was marginally significant in the tagged group (estimate = 0.0041, 95% CI 0.0009–0.0087; Z = 1.95, P = 0.051), suggesting a positive relationship between bird mass and the number of eggs hatched per nest in the tagged group (Fig. 2). This relationship highlighted that heavier birds could potentially be less impacted by the harness attachment (mean mass of successful and failed tagged individuals were 1886 g (sd = 251) and 1672 g (sd = 194), respectively). The relationships between bird mass and the other breeding metrics in the tagged group were also positive, but were not significant in any case and did not significantly reduce model variance compared with the simplest model (Table 4).

Handling effect

Differences in bird handling times within the handled group (range 5–23 min) did not significantly affect hatching success (Δdev = –0.01, df = 1, P = 0.735) or the number of eggs hatched per nest (Δdev = –0.01, df = 1, P = 0.891).

Return rate

In 2021, individual MA43184 presumably died at sea 5 days after GPS deployment. The tag was subsequently recovered on 14 July, 64 days after deployment, on a beach near Kirkcaldy (Fife) by one of the authors of the study without any signs of the bird. The cause of death could not be determined, but the most likely scenario is that the bird died, since the harness was not broken, and the bird was not resighted back in the colony in 2021 or 2022. No other mortality events were recorded during the 2021 breeding season.

Table 4. Model comparison based on analysis of deviance.

Response variable	Model terms	df	Residual deviance	Δ Deviance	*P*
Eggs hatched	Nest type	32	38.97	0.00	–
	Nest type + Bird mass	31	37.62	−1.35	0.245
	Nest type + Bird mass + Nest type:Bird mass	**30**	**33.38**	**−4.24**	**0.039**
Hatching success	Nest type	32	34.15	0.00	–
	Nest type + Bird mass	31	33.01	−1.13	0.287
	Nest type + Bird mass + Nest type:Bird mass	30	31.81	−1.20	0.272
Fledging success	Nest type	20	26.29	0.00	–
	Nest type + Bird mass	19	25.94	0.30	0.582
	Nest type + Bird mass + Nest type:Bird mass	18	25.94	0.00	1.000
Productivity	Nest type	32	44.40	0.00	–
	Nest type + Bird mass	31	42.71	−1.69	0.193
	Nest type + Bird mass + Nest type:Bird mass	30	39.67	−3.06	0.081

Models that significantly reduced residual deviance in relation to the simplest model which only included nest type as an explanatory variable are highlighted in bold.

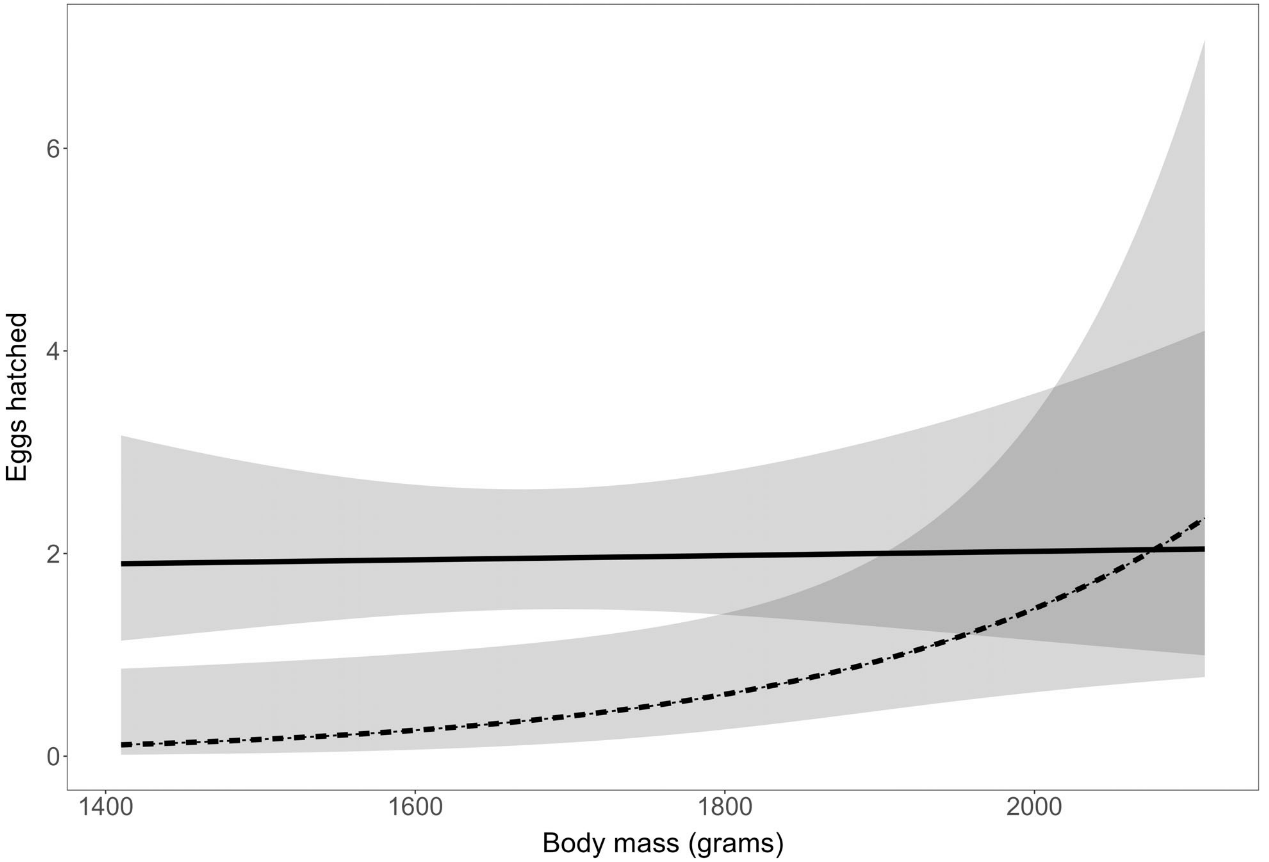

Figure 2. Poisson GLM prediction of the number of eggs hatched per nest as a function of adult Great Black-backed Gull body mass in two groups of Great Black-backed Gulls: handled-only individuals (solid black line) and tagged individuals (dashed black line). Shaded areas represent 95% confidence intervals.

Table 5. Overwinter return rate of Great Black-backed Gulls breeding on the Isle of May between 2021 and 2022, measured as the percentage of birds marked in 2021 that were resighted in 2022 through observations 'Resighted 2022 (%)', and through observations plus remotely accessed location via GPS device 'Resighted + GPS 2022 (%)'.

Group	Birds marked 2021	Resighted 2022 (%)	Resighted + GPS 2022 (%)
Handled	23	13/23 (56)	–
Tagged	10	4/11 (36)	6/11 (54)

Overwinter return rates (from 2021 to 2022) could be estimated from 34 adult birds that were colour-ringed on the Isle of May in 2021, comprising 23 handled and 11 tagged birds. The resighting rate of tagged individuals was lower than handled individuals in 2022 but this difference was not statistically significant (Δdev = −1.22, df = 1, $P = 0.269$). Additionally, we confirmed a further two individuals were still alive (one in the colony and the other away from the colony) via remotely accessed positional data provided by GPS/GSM, increasing the number of known live tagged birds to six (Table 5).

During the 2022 breeding season, at least three individuals skipped breeding. Individual MA43188 was known to not have left its wintering site (155 km from the Isle of May) based on GPS data. Individual HW99176 was resighted during the breeding season by an observer 10 km from the Isle of May where the bird wintered but was not resighted on the Isle of May in 2022. Lastly, individual MA43183 was present on the Isle of May throughout the 2022 breeding season but no nesting attempt was recorded.

DISCUSSION

Our results indicated tagged individuals had lower breeding performance during incubation than control and handled individuals, both in terms of the mean number of eggs that reached hatching per nest and the percentage of nests that reached hatching. We found no differences between handled and control nests, suggesting that the device attachment was the driver of nest failure in tagged birds. Fledging success was 100% in the tagged group, much higher than in the handled and control groups, but this difference was not statistically significant, and caution must be taken when interpreting such a figure due to the small sample size of the tagged group ($n = 3$). These two factors, namely sample size and the high chick-rearing performance of tagged birds, were able to offset at least partially the low hatching success of the group, leading to an overall productivity that was lower than the other two groups but not significantly different. Our findings agreed with previous observations made by Maynard *et al.* (2022) in Canada where six of eight Great Black-backed Gulls tagged with leg-loop harnesses failed during incubation. Furthermore, we demonstrated that handling alone for periods of 5–23 min for purposes other than tagging did not appear to adversely impact breeding performance, in agreement with previous studies where Great Black-backed Gulls captured for blood sampling and ringing had a similar hatching success to controls (Butler & Trivelpiece 1981, Helberg *et al.* 2005). Overall, our findings suggested Great Black-backed Gulls are sensitive to harness attachments but probably not handling.

Breeding failure of tagged individuals always occurred during incubation, generally within a week after GPS deployment. From casual observations, some tagged birds were recorded exhibiting 'normal' behaviours during days following capture (e.g. incubating and present in their territory), although we were not able formally to compare their colony attendance or time budgets with control birds. There were, however, two instances where tagged birds were reluctant to return to incubate after capture, resulting in breeding failure, one due to abandonment of the nest and the other due to predation of eggs while the bird was away from the nest for an extended time. Nest desertion may be caused by satellite transmitters, particularly when they weigh > 3% of the bird's body mass (Phillips *et al.* 2003). Conversely, nest abandonment and failure can also be driven by handling alone, such as recorded in Rhinoceros Auklets *Cerorhinca monocerata* (Lamb *et al.* 2017, Sun *et al.* 2020). We were unable to determine whether failure and abandonment responses by Great Black-backed Gulls were solely due to the harness attachment, or also to the longer and more intrusive handling associated with tag fitting. Longer handling times can cause individuals to spend longer times away from the breeding site after release (Wilson & Gaston 2001). As tagged birds in our study were handled for significantly longer than handled birds, we could not account for handling time in our models; this represented the greatest limitation of this study. However, longer handling times within the handled group did not significantly affect the number of eggs hatched or hatching success per nest, suggesting that handling was not a primary driver of nest failure, at least when handling times were shorter than 23 min. Furthermore, our results suggested bird mass could potentially be a determinant of breeding performance, as we found a positive relationship between the number of eggs hatched and bird mass in the tagged group but not in the handled group, suggesting that heavier individuals are perhaps less impacted by the tag attachment than lighter individuals. The lack of apparent handling impacts within the handled group and the potential importance of bird mass in determining the number of eggs hatched per nest within the tagged group identified the harness attachment as the likely primary driver of nest failure.

Regarding potential negative impacts on survival, there were initial concerns in 2021 after individual MA43184 presumably died at sea 5 days after GPS deployment. This meant the harness design used in this study could have potentially caused the direct death of an individual, but little could be concluded from this single event. No further mortality events were recorded in 2021, and all observed tagged individuals in 2022 were still carrying their GPS devices with no apparent anomalies in tag placement or harness fit.

Overwinter return rates suggested the resighting rate of tagged birds was slightly lower than handled birds when excluding birds detected via GPS only. However, expected return and survival rates of long-lived seabirds such as gulls are generally much higher (70–90%; Breton *et al.* 2008, Rock &

Vaughan 2013) than the return rates of handled and tagged birds recorded in our study. Although such a difference could be due to the Great Black-backed Gull population of the Isle of May having different demographic rates to other gull populations, it was more likely due to the limited resighting effort undertaken during the 2022 breeding season, as observations were carried out sporadically; this probably hampered our ability to detect real differences between groups. Overall, there appeared to be no significant or obvious differences in return rates between handled and tagged birds and we could rule out extremely severe impacts on survival such as those recorded in Great Skuas in the year following tagging, when < 10% individuals returned (Thaxter *et al.* 2016).

The methodology and results of this study were focused on differences in breeding performance and return rates between groups, but adverse impacts may also appear at a more subtle, sublethal level, where individuals sacrifice aspects of their fitness, such as increased energy expenditure and rapid loss of body mass, to compensate for carrying a device (Evans *et al.* 2020). There were indications of potential carry-over effects into 2022 in tagged Great Black-backed Gulls; a minimum of three individuals skipped breeding. Skipped breeding may have been driven by device effects (Barron *et al.* 2010) but we must also consider other possible causes of skipped breeding, such as birds taking sabbatical years (Kazama *et al.* 2013). Skipped breeding may have been more frequent in 2022, as it was the worst breeding season since records started in 2015 (mean of 0.30 chicks fledged per nest compared with the longer-term mean of 1.14; H. R. Greetham & D. Steel unpubl. data) and given that there is typically a positive correlation between average breeding success and proportion of individuals not breeding (Aebischer 1986).

The overarching theme in the assessment of device effects is that generalizations cannot be made between species or even between populations because adverse impacts can vary due to a multitude of factors (Kelly *et al.* 2015, Bodey *et al.* 2017). Differences in the deployment technique and device characteristics impact individuals differently (Thaxter *et al.* 2014, Vandenabeele *et al.* 2014) but there may be additional extrinsic factors beyond the researcher's control that influence the severity of adverse impacts, such as the fitness of the tagged individual and the environmental conditions that dictate individual fitness. If a period of high energy expenditure (e.g. breeding season) is coupled with low food availability, device effects could perhaps manifest themselves more strongly due to increased stress compared with a breeding season with higher individual fitness and food availability. This potentially is what took place on the Isle of May in 2021 and 2022, when there was in all likelihood a lack of food, as high breeding failure occurred during chick rearing (S. Langlois Lopez unpubl. data). During this time, adult fitness may have been compromised and the device effects detected in this study might be higher than if tagging had taken place in breeding seasons with higher food availability and average individual fitness. Device effects may therefore vary between years and populations, highlighting the value of including systematic reporting and assessment of device effects as part of all bio-logging studies to increase species-specific study sample sizes, which can then be used to develop and implement species-specific tagging guidelines to mitigate device effects.

We have demonstrated that Great Black-backed Gulls appear to be sensitive to harness attachments, and such findings should be explicitly considered when obtaining ethical approval for future studies. We would not recommend that devices fitted with body harnesses be deployed on Great Black-backed Gulls without modification of the protocols used in this study and re-evaluation of the impacts. Alternative protocols may involve capture of birds away from the nest-site or outside of the breeding period entirely. If capture is necessary on or near the nest, then temporary removal and incubation of the eggs and replacement with dummy eggs may be a useful mitigation until adults are observed back on the territory. Our results also suggested heavier individuals were potentially less affected by the tag attachment; targeting males, which are generally larger and heavier than females, or larger females in future studies might therefore reduce adverse impacts. General best practice when nest trapping adult gulls intuitively includes avoiding trapping earlier during incubation and keeping disturbance before and after capture events to a minimum. We would still recommend trapping during late incubation and reducing disturbance; however, our data and observations did not support that these were important factors in this study. If future backpack harness studies were to be trialled on Great Black-backed Gulls, we would recommend making improvements to reduce the overall fitting time, although not at the expense of the quality of fit. This may include use of crimps to secure the harness instead of stitching and improved device housing designs to speed up sizing adjustments. We estimate handling time could be reduced to 20–30 min with improved protocols, bringing the fitting procedure down to handling times known to have no apparent adverse impacts. However, it is unclear whether this would reduce nest failure without amendments to the catching protocol and the harness and device themselves (miniaturization and reduced invasiveness).

CONCLUSION

Bio-logging studies of seabirds are central to understanding their interactions with the marine environment and anthropogenic developments. As part of such work, increasing our knowledge of species-specific device effects should be a priority to continue to improve animal welfare and data quality. This is particularly important when using long-term, higher-risk attachment methods such as harnesses, which may impact individuals over multiple years. We demonstrated Great Black-backed Gulls appear to be sensitive to harness-mounted devices, leading to higher rates of nest failure compared with control and handled-only groups. Handling alone did not appear to have an adverse impact on the breeding performance of Great Black-backed Gulls when handling times ranged from 5 to 23 min. However, we could not determine whether the longer handling times (35–60 min) experienced by tagged birds also contributed to breeding failure. Harness attachments did not appear to have severe impacts on inter-annual survival, and return rates between tagged and handled birds were similar, although robust comparisons could not be carried out. Overall, we recommend extreme caution be taken by those intending to use harnesses on Great Black-backed Gulls and other species where device effects have not been previously investigated, and we highlight the need for robust assessment and reporting of device effects as part of all bio-logging studies.

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AUTHOR CONTRIBUTIONS

Samuel Langlois Lopez: Conceptualization; investigation; writing – original draft; methodology; validation; visualization; software; formal analysis; project administration; data curation; resources. **Gary D. Clewley:** Conceptualization; investigation; methodology; validation; visualization; writing – review and editing; data curation. **Daniel T. Johnston:** Investigation; methodology; validation; visualization; writing – review and editing. **Francis Daunt:** Conceptualization; validation; visualization; supervision. **Jared M. Wilson:** Funding acquisition; validation; visualization; writing – review and editing; supervision; project administration. **Nina J. O'Hanlon:** Conceptualization; methodology; validation; visualization; writing – review and editing; supervision. **Elizabeth Masden:** Conceptualization; funding acquisition; methodology; validation; visualization; project administration; resources; supervision.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

ETHICS

All procedures described in this study were approved by the relevant authorities with ethical approval obtained from the BTO and the University of the Highlands and Islands. Additionally, feather clipping and thoracic harness attachment permits were obtained from the BTO Special Methods Technical Panel, and research licences to carry out work on the Isle of May National Nature Reserve were obtained from NatureScot.

NatureScot Science and Research licence – 180 878.

British Trust for Ornithology bird ringing permits – 6690 and 5754.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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