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# Acute impacts of biologging devices on the diving behaviour of Manx shearwaters

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**Abstract**

Biologging studies rely on the assumption that equipped animal behaviours are representative of the ones displayed by unequipped individuals. Identifying any tagging effects is therefore necessary to correctly interpret recorded data from equipped animals. The majority of seabird studies report an absence of tag effects using broad metrics such as breeding success or foraging trip duration. However, animals may compensate for tag attachment through increased effort or behavioural responses. We compared foraging trip and dive characteristics of 42 breeding Manx shearwaters (*Puffinus puffinus*) equipped with a range of biologging tags representing 0.9–3.7% body mass. There was no evidence that increasing tag weight affected foraging trip duration, but individuals equipped with heavier tags travelled shorter distances and at slower speed as well as spending more time in Area Restricted Search behaviour. The number of dives performed per hour of foraging trip was not affected by increasing tag weight, but individuals with the heaviest tags conducted shorter and shallower dives with slower ascent rates than those equipped with lighter tags. Additionally, birds equipped with the heaviest tags increased resting time between dives, suggesting a need to recover from a greater physiological cost of diving when equipped. Our study is one of the few that describe acute tagging impacts on seabird diving behaviour and foraging effort, suggesting that deployments should be kept as short as possible to limit cumulative impacts.

**Keywords** Biotelemetry, Behavioural compensation, Foraging behaviour, Seabird tracking, Tag effects, Tag weight

## Background

Technological advances have given scientists unprecedented opportunities to use biologgers to record wild animal physiology [1], behaviour [2], and movement [3] while sampling in situ atmospheric and oceanic conditions experienced by tracked individuals [4]. Since the 1990s, the number of biologging studies has increased dramatically, with more than 300 papers produced per year between 2017 and 2019 [5]. This has culminated in the accumulation of vast datasets, expanding the field into the realm of big data science [6]. Biologgers have been a crucial tool to study and conserve marine species, including crustaceans [7], jellyfish [8], marine mammals [9], fish [10], seabirds [11], and turtles [12], for which direct observations throughout their life cycle are difficult due to their elusive ecology.

Seabirds, breeding on land and thus being relatively accessible to deploy and retrieve biologgers, have been extensively tracked over the last four decades with more than 216 out of 363 existent seabird species equipped with tracking devices [13]. Alongside tracking tags, accelerometers [14], magnetometers [15], time-depth recorders [16], cameras [17], microphones [18], as well as internal loggers such as temperature probes

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[19] and heart rate loggers (e.g. [20]), have enabled the study of fine-scale movements, migrations, energetic expenditure, foraging behaviour and responses to environmental cues. Seabirds are one of the most threatened bird groups [21] and biologging data have made important contributions to identifying interactions or overlap with anthropogenic activities and associated risks e.g. [21–23] and establish evidence-based conservation strategies including the creation of Marine Protected Areas [25].

Despite the great value of biologging data in understanding the ecology of marine species, researchers have raised concerns over the impacts of tags on equipped seabirds since the early use of biologging devices [26]. In order to justify the use of these methods and secure ethics and research approvals as well as public acceptance required for effective conservation, it is crucial to assess the balance between the costs to equipped animals and the benefits of biologging studies at individual, population, and ecosystem levels [27]. Beyond the ethical aspects and animal welfare concerns, researchers assume that logger-recorded traits are representative of those natural ones displayed by untagged animals. Most seabird biologging studies follow the practice of tag weight not exceeding 3% of the individual body mass to limit potential impacts [28, 29], while recognising that such a threshold is overly simplistic and not widely applicable across all species [30–32]. Potential tag effects on (sea) birds has received important attention see for example [28, 31, 32], demonstrating that effects of tag attachment are species dependent e.g. [33, 34] and vary with tag weight, size, shape and position [26, 32, 35–39] as well as attachment type [30] and tagging duration [40]. It is therefore important to assess and report on tag effects in studies using biologgers. Although the presence of a control group increases the likelihood of a study reporting tag effects [33], it limits the range of metrics comparable between equipped and non-equipped individuals to traits directly observable. Therefore, most studies assess tagging impacts by comparing breeding success, survival, number and duration of foraging trips, abandonment, and provisioning rates between equipped and non-equipped birds see for example [28, 34, 39–43]. However, control and equipped individuals may represent non-random samples from the population, as it may be unconsciously biased towards easily accessible or easily recapturable individuals, and might not be comparable [44]. Furthermore, tag effects on breeding success or chick body condition might be masked by compensation by the unequipped partner [41, 45], and impacts on foraging trip numbers and duration might be masked by adjustments of the time–activity budget (e.g. less time flying [45]). Only 26% of biologging studies focussing on birds, and in which tag effects have been reported, considered such behavioural aspects [30].

Directly comparing the at-sea behaviour between equipped and unequipped seabirds is virtually impossible, making the use of wind-tunnel experiments as well as mechanistic and computational fluid dynamics modelling particularly valuable to understand how tag drag and weight might increase seabird flight and dive costs [31, 38, 39]. Another method to estimate the impacts of tags on seabird behaviour is to compare individuals equipped with tags having different weight, size or position. Focussing on flight, this approach has been used on black-legged kittiwake (*Rissa tridactyla*) [46] and Manx shearwater [47], and demonstrated that birds equipped with heavier tags adjusted their at-sea behaviour, spending less time flying, but showed no difference in individual body mass or breeding success. Similar studies focussing on diving behaviour of penguins [48], cormorants [39] and guillemots [49–51] highlighted results from no detectable effect to increased recovery time between dives, decreased dive depth, decreased descent rates, and decreased time spent diving depending on species and tags. The low drag coefficient of those highly specialised pursuit divers [52, 53] makes them particularly sensitive to increases in drag due to external tagging [39], but tag effects on diving behaviour of less specialised species require more investigations.

Manx shearwaters (*Puffinus puffinus*) are well known to travel large distances on foraging trips [54, 55] by minimising their flight costs through performing dynamic soaring [56]. However, morphological adaptations to soaring flight do not prevent them reaching considerable dive depths (e.g. 50 m, [57]), and the impacts of tagging on the diving behaviour of a seabird whose morphology is specialised for efficient long-distance flight remains unknown. In this study, we aimed to investigate how externally attached biologging tags might impact fine-scale foraging trip and dive characteristics of Manx shearwaters, by comparing behaviour of individuals equipped with a range of biologging tags representing 0.9–3.7% body mass.

## Methods

### Data collection

A total of 52 biologging tag combinations were deployed on 42 breeding Manx shearwaters from Little Saltee Island (52.138, −6.586), Ireland, between June and August 2021 (n = 40), and in July 2022 (*n* = 12) (Table 1 and Appendix I). Birds were captured by hand at the nest or using purse nets at the burrow entrance. Handling time was minimised and always below 10 min. Some individuals were recaptured and retagged within the same year with new tags. In order to avoid potential

**Table 1** Details of the tag deployments

| | Pathtrack nanoFix Geo | CatLog genII+ | Pathtrack nanoFix Geo & Edic microphone | CatLog genII+ & Cefas G5 |
|---|---|---|---|---|
| Data recorded | GPS+TDR | GPS | GPS+TDR (+audio) | GPS+TDR |
| Weight (g) | 3.8 | 12 | 12.9 | 14.9 |
| Average % of individual body mass | 0.93±0.08 | 2.89±0.19 | 3±0.05 | 3.7±0.29 |
| Dimensions l x w x h (cm) | 2.6×1.4x1.4 | 4.2×2.3×1.3 | 8.3×2.3×1.3 | 7.1×2.3×1.3 |
| 2021 deployments | 9 | 22 | 2 | 7 |
| 2022 deployments | 12 | – | – | – |

Weights include Tesa tape and heat shrink needed for attachment and waterproofing, respectively. Dimensions of tag combinations correspond to total combined lengths while width and height are the widest and highest measurement of either tag

impacts of successive deployments on our conclusions, we removed from our study deployments that were conducted less than one week after the previous retrieval to ensure birds could forage unencumbered between deployments, assuming no long-lasting effects of tagging on the diving and foraging metrics tested in this study. In 2021, three tag combinations were deployed (Table 1), with Pathtrack nanoFix Geo (3.8 g) or CatLog genII+GPS tags 12 g recording high accuracy GPS fixes every 5 min. CatLog GPS tags were paired with Cefas G5 Time Depth Recorders (TDR, 2.9 g) on 7 individuals. Pathtrack GPS tags have an integrated TDR and were paired with an additional Edic microphone (9.1 g) on 2 individuals for the purposes of another study. In 2022, only Pathtrack nanoFix Geo were deployed. Pathtrack TDRs recorded depth at 0.5 Hz when underwater, with an accuracy of ±1% up to 50 m and a resolution of 1 cm. Cefas TDRs were set to record depth at 0.5 Hz constantly, and 4 Hz when underwater, with an accuracy of ±1% and a resolution of <4 cm. All depth data were resampled to 0.5 Hz to match the temporal resolution of the Pathtrack TDRs. Tags were attached to back feathers, slightly behind the highest point to limit hydro and aerodynamic impacts of tag attachment using Tesa tape 4651 [58].

### Foraging trips description

All analyses were conducted using R software (version 3.6.3). Tracks were linearly interpolated to 5-min intervals using the package *PathInterpolateR* (github.com/jedalong/PathInterpolatR). To avoid interpolating locations over long periods with no fixes (due to scheduled GPS failing to acquire fixes, e.g. due to a bird being underwater on a dive), tracks were split into sections when gaps of greater than 1 h were present in the raw GPS data. Following Darby et al. [58], foraging trips were defined as when an individual spent at least 6 h further than 5 km from the colony, with locations at the colony (1 km radius) excluded from further analysis to exclude time spent on land or attempting to land. Departure and return times from/to the colony were noted for each foraging trip. Incomplete trips (e.g. unrecorded arrival back at the colony due depleted battery) were excluded from analysis relying on total trip length or duration. For each foraging trip, the distance between successive locations was calculated using the package *raster* [59] before being summed to obtain the total distance travelled. The distance between the colony and the furthest point of each foraging trip was also calculated using the same package.

We inferred three behavioural states (rest, area-restricted search (ARS), and transit) using step lengths and turning angles between successive points, using the package *momentuHMM* [60] and parameters from Kane et al. [61]. ARS is assumed to represent active foraging behaviour [62], usually with steep turning angles and intermediate distances between points. The time spent in each behavioural state per foraging trip was then calculated.

### Dive metrics

Dives were identified as >2 consecutive depth readings deeper than 1 m. Dives separated by less than 5 min were grouped into bouts of diving activity [58] using a bout ending criterion calculated using the DiveMove package [63] based on a nonlinear least-squares regression applied to time intervals between dives. The number of dives per hour of foraging trip were calculated, as well as dive duration, maximum depth per dive, and time interval between dives within the same bout. Dives were linked to the closest track point timewise and its distance from the colony was calculated using the *raster* package. Using the package *DiveMove* [63] we defined descent, bottom, and ascent phases of each dive. The duration of each dive phase was calculated and rates of descent and ascent were calculated by dividing the phase duration by difference in depth between the start and end of the phase. Finally, we sorted dives into two strategies (see examples in Appendix II): 1) short and typically shallow dives ("V-shaped", bottom phase < 4 s) and 2) pursuit dives ("U-shaped", bottom phase > 4 s) which are usually deeper and longer and involving more swimming at the bottom phase of the dive [64].

### Modelling tag effects on foraging trip and dive characteristics

Using ANOVA tests in the *lme4* package [65], we first checked for differences in deployment duration for the different tag combinations to ensure that potential differences on trip and dive characteristics were not driven by shorter or longer periods carrying the tags. To investigate tag effects on foraging trip characteristics, we grouped together trips performed by individuals equipped with CatLog, Pathtrack + Edic and CatLog + Cefas under the "Heavier tags" category, as trip sample size per combination was small. We did not perform this grouping while investigating tag effects on diving, as dive models had a far greater sample size to work with.

We investigated the effects of tags on the number of dives, distance travelled per hour of foraging trips (hereafter speed), and maximum foraging range, building three distinct linear mixed effects models (LMMs) (Table 2). The maximum foraging range was log transformed to reduce positive skew and improve model residual distribution (Table 2).

Time spent resting or in ARS per foraging trip was modelled against tag type in generalized linear mixed effects models (GLMMs) with a Poisson error structure (link = log) including the log transformed duration of the foraging trip as an offset to account for the proportional nature of the response [66].

We modelled dive duration, dive depth, and time interval between dives (within the same bout) against tag type in three LMMs using the *nlme* package [67] including a autoregression first order (corCAR (1)) autocorrelation structure taking into account similarities between dives that occurred in temporal clusters (Table 2). Dive depth and time interval between dives were log transformed to meet the residual distribution assumptions (Table 2). Dive depth was also log transformed and scaled before being included as an additional explanatory variable while modelling time interval between dives as we assumed deeper dives might be followed by longer resting time [68].

Descent and ascent rates were modelled against tag type using LMMs (Table 2) including scaled dive depth as an additional explanatory variable as we predicted deeper dives might be associated with faster vertical movements.

Finally, we modelled the likelihood of performing "U-shaped" dives against tag type in a GLMM with a binomial error structure (link = logit), including scaled distance to the colony as a covariate, as we anticipated dive strategy to be dependent on foraging location and trip type [64]. We also investigated the tag impacts on the

**Table 2** Overview of the (G) LMMs conducted to investigate tag impacts on foraging trips and diving behaviour

| Response variable | Fixed effects | Random effect | Autocorrelation term |
|---|---|---|---|
| Foraging trip characteristics | | | |
| log (maximum trip range) | *Tag type* + scale(day of the year) | Bird ID | – |
| Speed | *Tag type* + scale(day of the year) | Bird ID | – |
| Time spent in ARS* per foraging trip | *Tag type* + scale(day of the year) + offset(log(Foraging trip duration)) | Bird ID | – |
| Number of dives per hour of foraging trip | *Tag type* + scale(day of the year) | Bird ID | – |
| Total dive duration per hour of foraging trip | *Tag type* + scale(day of the year) | Bird ID | – |
| Dive characteristics | | | |
| Dive duration | Tag type + scale(day of the year) + scale(solar angle) | Bird ID | corCAR1(form = ~ Date_Time \| ID) |
| log(dive depth) | Tag type + scale(day of the year) + scale(solar angle) | Bird ID | corCAR1(form = ~ Date_Time \| ID) |
| log(time interval between dives) | Tag type + scale(day of the year) + scale(solar angle) + scale(log(dive depth)) | Bird ID | corCAR1(form = ~ Date_Time \| ID) |
| Descent rate | Tag type + scale(solar angle) + scale(dive depth) | Bird ID | – |
| Ascent rate | Tag type + scale(solar angle) + scale(dive depth) | Bird ID | – |
| Dive shape** | Tag type + scale(day of the year) + scale(solar angle) + scale(Distance from the colony) | Bird ID | – |
| Bottom time*** | Tag type + scale(solar angle) | Bird ID | – |

Where tag type is in italic, CatLog, Pathtrack + Edic and Catlog + Cefas were grouped into one "Heavier tags" category. *Same models were conducted with time spent resting. **This model is a binomial GLMM were "U-shaped" dives were coded as 1 and "V-shaped" as 0. *** This model was run for "U-shaped" dives only bottom phase duration of those dives in a GLMM with a Poisson error structure (link = log).

Each foraging trip and dive event was appended with its corresponding "day of the year" before scaling and including this variable in the above models (Table 2) to account for potential impacts of the breeding stage on foraging/diving behaviour [69]. The solar angle for each dive, calculated using the *oce* package [70], was scaled and included (Table 2) as a proxy of light availability, which is known to influence diving behaviour [58].

In all models, a random intercept of bird ID was included to account for inter-individual variation in behaviour and avoid pseudo-replication. Collinearity between variables was tested using Pearson pairwise correlations and Variance Inflation Factor (ensuring VIF < 2). Residual normality, heteroskedasticity, and autocorrelation were checked for any patterns indicative of a violation of model assumptions. When not specified otherwise, the (G)LMMs were run with the *glmmTMB* package [71]. Marginal and conditional $R^2$ were obtained using the *MuMin* package [72]. Finally, the impact of tags on foraging trip duration was investigated using a Wilcoxon test, as residuals obtained when using a GLMM were violating residual distribution assumptions. We present our results following Muff et al. [73], excluding vocabulary associated with null-hypothesis significance testing and replacing it with the gradual language of evidence advised by the authors.

## Results

Across deployments with the four tag combinations, 96 complete foraging trips with 10,009 dives (of which more than 93% were V-shape dives) were recorded and described (Table 3). There was little evidence that the deployment duration was different for the different tag combinations (ANOVA, $p = 0.16$).

There was little or no evidence that foraging trip duration (Wilcoxon test, $p = 0.6$), number of dives per hour of foraging trip and % of time spent resting or in transit were different across tag types (Appendix III). Our remaining models predicted that individuals equipped with the heavier tags travelled shorter distances, travelled at slower flight speed, and spent more time in Area Restricted Search than birds equipped with lighter tags (Fig. 1 and Appendix III).

There was strong and very strong evidence, respectively, that individuals equipped with the heaviest CatLog + Cefas combination undertook shorter and shallower dives, and spent longer time intervals between dives than those equipped with both Pathtrack and

**Table 3** Foraging trip and dive characteristic means and standard deviations per tag type

| **Variables** | **Pathtrack nanoFix Geo** | | **CatLog genII+** | | **Pathtrack nanoFix Geo & Edic microphone** | | **CatLog genII+ & Cefas G5** | |
|---|---|---|---|---|---|---|---|---|
| **Number of foraging trips** | **43** | | **34** | | **3** | | **16** | |
| | **Mean** | **± SD** | **Mean** | **± SD** | **Mean** | **± SD** | **Mean** | **± SD** |
| Foraging trip characteristics | | | | | | | | |
| Maximum trip range (km) | 75 | 71.8 | 59.4 | 60.5 | 34.7 | 26.4 | 49.6 | 30 |
| Speed (km.h$^{-1}$) | 8.5 | 3.3 | 7 | 2.8 | 5.8 | 1 | 7.8 | 2.8 |
| Trip duration (h) | 41.2 | 35.6 | 44.2 | 41 | 24.5 | 17.7 | 24.4 | 11.2 |
| % Time spent resting per foraging trip | 36.2 | 11 | 38.4 | 10.7 | 43.2 | 2.8 | 33.2 | 9.4 |
| % Time spent in ARS per foraging trip | 48.2 | 9.7 | 49.8 | 7.6 | 47.2 | 0.4 | 53.4 | 10.9 |
| % Time spent in transit per foraging trip | 15.2 | 6.7 | 12.1 | 8.6 | 5.1 | 4.5 | 13.8 | 7.9 |
| Number of dives per hour of foraging trip | 3.8 | 1.9 | – | – | 3.01 | 1.2 | 4.1 | 1.8 |
| Total dive duration per hour of foraging trip (min) | 50.4 | 28.3 | – | – | 55.6 | 19.8 | 58.4 | 34.5 |
| Dives characteristics | | | | | | | | |
| Number of dives | 8046 | | – | | 224 | | 1739 | |
| % of U-shaped dives | 6.56 | | – | | 10.7 | | 7.4 | |
| Dive duration (s) | 12.54 | 9.04 | – | – | 18.4 | 11.7 | 14 | 10 |
| Dive depth (m) | 5.9 | 5.2 | – | – | 9 | 7.2 | 6.4 | 5.8 |
| Time interval between dives (s) | 1.03 | 1.1 | – | – | 1.3 | 1.3 | 1.1 | 1.0 |
| Descent rate (m.s$^{-1}$) | 0.95 | 0.37 | – | – | 1 | 0.38 | 0.94 | 0.37 |
| Ascent rate (m.s$^{-1}$) | 1 | 0.36 | – | – | 1.04 | 0.36 | 0.94 | 0.33 |
| Bottom time * (s) | 9 | 4.1 | – | – | 10 | 4.2 | 8.8 | 3.4 |

* Bottom time is only presented here for "U-shaped" dives

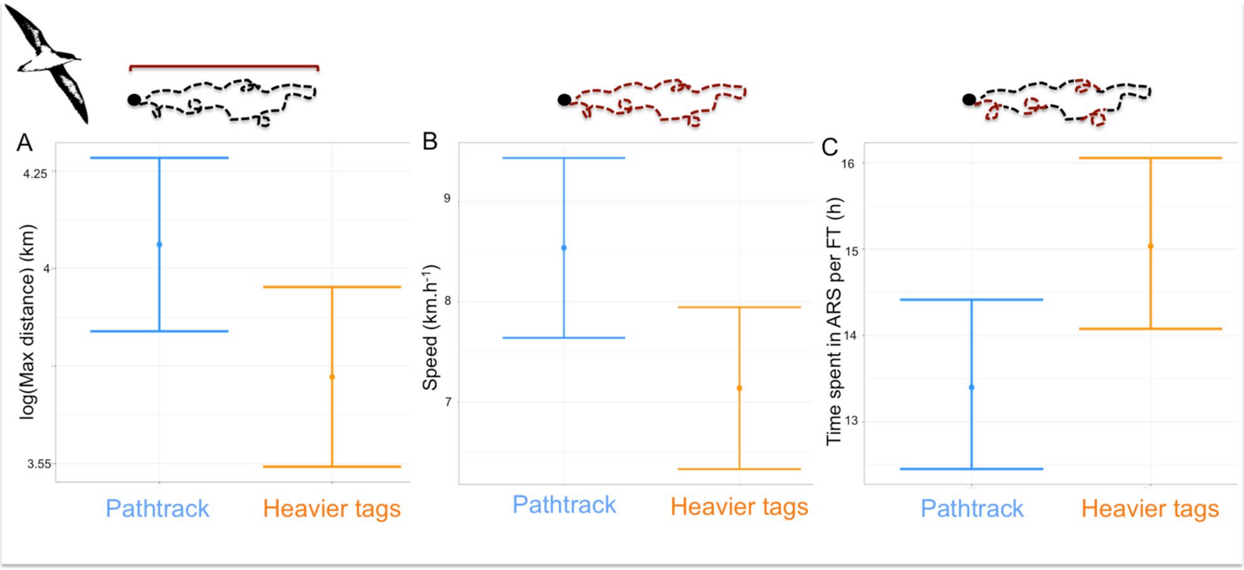

**Fig. 1** Partial effects of tag type while modelling **A** the maximum foraging range (log transformed), **B** the speed during foraging trip and **C** the time spent in ARS per foraging trip. Error bars represent 95% confidence intervals

Pathtrack + Edic tags (Fig. 2 and Appendix III). There was moderate evidence, that individuals carrying CatLog + Cefas combination had slower ascent rates than individuals equipped with the lighter Pathtrack only tags. There was little or no evidence that descent rate, likelihood of performing "U-shaped" dives, and bottom time of "U-shaped" dives were different across tag combinations.

## Discussion

### Tag effects on Manx shearwater foraging trips

By comparing foraging trip and dive characteristics of Manx shearwaters equipped with a range of tag weights and sizes, we demonstrate acute tag effects on a number of key foraging parameters. Our study was conducted during the energetically demanding breeding season during which breeders have to balance their activity costs and benefits between their own self-maintenance and chick rearing [74]. In this context, our results suggest that individuals equipped with heavier tags maintained similar trip durations than those with lighter tags (and presumably provisioning rate) and compensated for tag effects through travelling shorter distances at slower speed. Although our result on trip duration is in agreement with previous comparisons between untagged and tagged Manx shearwaters [75], Gillies and colleagues [47] observed that birds equipped with heavier tags (up to 4.8% body mass) were undertaking significantly longer trips than birds tagged with lighter devices (0.6% body mass) and were even doubling trip duration in comparison with untagged birds. The discrepancy with the latter study could be due to differences in protocols (e.g. different tag characteristics such as position on the bird or tag:body mass ratio (max 3.7% in our study vs 4.8%)), and/or environmental conditions encountered by tracked birds as tag impacts may be more pronounced during years of poor food availability [76].

Few studies report tag impacts on seabird spatial use (but see [45]), a factor of importance when considering tracking data is often used to identify seabird hotspots and inform conservation measures such as designation of Marine Protected Areas e.g. [24]. In our study, individuals equipped with heavier tags stayed closer to the colony to forage, but unlike in Gillies et al. [47], spent more time in ARS during their foraging trips while time spent resting and transiting were unaffected. This suggests that birds carrying heavier tags might compensate for their increased load by intensifying their search effort within proximate areas rather than commuting to distant feeding grounds: birds with heavier tags might prioritise minimising energy cost linked to travel by focusing on nearby patches. As those birds spent more time in ARS, these birds may encounter reduced prey availability or profitability compared to birds with lighter tags, which can exploit more distant foraging areas. As the number of dives per hour of foraging trips was similar across tag types, this might reflect the biological need for individuals to meet their energetic requirements and provisioning obligations regardless of tagging and might be an adaptive strategy to ensure sufficient foraging success despite the added load. However, the absence of data on prey availability and patch quality within ARS zones limits

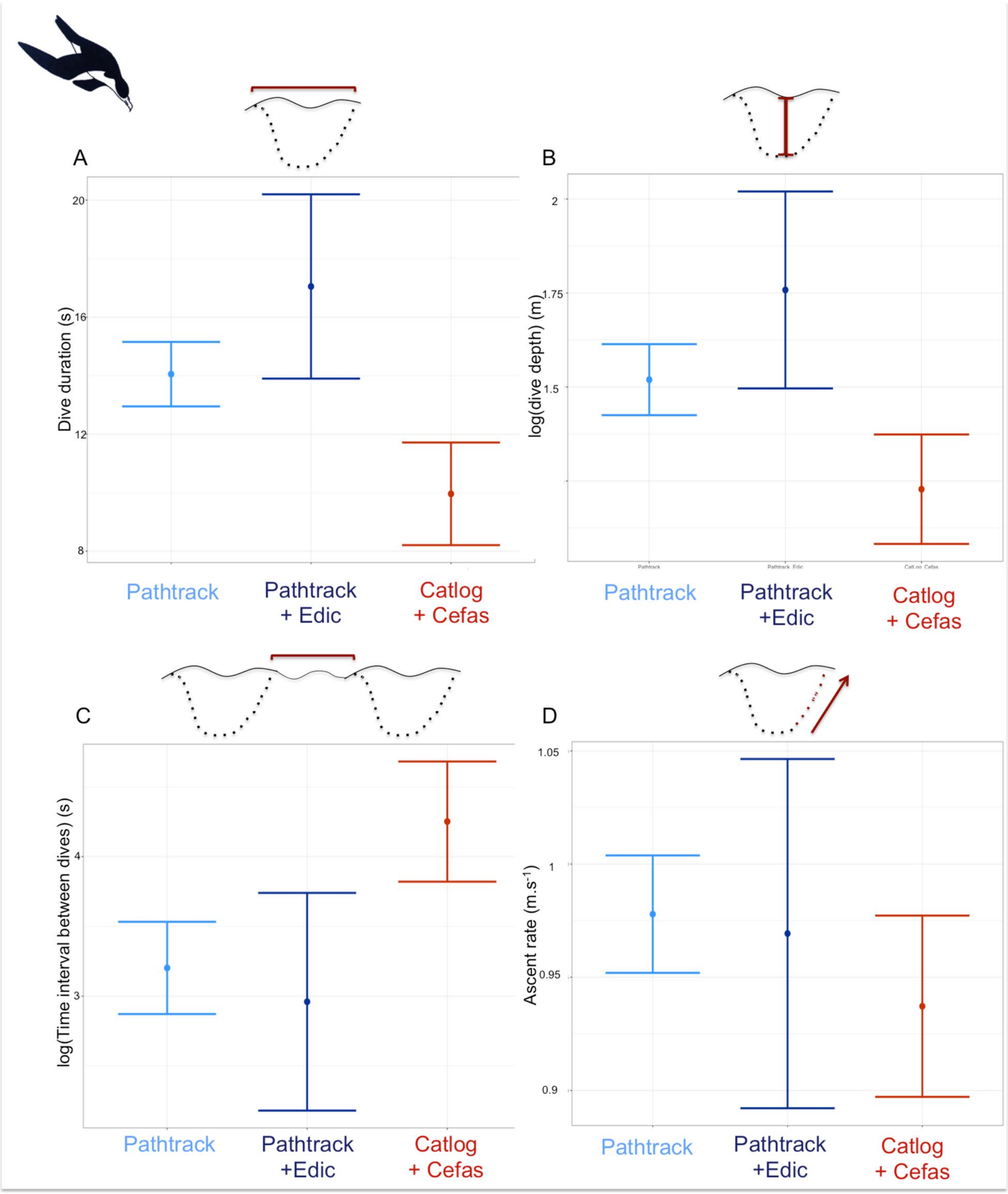

**Fig. 2** Partial effects of tag type while modelling **A** the dive duration, **B** the dive depth (log transformed), **C** the time interval between dives (log transformed) and **D** the ascent rate. Error bars represent 95% confidence intervals

our ability to disentangle whether the observed differences are due to energetic constraints, environmental variability, or behavioural strategies adopted by tagged individuals to maintain energy balance. Further, we did not consider GPS locations in the vicinity of the colony (1 km radius) to focus on foraging trips only, potentially missing differences in use of those areas for maintenance (e.g. loafing, preening) and resting behaviours. This could explain why the time spent resting during foraging trips was similar across tag types, as it is possible that individuals equipped with larger tags could have spent more time resting near/at the colony to recover from potential tag impacts.

### Tag impacts on Manx shearwater dives

Similar to king penguins and guillemots [48, 49], individuals equipped with larger tags did not reach the same depth as those equipped with lighter devices. The likelihood of performing "U-shaped" dives was similar across tag types, but we cannot exclude potential differences in surface seizing frequency, as those events would have been undetected by the TDR (above the 1 m dive threshold). It is possible that individuals carrying heavier tags may adopt energy-saving strategies, such as shallower dives. Such adjustments could hypothetically lead to changes in diet composition, though our study did not directly evaluate this aspect. Further dietary studies would be required to better understand how the interplay between dive strategy, dive depth, and diet could be impacted by tagging.

Manx shearwaters are wing-propelled divers, with descent and bottom phases being the active and energetically costly part of dives [77, 78]. As dive descent rate and bottom time were similar across tag types, we suggest that individuals equipped with larger heavier tags were able to compensate for the additional drag by working harder to move through the water. The increased energy expenditure associated with this compensation is likely why birds carrying heavier tags achieved shallower dive depths, performed shorter dives, and had longer time intervals between successive dives, presumably to increase their recovery time [48, 49]. Such behavioural compensation of tag effects to maintain descent rate has already been observed in guillemots, but accelerometry data would be required to identify the underlying mechanisms and energetic consequences, as individuals can increase their swimming effort and/or increase their pitch angle in order to compensate the extra drag and weight [50]. The ascent phase is considered a less energetically demanding phase of dives, as Manx shearwaters use their positive buoyancy to return to the surface [77, 78]. Birds carrying heavier tags faced more drag and carried more weight than those equipped with lighter and more streamlined ones, potentially explaining their slower ascent rates. Although negatively buoyant, our tag weight and drag were correlated, making it difficult to understand which parameter most impacts dives. Standardised deployments allowing such assessment are particularly rare on free-ranging animals (but see for example [37, 46]), highlighting the utility of wind-tunnel experiments e.g. [35] and computational fluid dynamic modelling [38] to optimise future tag design and deployment protocols. Ultimately, by estimating the power an unequipped individual uses to move through air and water, and adding the forces required to carry biologgers, researchers can calculate the additional energetic cost an equipped animal faces to maintain its natural activity levels [79]. However, our understanding of how tagging impacts the overall energy balance of equipped individuals is still limited by our lack of data on how it might impact diet and foraging success.

## Conclusions

Our study revealed changes in foraging and diving behaviours in response to tagging, likely reflecting compensatory behaviour aimed at balancing individual condition and reproductive output. Breeding seabirds face a fundamental trade-off between self-maintenance and reproductive investment in a context of limited energy budget [80]. However, long-lived species like shearwaters tend to prioritise their own survival over that of their offspring to maximise their lifetime reproductive success [81]. Our study could not assess what strategy was at play here as we did not monitor key fitness traits, but Gillies and colleagues (2020) [47] demonstrated that Manx shearwaters altered their foraging behaviour in response of tagging without any consequences on their breeding success. Although focussing only on fitness metrics to assess tag effects might lead to overlooking substantial effects on behaviours, such fitness data are crucial to understand whether behavioural adaptations are entirely effective or if they impose subtle, longer-term reproductive or survival costs. Future research that integrates behavioural and physiological data with direct measures of fitness will be essential to fully unravel these dynamics in tagged seabirds.

While comparing individuals equipped with tags of varying characteristics provides valuable insights into the relative effects of different tag designs on behaviours, this approach does not allow us to determine the absolute impact of tagging. Specifically, although our study suggests that tags exceeding the commonly accepted 3% of the bird's body mass influence foraging and diving behaviours, the absence of a control group of untagged individuals prevents us from verifying whether even lighter tags (below the 3% threshold) might also have subtle effects. However, while the recent decrease in reported tag impacts [33] may partially be due to the miniaturisation of biologging devices, the ratio of body mass to tag weight has not decreased markedly over the previous decades as smaller species are being tagged as devices become smaller [82]. This trend does not reflect disregard for animal welfare, but rather is a response to the opportunity to study and protect species that were understudied due to technological limitations, with such research greatly enhancing their conservation (see [83] for example).

Our study demonstrates that birds equipped with different tags exhibit varying behaviours, and highlights the importance of accounting for potential tag effects when analysing, interpreting, and comparing tracking data collected using different devices or across studies. This consideration is particularly pertinent as the biologging science transitions into the era of big data, where large-scale tracking datasets are increasingly utilised for meta-analyses [6]. Documenting the specific impacts of tags across species, device characteristics, and deployment durations enables the continued use of previously collected data by allowing deployment characteristics to be included (in models for example) to ensure informed interpretation of results.

Finally, as our results showed acute tag effects on Manx shearwater foraging behaviour that are likely to be cumulative, we argue for minimising deployment duration within the constraints of collecting sufficient data to answer research questions. Ultimately, tracking requires making the most of each tag deployment, highlighting the importance of data sharing and collective optimisation of new data collection [13].

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-025-00399-0.

Supplementary material 1

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### Author Contributions

MJ and JD were responsible of funding acquisition and MJ was the project administrator. JD, MJ and MC conceptualized the study and collected the data. MC, JD and EC performed the analysis. MC produced associated figures. MC wrote the original draft with edits from JD, MJ and EC. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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### Availability of data and materials

The datasets used during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate

All capture, handling and tagging was conducted under licence from the National Parks and Wildlife Service (54/2021, C155/2021) and the British Trust for Ornithology (CO/6143).

### Consent for publication

Not applicable.

### Competing interests

The authors declare no competing interests.

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## Publisher's Note