CORA Cork Open Research Archive
Cartlann Taighde Oscailte Chorcaí

Title	Decadal increase in vessel interactions by a scavenging pelagic seabird across the North Atlantic
Authors	Darby, J. H.;Clairbaux, M.;Quinn, J. L.;Thompson, P.;Quinn, L.;Cabot, David;Strøm, H.;Thórarinsson, T. L.;Kempf, J.;Jessopp, M. J.
Publication date	2023
Original Citation	Darby, J.H., Clairbaux, M., Quinn, J.L., Thompson, P., Quinn, L., Cabot, D., Strøm, H., Thorarinsson, T.L., Kempf, J. and Jessopp, M.J. (2023) 'Decadal increase in vessel interactions by a scavenging pelagic seabird across the North Atlantic', Current Biology, 33(19), pp.4225-4231. https://doi.org/10.1016/j.cub.2023.08.033
Type of publication	Article (peer-reviewed)
Link to publisher's version	10.1016/j.cub.2023.08.033
Rights	© 2023, The Author(s). This work is made available under the CC BY license (https://creativecommons.org/licenses/by/4.0/) - https://creativecommons.org/licenses/by/4.0/
Download date	2026-11-05 17:30:43
Item downloaded from	https://hdl.handle.net/10468/16823

UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

Report

Current Biology

Decadal increase in vessel interactions by a scavenging pelagic seabird across the North Atlantic

Highlights

- Geolocator tracking data for 296 individual northern fulmars, a scavenging seabird
- Fulmar vessel encounters identified across the North Atlantic over a 16-year period
- Long-term increases in vessel encounter rates for all study colonies
- Fulmars that attend vessels have reduced ranges and time spent foraging

Authors

Jamie H. Darby, Manon Clairbaux, John L. Quinn, ..., Thorkell L. Thórarinsson, Jed Kempf, Mark J. Jessopp

Correspondence

jamie.darby@ucc.ie

In brief

Darby et al. use a 16-year tracking dataset to show that northern fulmars from four colonies across the North Atlantic increasingly encounter vessels at night. Fulmars are known scavengers of fishing waste, and vessel attendance leads to reduced range and time foraging. However, it also increases bycatch risk and may signal decreases in natural prey.

Darby et al., 2023, Current Biology *33*, 4225–4231
October 9, 2023 © 2023 The Author(s). Published by Elsevier Inc.
https://doi.org/10.1016/j.cub.2023.08.033

CellPress

Current Biology

CellPress
OPEN ACCESS

Report

Decadal increase in vessel interactions by a scavenging pelagic seabird across the North Atlantic

Jamie H. Darby,[1,2,9,*] Manon Clairbaux,[1,3] John L. Quinn,[1] Paul Thompson,[4] Lucy Quinn,[4,5] David Cabot,[1] Hallvard Strøm,[6] Thorkell L. Thórarinsson,[7] Jed Kempf,[1] and Mark J. Jessopp[1,3,8]

[1]School of Biological, Environmental and Earth Sciences, University College Cork, Cork T23 N73K, Ireland
[2]School of Environmental Sciences, University of Liverpool, Liverpool L3 5DA, UK
[3]MaREI Centre for Energy, Climate and Marine, Environmental Research Institute, University College Cork, Cork P43 C573, Ireland
[4]Lighthouse Field Station, School of Biological Sciences, University of Aberdeen, Cromarty IV11 8YL, Scotland
[5]NatureScot, Great Glen House, Leachkin Road, Inverness IV3 8NW, Scotland
[6]Norwegian Polar Institute, Fram Centre, Postbox 6606 Stakkevollan, 9296 Tromsø, Norway
[7]Northeast Iceland Nature Research Centre, Hafnarstétt 3, 640 Húsavík, Iceland
[8]X (formerly Twitter): @GannetGuy
[9]Lead contact
*Correspondence: jamie.darby@ucc.ie
https://doi.org/10.1016/j.cub.2023.08.033

SUMMARY

Fisheries waste is used by many seabirds as a supplementary source of food,[1] but interacting with fishing vessels to obtain this resource puts birds at risk of entanglement in fishing gear and mortality.[2] As a result, bycatch is one of the leading contributors to seabird decline worldwide,[3] and this risk may increase over time as birds increasingly associate fishing vessels with food. Light-level geolocators mounted on seabirds can detect light emitted from vessels at night year-round.[4] We used a 16-year time series of geolocator data from 296 northern fulmars (*Fulmarus glacialis*) breeding at temperate and arctic colonies to investigate trends of nocturnal vessel interactions in this scavenging pelagic seabird. Vessel attendance has progressively increased over the study period despite no corresponding increase in the number of vessels or availability of discards over the same time frame. Fulmars are highly mobile generalist surface feeders,[5] so this may signal a reduction in available prey biomass in the upper water column, leading to increased reliance on anthropogenic food subsidies[6] and increased risk of bycatch mortality in already threatened seabird populations. Individuals were consistent in the extent to which they interacted with vessels, as shown in other species,[7] suggesting that population-level increases may be due to a higher proportion of fulmars following vessels rather than changes at an individual level. Higher encounter rates were correlated with lower time spent foraging and a geographically restricted overwintering distribution, suggesting an energetic advantage for these scavenging strategists compared with foraging for natural prey.

RESULTS

Vessel encounters

A total of 12,689 vessel encounters were detected using geolocator light data in over 180,000 nocturnal periods, i.e., one encounter per ~15 nights of data, across a vast area of the North Atlantic (Figure 1). A binomial model predicting the presence/absence of encounters per night showed that fulmars from all colonies showed a significant positive correlation between year and likelihood of encounter (Figure 2A), with fulmars from Scotland significantly more likely to encounter vessels than in the other three colonies. Intuitively, detecting interactions was more likely in areas with intense fisheries (Figure 2B), and when nights were longer. Males were more than twice as likely to encounter a vessel than females (Figure 2C), and encounters were less likely in April and May, during the pre-breeding exodus, as well as in September, during the post-breeding molt (Figure 2D). All initial covariates were retained in the final model (Table 1). This model had good predictive power (area under curve > 80%).

Annual vessel encounters and individual repeatability

Individual fulmars were consistent in the extent to which they attended vessels across years (repeatability, 0.85 ± 0.02 SE). Similar to the previous section, the linear component of this model indicated a progressive increase in encounters per year, with a similar trend apparent across the four study colonies (Figure 3A). Number of encounters per non-breeding season varied between colonies, irrespective of year. This model also suggested that the total overwintering area was negatively correlated with the number of encounters during that same period, though this may simply be a product of higher fishing vessel presence concentrated around fulmar colonies.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

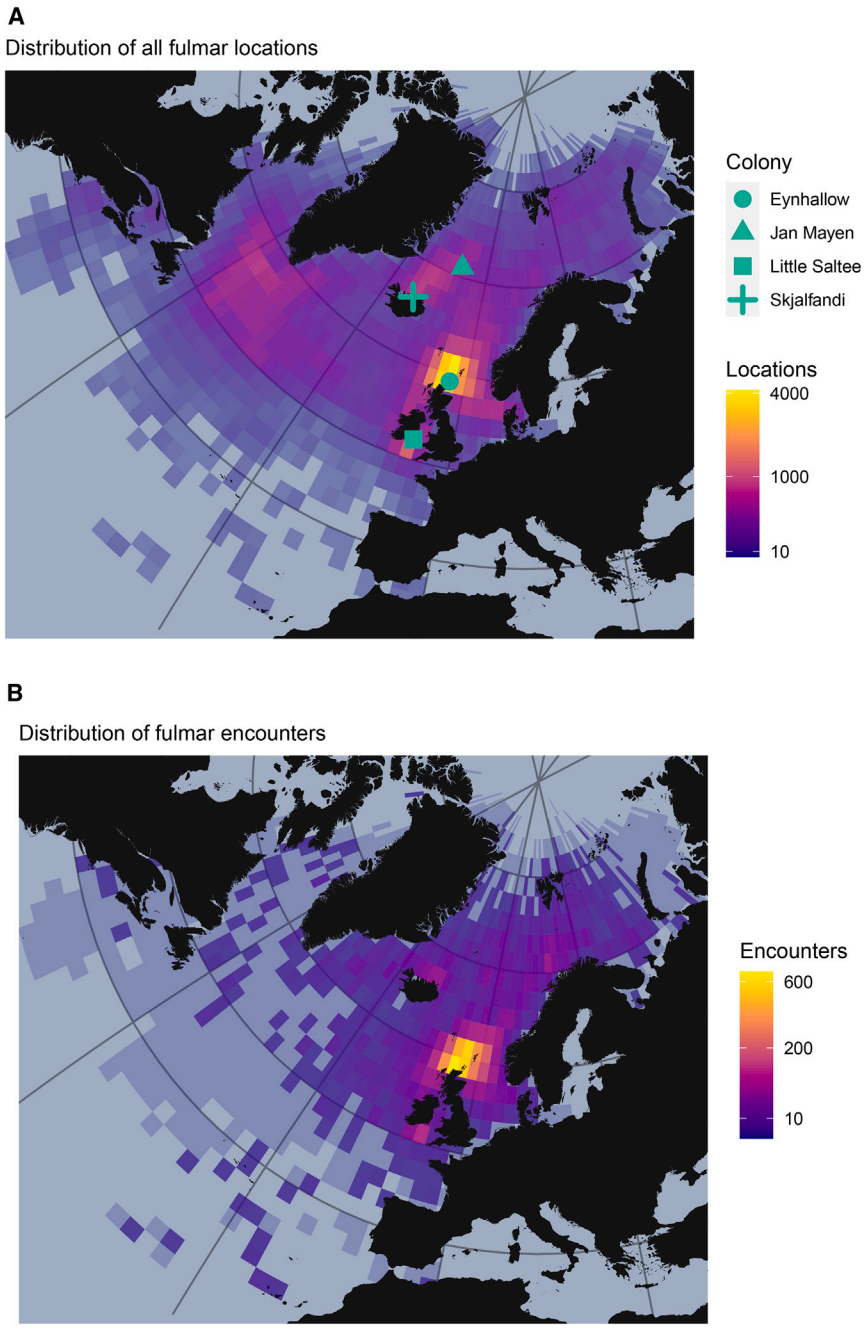


Figure 1. Fulmar encounter distribution

(A) The distribution of fulmar locations across the North Atlantic in 2° × 2° grid cells, with the locations of the colonies overlaid.

(B) The count of nocturnal vessel encounters. Areas grayed out are cells, which contained locations but no encounters.

Modeling of behavior

Analyses of wet-dry data from the dataloggers indicated that time spent foraging was significantly negatively correlated with number of encounters per year. Fulmars that did not regularly encounter vessels showed an increase in time spent foraging overall in the study period, while fulmars that extensively encountered vessels did not (Figure 3B). This interaction was marginally non-significant by traditional measures ($p = 0.056$) but was retained by the model selection process and provides an important discussion point. Female fulmars spent a significantly greater proportion of time foraging. The effect of logger type was also significant, probably because one model of logger recorded a lower proportion of foraging behavior due to a coarser immersion sampling interval. This model had a good fit (marginal R^2 = 45%, conditional R^2 = 84%).

DISCUSSION

We show that fulmars from colonies spread across the Northeast Atlantic encounter vessels more often over time. Fleet sizes, gross fleet tonnage, total catch, and discard rates of many North Atlantic fisheries have dropped or remained static over the same period[8] (Figure S1), so increased availability of fisheries waste or additional vessel cues are unlikely to explain this trend. Fulmars are relatively generalistic feeders, consuming a wide range of prey,[5] a trait shared by many fisheries waste scavengers.[1] They primarily feed at the sea surface, with the limited biologging data available showing dives to depths of <3 m.[9] An increase in vessel attendance that is not explained by increased availability of vessels or waste may reflect reductions in natural prey abundance at, or just below, the water surface across the North Atlantic.

With the application of more sustainable fishing practices reducing discards through more selective gear types or landings obligations, scavenging seabirds may require more time attending vessels to feed sufficiently, which may extend vessel attendance duration. Fisheries with high bycatch risk, such as longlines, are often advised to set nets at night,[10] which may lead to a shift in fulmar behavior toward nocturnal scavenging. However, recent vessel tracking analysis shows that this recommendation is largely ignored, and as many as 97% of longline sets globally occurred at least partially in daylight hours.[11] Our results indicate that the relative profitability of scavenging versus natural foraging is increasing over the time frame of the study. This suggests that reduced natural prey availability and the energetic cost of search may be responsible for increased vessel encounters, as opposed to stochastic changes in fulmar behavior or changes in fisher behavior. Increasing interaction rates and time spent near vessels will inevitably result in higher risk of bycatch, a leading cause of mortality in fulmars and many other seabird species,[3,12] requiring incentivization of

CellPress
OPEN ACCESS

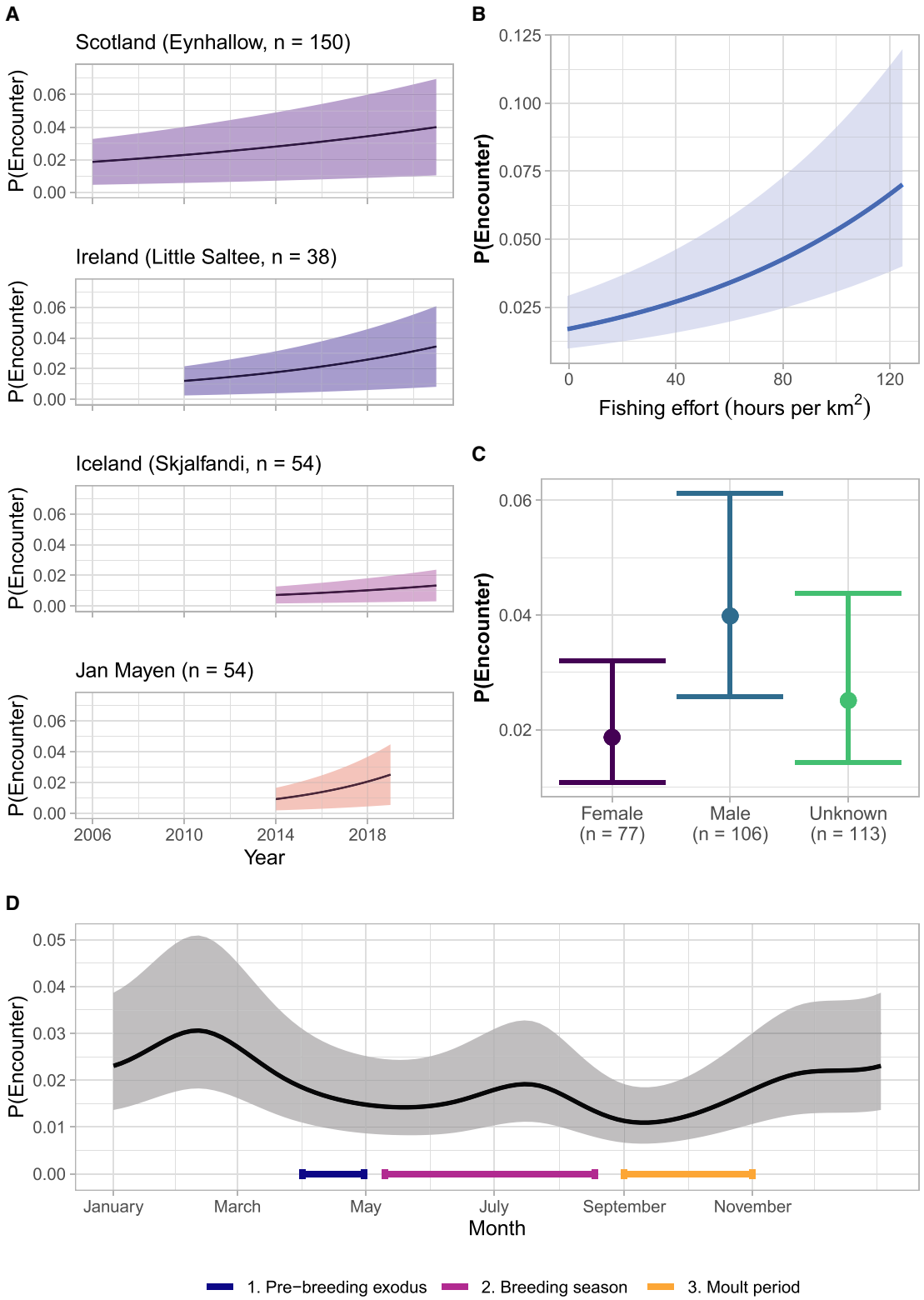


Figure 2. Model outputs explaining encounter rate

Covariates explaining probability of vessel encounter per night (P(Encounter) on the y axis of each subplot). Shaded areas in (A) represent the SE of associated model predictions. Shaded areas around trend lines in (B) and (D) and error bars in (C) represent 95% confidence intervals of partial effects. Timing of pre-laying exodus, breeding, and post-breeding molt is annotated below the plot describing the effect of time of year in (D), though these timings are coarse and can vary by colony, individual, and breeding success.

See also Figure S1.

Table 1. Model terms explaining the presence/absence of vessel encounters per night

Model term	df/edf	Chi-squared value	p value
s(julian day)	7.4	695.4	<0.001
s(n nocturnal fixes)	8.5	511.7	<0.001
fishing effort	1	152.4	<0.001
sex	2	23.0	<0.001
logger type	2	3.0	0.23
colony	3	39.6	<0.001
colony:year	4	92.5	<0.001

Covariates included as splines are denoted as s(covariate). Terms are reported with either degrees of freedom (df) or estimated degrees of freedom (edf), depending on whether they are included as spline or parametric terms. Chi-squared value represents covariate impact on model outputs. P value, or probability of that covariate having no effect on the response, is also reported. Values <0.05 are taken as statistically significant.

mitigation measures for bycatch-prone fisheries. Also, despite the effectiveness of night-setting for preventing the bycatch of many seabirds,[10] the prevalence of nocturnal vessel interactions in fulmars suggests that this measure alone may not prove effective in this case.

We predicted and observed a spatial relationship between vessel encounter rates and fishing intensity.[13] Using anomalous light-spikes recorded by geolocators to identify interactions with fishing vessels, significant predictors of encounter rates included distribution, colony, time of year, and sex, with males more likely to encounter vessels. As has been shown in other scavenging seabird species such as northern gannets (*Morus bassanus*),[14] attendance of vessels is highly repeatable on an individual basis. This suggests that increases in vessel interactions may be driven by a higher proportion of the population attending vessels rather than individual-level changes. Fulmars in more recently established colonies (Scotland and Ireland), had higher encounter rates than those at the long-established colonies in Iceland and Jan Mayen. Colonization at these more southerly sites in the early 20th century has historically been attributed to increasing availability of fisheries waste,[15] suggesting that these subsidies supplement the natural diet of fulmars.[5,16] Although likely to provide only a fraction of fulmars' food requirements,[17] the consistent availability of fisheries waste may increase the viability of colonies outside the historic range of this species.

Regionally varying fishing practices are further likely to influence the likelihood of seabirds attending vessels.[18] Fulmars from Iceland had the lowest vessel encounter rates, which may be related to Iceland's ban on discarding non-target catch coupled with high pelagic fish biomass. A similar result was found in breeding northern gannets from Icelandic colonies, which interacted less with fishing vessels compared with gannets from elsewhere.[19] Though fulmars scavenge offal as well as discards,[17,20] similar processes may result in the reduced fishing vessel attendance of Icelandic fulmars. Norway also imposes a long-standing discard ban,[21] which in combination with the relatively low fishing pressure around Jan Mayen, may help to explain the reduced encounter rates of fulmars from this colony. European Union fisheries have recently been subject to a landing obligation, which prevents the discarding of undersized commercial fish species but still allows the discarding of non-commercial species. Uptake and enforcement of the landing obligation practices have met with resistance for a number of reasons,[22] leading to reductions in discards falling short of targets. This may explain the higher vessel attendance of Irish and Scottish fulmars, where less species-targeted demersal trawlers may discard a greater proportion of unwanted non-commercial species.[16]

Fulmars were significantly less likely to encounter vessels in the immediate post-breeding period, corresponding with the timing of feather molt.[23] Changes in diet have been recorded during the molt of other bird species,[24] so changes in nutritional requirements may also partially explain reduced encounter rates at this time of year. Dietary shifts may also explain reduced encounter rates prior to summer, as seabirds stockpile energy and specific nutrients in advance of egg-laying and incubation.[25]

The energetic cost-benefit of scavenging on fisheries waste versus targeting prey naturally is largely unknown. It has been proposed that seabirds targeting vessels can suffer from the reduced nutritional content of waste compared with natural prey.[6] High encounter rates were correlated with the geographic extent of an individual's non-breeding distribution, with fulmars that covered a broader area generally interacting with fewer vessels. However, the cause and effect of this relationship is difficult to qualify. More mobile fulmars generally spend more time in the high seas, where fishing effort is reduced compared with areas closer to the coast. However, we provide the first evidence that fulmars interacting with vessels spend less time foraging overall, suggesting that subsidizing their diet with fisheries waste is time efficient. Further fine-scale data on energetic expenditure during natural foraging and scavenging, from accelerometers, for example,[26] would be required to quantify energetic differences between discards foraging and natural foraging.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- EXPERIMENTAL MODEL AND SUBJECT DETAILS
  - Deployment and recovery of geolocator devices
- METHOD DETAILS
  - Processing of locations
  - Distribution and behavior data
  - Nocturnal vessel encounters
  - Fishery data
- QUANTIFICATION AND STATISTICAL ANALYSIS
  - Modelling of vessel encounters
  - Annual vessel encounters and individual repeatability
  - Modelling of behavior

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.cub.2023.08.033.

CellPress
OPEN ACCESS

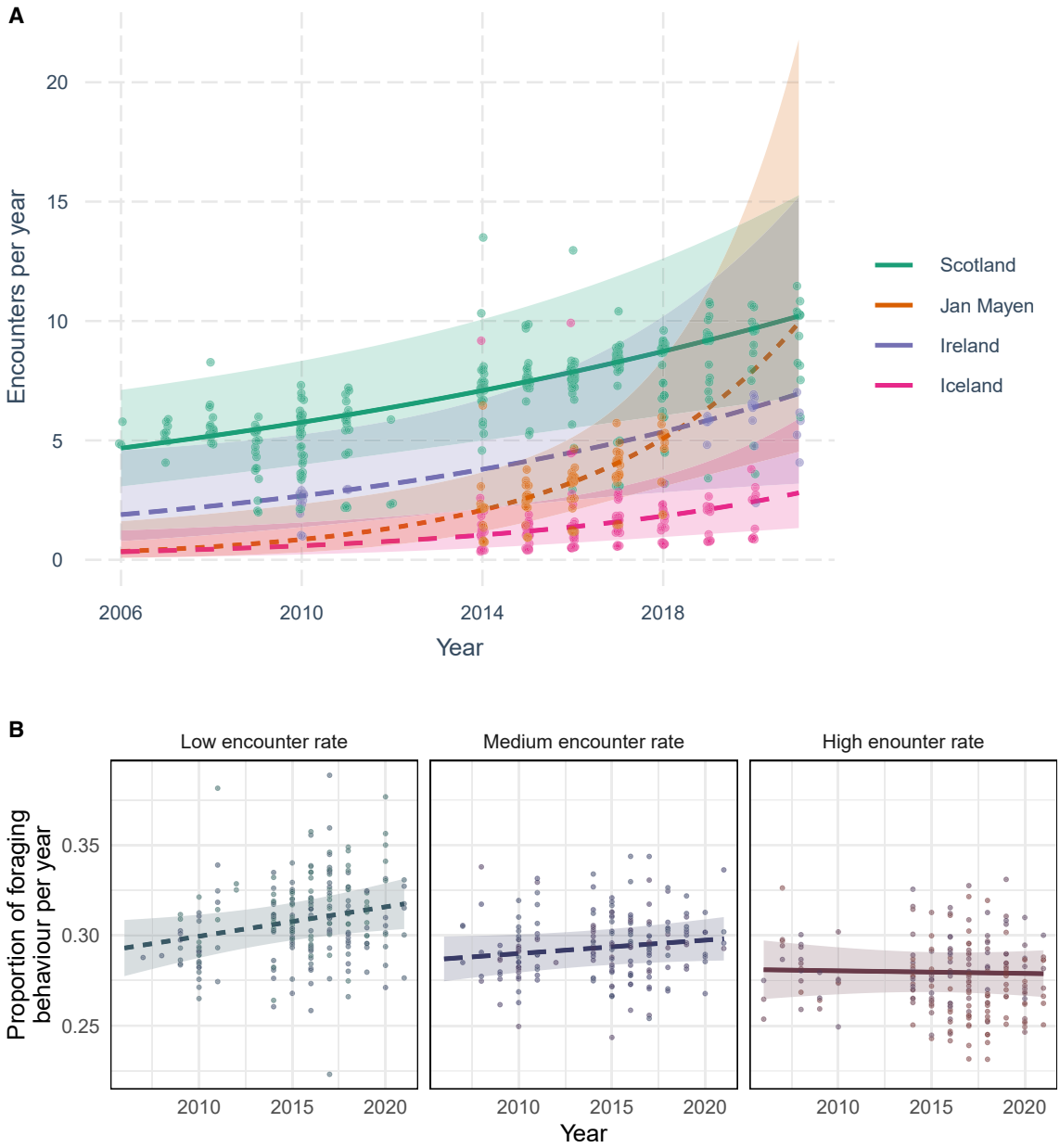


Figure 3. Trends of encounters and time-activity budgets

(A) The interaction between colony and year when explaining encounters per non-breeding season in the repeatability model. Plotted points are partial residuals and shaded areas around linear effects are the 95% confidence intervals. Note that trend lines extend beyond available data in earlier years for Jan Mayen, Ireland, and Iceland. See also Figure S1, which displays the available trends of fisheries production and recorded discards in the same time frame.

(B) Temporal patterns of time spent foraging for fulmars with high (left), medium (middle), and high (right) levels of nocturnal vessel encounters. Lines are partial effects, shaded areas are 95% confidence intervals, and points are partial residuals.

ACKNOWLEDGMENTS

J.H.D.'s position is funded by an Irish Research Council Enterprise Partnership Scheme (EPSPG/2019/469), M.C. is funded by the H2020 X-Rotor project (101007135), and the majority of GLS devices are funded by the SEATRACK program (seatrack.seapop.no, Norwegian Research Council grant no. 192141). We would like to recognize and thank all those who assisted in the deployment and recovery of GLS devices, too many to mention individually. We are indebted to Pat and Liezl Grattan-Bellew for accommodating fieldwork on Little Saltee, Orkney Islands Council for access to Eynhallow, the landowners at Laxamyri for access to the Skjalfandi colony, and the Norwegian Armed Forces for support and accommodation on Jan Mayen. Particular thanks to Françoise Amélineau and Ewan Edwards for helpful input during discussions on this topic at an early stage, and to Vegard Bråthen for collating, curating, and delivering the data for analysis. Thanks to the two anonymous reviewers for exceptionally helpful and constructive feedback.

AUTHOR CONTRIBUTIONS

J.H.D., M.C., J.Q., and M.J.J. created the concept. J.H.D., M.C., P.T., L.Q., D.C., H.S., T.L.T., and M.J.J. collected the data. J.H.D., M.C., and J.K. conducted statistical analyses. J.H.D. led the writing, with formative contributions and feedback from all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

Received: June 22, 2023
Revised: July 21, 2023
Accepted: August 10, 2023
Published: September 6, 2023

REFERENCES

1. Bicknell, A.W.J., Oro, D., Camphuysen, K.C.J., and Votier, S.C. (2013). Potential consequences of discard reform for seabird communities. J. Appl. Ecol. *50*, 649–658.
2. Brothers, N. (1991). Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. Biol. Conserv. *55*, 255–268.
3. Dias, M.P., Martin, R., Pearmain, E.J., Burfield, I.J., Small, C., Phillips, R.A., Yates, O., Lascelles, B., Borboroglu, P.G., and Croxall, J.P. (2019). Threats to seabirds: a global assessment. Biol. Conserv. *237*, 525–537.
4. Krüger, L., Paiva, V.H., Petry, M.V., and Ramos, J.A. (2017). Strange lights in the night: using abnormal peaks of light in geolocator data to infer interaction of seabirds with nocturnal fishing vessels. Polar Biol. *40*, 221–226.
5. Phillips, R.A., Petersen, M.K., Lilliendahl, K., Solmundsson, J., Hamer, K.C., Camphuysen, C.J., and Zonfrillo, B. (1999). Diet of the northern fulmar *Fulmarus glacialis*: reliance on commercial fisheries? Mar. Biol. *135*, 159–170.
6. Grémillet, D., Pichegru, L., Kuntz, G., Woakes, A.G., Wilkinson, S., Crawford, R.J.M., and Ryan, P.G. (2008). A junk-food hypothesis for gannets feeding on fishery waste. Proc. Biol. Sci. *275*, 1149–1156.
7. Patrick, S.C., Bearhop, S., Bodey, T.W., Grecian, W.J., Hamer, K.C., Lee, J., and Votier, S.C. (2015). Individual seabirds show consistent foraging strategies in response to predictable fisheries discards. J. Avian Biol. *46*, 431–440.
8. Eurostat (2019). Agriculture, forestry and fishery statistics. https://ec.europa.eu/eurostat/about/policies/copyright.
9. Garthe, S., and Furness, R.W. (2001). Frequent shallow diving by a northern fulmar feeding at Shetland. Waterbirds *24*, 287–289.
10. Jiménez, S., Domingo, A., Winker, H., Parker, D., Gianuca, D., Neves, T., Coelho, R., and Kerwath, S. (2020). Towards mitigation of seabird bycatch: large-scale effectiveness of night setting and Tori lines across multiple pelagic longline fleets. Biol. Conserv. *247*, 108642.
11. Kroodsma, D., Turner, J., Luck, C., Hochberg, T., Miller, N., Augustyn, P., and Prince, S. (2023). Global prevalence of setting longlines at dawn highlights bycatch risk for threatened albatross. Biol. Conserv. *283*, 110026.
12. Anderson, O.R.J., Thompson, D., and Parsons, M. (2022). Seabird bycatch mitigation: evidence base for possible UK application and research. JNCC Report No. 717 (JNCC). https://hub.jncc.gov.uk/assets/dbed3ea2-1c2a-40cf-b0f8-437372f1a036.
13. Dupuis, B., Amélineau, F., Tarroux, A., Bjørnstad, O., Bråthen, V., Danielsen, J., Descamps, S., Fauchald, P., Hallgrimsson, G.T., Hansen, E., et al. (2021). Light-level geolocators reveal spatial variations in interactions between northern fulmars and fisheries. Mar. Ecol. Prog. Ser. *676*, 159–172.
14. Votier, S.C., Bearhop, S., Witt, M.J., Inger, R., Thompson, D., and Newton, J. (2010). Individual responses of seabirds to commercial fisheries revealed using GPS tracking, stable isotopes and vessel monitoring systems. J. Appl. Ecol. *47*, 487–497.
15. Fisher, J. (1952). A history of the fulmar *Fulmarus* and its population problems. Ibis *94*, 334–354.
16. Darby, J.H., Dde Grissac, S., Arneill, G.E., Pirotta, E., Waggitt, J.J., Börger, L., Shepard, E., Cabot, D., Owen, E., Bolton, M., et al. (2021). Foraging distribution of breeding northern fulmars is predicted by commercial fisheries. Mar. Ecol. Prog. Ser. *679*, 181–194.
17. Camphuysen, K., and Garthe, S. (1997). An evaluation of the distribution and scavenging habits of northern fulmars (*Fulmarus glacialis*) in the North Sea. ICES J. Mar. Sci. *54*, 654–683.
18. Soriano-Redondo, A., Cortés, V., Reyes-González, J.M., Guallar, S., Bécares, J., Rodríguez, B., Arcos, J.M., and González-Solís, J. (2016). Relative abundance and distribution of fisheries influence risk of seabird bycatch. Sci. Rep. *6*, 37373.
19. Clark, B.L., Vigfúsdóttir, F., Jessopp, M.J., Burgos, J.M., Bodey, T.W., and Votier, S.C. (2020). Gannets are not attracted to fishing vessels in Iceland—potential influence of a discard ban and food availability. ICES J. Mar. Sci. *77*, 692–700.
20. Ojowski, U., Eidtmann, C., Furness, R., and Garthe, S. (2001). Diet and nest attendance of incubating and chick-rearing northern fulmars (*Fulmarus glacialis*) in Shetland. Mar. Biol. *139*, 1193–1200.
21. Gullestad, P., Blom, G., Bakke, G., and Bogstad, B. (2015). The "Discard Ban Package": experiences in efforts to improve the exploitation patterns in Norwegian fisheries. Mar. Policy *54*, 1–9.
22. Soto-Oñate, D., and Lemos-Nobre, A.C. (2021). The European Union landing obligation: the compliance problems derived from its multilevel approach. Mar. Policy *132*, 104666.
23. Grissot, A., Graham, I.M., Quinn, L., Bråthen, V.S., and Thompson, P.M. (2020). Breeding status influences timing but not duration of moult in the northern fulmar Fulmarus glacialis. Ibis *162*, 446–459.
24. Anderson, J.T., Smith, L.M., and Haukos, D.A. (2000). Food selection and feather molt by nonbreeding American green-winged teal in Texas playas. J. Wildl. Manag. *64*, 222–230.
25. Mallory, M.L., Forbes, M.R., Ankney, C.D., and Alisauskas, R.T. (2008). Nutrient dynamics and constraints on the pre-laying exodus of high Arctic northern fulmars. Aquat. Biol. *4*, 211–223.
26. Elliott, K.H., Le Vaillant, M., Kato, A., Speakman, J.R., and Ropert-Coudert, Y. (2013). Accelerometry predicts daily energy expenditure in a bird with high activity levels. Biol. Lett. *9*, 20120919.
27. van Franeker, J.A., and Ter Braak, C.J.F. (1993). A generalized discriminant for sexing Fulmarine petrels from external measurements. Auk *110*, 492–502.
28. Lisovski, S., Bauer, S., Briedis, M., Davidson, S.C., Dhanjal-Adams, K.L., Hallworth, M.T., Karagicheva, J., Meier, C.M., Merkel, B., Ouwehand, J., et al. (2020). Light-level geolocator analyses: a user's guide. J. Anim. Ecol. *89*, 221–236.
29. Merkel, B., Phillips, R.A., Descamps, S., Yoccoz, N.G., Moe, B., and Strøm, H. (2016). A probabilistic algorithm to process geolocation data. Mov. Ecol. *4*, 26.
30. Calenge, C. (2006). The package "adehabitat" for the R software: a tool for the analysis of space and habitat use by animals. Ecol. Modell. *197*, 516–519.
31. Mattern, T., Masello, J.F., Ellenberg, U., and Quillfeldt, P. (2015). Actave.net – a web-based tool for the analysis of seabird activity patterns from saltwater immersion geolocators. Methods Ecol. Evol. *6*, 859–864.
32. Rayner, M.J., Taylor, G.A., Gummer, H.D., Phillips, R.A., Sagar, P.M., Shaffer, S.A., and Thompson, D.R. (2012). The breeding cycle, year-round distribution and activity patterns of the endangered Chatham Petrel (*Pterodroma axillaris*). Emu – Austral Ornithology *112*, 107–116.
33. Kelley, D., and Richards, C. (2020). oce: analysis of oceanographic data. CRAN. https://cran.r-project.org/web/packages/oce/oce.pdf.

CellPress
OPEN ACCESS

34. Kroodsma, D.A., Mayorga, J., Hochberg, T., Miller, N.A., Boerder, K., Ferretti, F., Wilson, A., Bergman, B., White, T.D., Block, B.A., et al. (2018). Tracking the global footprint of fisheries. Science *359*, 904–908.

35. Wood, S.N. (2008). Fast stable direct fitting and smoothness selection for generalized additive models. J. R. Stat. Soc. B *70*, 495–518.

36. Hartig, F. (2022). DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. CRAN. https://cran.r-project.org/web/packages/DHARMa/vignettes/DHARMa.html.

37. Stoffel, M.A., Nakagawa, S., and Schielzeth, H. (2017). rptR: repeatability estimation and variance decomposition by generalized linear mixed-effects models. Methods Ecol. Evol. *8*, 1639–1644.

38. Bates, D., Mächler, M., Bolker, B., and Walker, S. (2015). Fitting linear mixed-effects models using lme4. J. Stat. Softw. *67*, 1–48.

39. Bartoń, K. (2020). MuMIn: multi-model inference. CRAN. https://cran.r-project.org/web/packages/MuMIn/MuMIn.pdf.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental models: Organisms/strains		
Northern fulmar (*Fulmarus glacialis*, n = 150, 2006 - 2022)	Eynhallow, Scotland	N/A
Northern fulmar (*Fulmarus glacialis*, n = 38, 2010 - 2012, 2019 - 2022)	Little Saltee, Ireland	N/A
Northern fulmar (*Fulmarus glacialis*, n = 54, 2014 - 2021)	Skjalfandi, Iceland	N/A
Northern fulmar (*Fulmarus glacialis*, n = 54, 2014 - 2021)	Jan Mayen, Norway	N/A
Deposited data		
Code to complete all statistical analyses	This study	https://doi.org/10.5281/zenodo.8197312/
Software and algorithms		
R software version 4.1.2	www.r-project.org/	N/A

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Jamie Darby (jamie.darby@ucc.ie).

Materials availability

This study did not generate new unique reagents.

Data and code availability

All fulmar location data are available from SEATRACK, seatrack.seapop.no/map/. All anonymized fishing vessel data are available from global fishing watch, globalfishingwatch.org/map/. All original code has been deposited at www.zenodo.org and is publicly available as of the date of publication. The DOI is listed in the key resources table. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Deployment and recovery of geolocator devices

GLS devices were deployed and recovered on 296 breeding adult fulmars from 2006 to 2022 in four colonies across the Northeast Atlantic. Recoveries were often > 1 year after deployment, providing a total of 737 years of data from 296 individuals. Geolocators were attached to a colored plastic ring fitted around the tarsus, with total deployment weight (devices plus leg ring and cable tie attachment) always < 1% body mass. Breeding adult fulmars were captured at the nest or in the air by hand, hand net, or noose pole and handling time was kept to a minimum. Several types of geolocator were used, and immersion sampling rate and light sampling units varied between models which could impact encounter detection or behavioral classification. Data were therefore grouped into 3 classes for subsequent analyses based on logger functionality.[13] Individuals were sexed where possible (n = 183), either genetically or using morphological measurements.[27] All fulmar capture, handling, and tag attachments were conducted under appropriate region-specific licenses.

METHOD DETAILS

Processing of locations

Light level data from different geolocator types were standardized and scaled from 0 to 1 (Figure S2). Using a threshold method,[28] transitions between day and night (twilight events) were identified, allowing the calculation of latitudes (using the length of day and

night) and longitudes (based on the time of noon and midnight). Unrealistic twilights, due to shading or encounters with anthropogenic light sources, were filtered out using a moving-window smoothing function. Using a probabilistic algorithm, 600 locations were estimated for each inter-twilight period.[29] To mitigate against unrealistic location estimation, the most likely location of these 600 was selected using additional temperature and immersion data from the geolocators combined with satellite-derived estimates of sea-surface temperature as well as estimated range and maximum flight speed of the species.[29]

Distribution and behavior data

Home ranges were calculated for each bird for each non-breeding season (September 1st to April 30th the following year), using the *adehabitatHR* package[30] to calculate the 90% utilization distribution (UD) of location estimates. Prior to UD estimation, locations were reprojected to azimuthal equidistant projection centered on each colony. The breeding season (May to August) was excluded when estimating home range because distributions will be central-place constrained, and light sensors on geolocators are often obscured when the bird is sitting on the nest, limiting the proportion of usable twilight data at this time of year. Behavior of the bird was calculated using geolocator immersion data recording the proportion of time spent immersed in saltwater per 10-minute interval.[31] If the logger was immersed for $\geq$ 95% of this interval, the bird was assumed to be sitting on the water. If the logger was immersed for $\leq$ 5% of the interval, the bird was assumed to either be in sustained flight or sitting on the nest. Anything between these two values was labelled as mixed behavior, and most likely represents foraging, when the bird is flying for short periods of time between landing on the water surface to feed.[32] The proportion of time per day spent engaged in mixed behavior was therefore considered a proxy for foraging behavior and calculated over the entire non-breeding season. Movement modes may vary between natural search behavior and scavenging. However, fulmars have been shown to engage in this "mixed" behavior when following vessels,[13] repeatedly landing and taking off (unpublished data), suggesting that immersion data are likely similar for both activities.

Nocturnal vessel encounters

Nocturnal vessel encounters were identified using the same principle as previous studies,[4,13] identifying anomalously high values in raw light data during the night (light spikes). Expected solar angle (αs) of each raw light datapoint was calculated based on time, date, and nearest estimated location using the *oce* package.[33] Datapoints without a successful location estimate within 4 days of their timestamp were excluded to avoid excessive inaccuracy when calculating αs. Depending on solar angle (αs), two thresholds of light level were used to define light spikes: For αs between 9 and 12 degrees below the horizon, standardized light levels were classified as light spikes when above 0.2. For αs greater than 12 degrees below the horizon, this threshold was reduced to 0.02. Natural light readings for all tag types are 0 for a αs greater than 6 degrees below the horizon, so these threshold values were conservative to avoid false classification of light spikes. To further reduce the likelihood of false positives, light spikes that weren't preceded and followed by a period of darkness lasting at least one fix interval, and those without any time immersed in saltwater in the preceding or following 20 minutes, were excluded. Light spikes were then grouped into encounters when no more than 40 minutes separated them, following established methods.[13] Number of encounters per calendar date, proportion of nocturnal fixes (αs < -9) per calendar date, and number of encounters per year tagged (July 1st to June 30th of the subsequent year) were then calculated. GPS tracking data and associated vessel monitoring data from a previous study[16] were used to demonstrate that vessel encounters at night were likely to be indicative of vessel interactions overall (Figure S3).

Fishery data

The spatial distribution of fishing effort was calculated over the observed range of all fulmar locations obtained in the study. Fishery data were sourced from Global Fishing Watch's collated Automatic Identification System dataset.[34] These data were available from 2012 to 2020, with increasing coverage over time, so the entire dataset was aggregated to a single spatial layer at 1 x 1° resolution to provide a metric for *persistent* fishing effort. Values in each grid cell were calculated as hours fished per km^2, accounting for latitudinal differences in grid cell size. These values were then appended to all fulmar track points.

QUANTIFICATION AND STATISTICAL ANALYSIS

Modelling of vessel encounters

Vessel encounters per night were modelled using generalized additive mixed-effects models (GAMMs) against spatial and temporal covariates using the *mgcv* package.[35] Two models were run, one with encounters per night as the response with a negative binomial error structure, and another with presence/absence of encounter in each night (0 or 1) as the response with a binomial error structure. The suitability of each model structure was tested with simulated residuals using the *DHARMa* package[36] and the binomial error structure was selected as the better fit. Fishing effort was included as a linear fixed effect. Proportion of nocturnal fixes per day (αs < -9) was also included as a spline, as this will affect the likelihood of detecting encounters, while Julian day was included as a cyclic cubic spline to explore variation throughout the annual cycle. Bird identity was included as a random effect to capture inter-individual variation in vessel attraction. Logger type was included as a fixed effect to account for differences in light sensitivity not captured by the light-level standardization process. The interaction between the linear effect of breeding year (July 1st to June 30th of the subsequent year) and colony was included as a covariate to assess trends of vessel encounters over time across the four study colonies. Sex was included as a factor, also retaining birds of unknown sex to avoid reducing the sample size. Serial

autocorrelation was tested for in both model structures using an autocorrelation function plot, and a first-order autoregressive error structure was applied. Model predictive power was tested by calculating the area under the receiver-operator curve (AUC).

Annual vessel encounters and individual repeatability

The individual repeatability of vessel encounters was modelled using the *rptR* package,[37] with encounters per year per individual as the response variable with a Poisson error structure. Individual identity was included as the random effect and grouping variable for repeatability estimation. Other covariates included mean fishing effort, sex, colony, year, 90% UD area, number of days recorded by the logger that year (minimum 150), and logger type. The *lme4* package[38] was initially used to fit and select a generalized linear mixed-effect model (GLMM) prior to fitting the repeatability estimation model. Two models were initially compared, one with year and colony included as an interaction, and one with each included separately, then the fit of each compared using AIC. The latter was chosen, and then the best fitting combination of covariates within this model was selected using the *dredge* function in the *Mu*MIn package,[39] again using AIC as the selection metric. Variance inflation factors were checked for retained variables to check for collinearity. The final model was then fitted using *rptR*. Annual change in encounter rates of individuals was also tested for individuals with repeat years of data to verify that individuals remained consistent in their vessel interaction rates over time.

Modelling of behavior

A GLMM was used to identify spatial and temporal trends in non-breeding season behavior over time. Proportion of time spent in "mixed" behavior was used as the response variable as putative foraging behavior. Number of encounters per year was used as a proxy for vessel attendance, taken as the square root to account for positive skew. This was included as an interactive term with year to understand how vessel attendance might drive temporal trends of foraging behavior. Other covariates included were sex and logger type. Individual identity was included as a random effect nested within colony. Colony was included as a random effect in this instance, as the specific trend per colony over time was not the primary point of interest, rather how vessel attendance might drive changes in activity budgets generally.