Supporting Protected Seabird Populations

Ecological Research into Generating Ecosystem Benefits from Fish Offal Waste

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Foreword

This research was commissioned to explore the possible benefits that seabirds in England could experience from changes to fisheries waste management practices. It is the companion report to Archer et al. (2024) and collectively will provide the evidence to allow Natural England and others to consider whether experimental trials are worthwhile. The findings may be applicable to situations where species recovery is required, or where offsetting of impact is necessary.

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Executive summary

Background

Seabirds are under threat worldwide from a variety of pressures both on land and at sea. While clear conservation solutions exist to address some of these threats, others like climate change or offshore energy development may be harder to address directly. Food availability is often an important driver of seabird survival and productivity, so one possible option to mitigate potential impact is offsetting in the form of provisioning (feeding) of local populations with additional sources of food. Given that large amounts of offal are discarded by the fishing industry in the North Sea, with many seabirds already making use of this fisheries waste as part of their diet, targeted offal provisioning has been suggested as a means of bolstering specific seabird populations most affected by human activities. To this end, in the following report we assess the feasibility, potential effectiveness and some of the ecological consequences of provisioning offal to a local population of seabirds in the Flamborough and Filey Coast (FFC) Special Protection Area (SPA).

Species-level assessment of risk and viability

To assess which species are most at risk, we conducted population modelling of eight local seabird populations in the FFC SPA. More than half of the species censused had declining population trends, and when combined with information on species vulnerability and national population status, we identified six species of conservation concern. A literature review of seabird-fishing vessel interactions highlighted that of the species identified, two do not consume any form of fisheries waste, and two consume almost exclusively discards, leaving two remaining focal species that consistently make use of offal: black-legged kittiwake (*Rissa tridactyla*), and northern fulmar (*Fulmarus glacialis*). Spatio-temporal analyses of tracking data from these two focal species estimated that local distributions of the two focal species overlap considerably, with minimal spatial opportunity for species-specific provisioning (though still some distance from the mean offshore foraging range for other discard-consuming gull species). Temporal analyses indicated the potential for targeted black-legged kittiwake provisioning in the afternoon (12:00–18:00 h). Exploration of the literature on seabird-bycatch mitigation highlighted how most broad-spectrum methods would be unsuitable for targeted provisioning, though specially designed selective feeders may have some use.

Energetic modelling of offal provisioning

Using recent data on North Sea offal discards, we built energetic models to estimate how many seabirds could be supported under three different scenarios (i–iii) of offal availability. In the current scenario (i), the offal available to seabirds in the FFC SPA supports an estimated two hundred individuals in the breeding season. Under a broader scenario (ii) that includes all offal within ~185 km of simulated seabird distributions (ie, within one day's transport by a fishing vessel), an estimated one thousand breeding individuals in the FFC SPA could be supported. In the broadest scenario (iii) that includes all offal discards in the entire ICES statistical area 27.4.b, we estimate that close to six thousand individuals could be supported during the breeding season (roughly 5% of the censused population in the FFC SPA). We also reviewed the impacts of offal consumption on seabird populations to assess the potential ecological implications of offal provisioning. There is a severe lack of research into the effects of an offal-rich diet on seabirds, though generalising from findings of discard-foraging species suggests there could be significant detrimental effects for both adults and their chicks. There may be also important ecosystem-level ramifications of offal provisioning, with the potential for trophic cascades occurring within both seabird and benthic communities.

Limitations and outlook

There are several key limitations in the work presented. The tracking data used only captures a subset of species present in the FFC SPA, and using simulations for birds tracked outside of the FFC SPA may be a poor representation of fine-scale habitat use for individuals inside the FFC SPA. Our bioenergetics models may not be well-parameterised to local dietary specialisation, and great care must be taken when using estimates and extrapolations which carry large degrees of uncertainty. To address these limitations and the remaining knowledge gaps, we provide a series of recommendations for future work to be conducted, including additional tracking work on more focal seabird species within the FFC SPA, a series of observational studies on local discard consumption behaviour, design and testing of a selective offal feeder, and baseline chemical analyses of the nutritional, energetic and heavy metal content of offal.

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Introduction

Background

Seabirds are under threat worldwide from a variety of pressures both on land and at sea (Dias et al., 2019). While conservation solutions exist to counteract many of these threats, such as bycatch mitigation measures (e.g. Maree et al., 2014) or fisheries controls (e.g., Searle et al., 2023), for some newer and emerging threats like climate change or offshore energy development direct counter measures may be harder to implement. An alternative is to offset any increased mortality stemming from these threats by benefitting seabird populations in some other way (McGregor, Ross et al., 2022). Approaches to offsetting anthropogenic impacts to seabird populations remain largely novel and untested. Offsetting may focus, for example, on improving conditions at breeding sites by removing invasive species (Spatz et al., 2017), reducing human disturbance (Ellenburg et al., 2006), improving nesting habitat (Sherley et al., 2012), or creating new colonies (Miskelly et al., 2009). Another option, to be explored in this project, is to increase food availability to improve reproductive success or survival. In order to make evidence-based decisions about the technical feasibility, likely effectiveness and ecological consequences of such measures, it is important to consider the practicalities, how to monitor any effects, the likelihood of success and wider ecological considerations relevant to such a potential project.

Human control over food resources is effective for some birds (e.g., vultures; Oro et al., 2008 and garden birds; Oro et al., 2013), but it is less well studied for seabirds. However, small-scale supplementary feeding of anthropogenic food has led to improved breeding success and higher return rates in Arctic skuas (*Stercorarius parasiticus*) (Davis et al., 2005), and whole fish provisioning has shown long-term beneficial carry-over effects in black-legged kittiwakes (Vincenzi et al., 2015). Nevertheless, approximately 9 million tonnes of fisheries waste are disposed of at sea each year, which equates to incidental supplementary feeding on a global scale (Zeller et al., 2018). Discards and offal can support millions of seabirds (Sherley et al., 2020b) and there is also anecdotal evidence for population increase of some scavenging species (Oro et al., 2013; Votier et al., 2004). Concerns about the sustainability of dumping undersized or over quota catch has led to discard bans in Europe, Norway, New Zealand, Chile, and Iceland. However, offal – including the livers and intestines of marketable fish removed during sorting and cleaning – is a waste product which is otherwise dumped at sea but could provide food for seabirds. Therefore, strategic provision of offal may benefit some seabirds, potentially helping to offset predicted losses due to impacts from human activities, without the sustainability concerns presented by other supplementary feeding.

The UK supports internationally important, protected, seabird populations which use an increasingly crowded marine space. This not only creates conservation challenges but also a requirement to counterbalance deleterious effects. Another feature of the UK seabird assemblage is the high proportion of facultative discard consumers (Bicknell et al., 2013; Sherley et al., 2020b). This is thought to have facilitated an increased abundance of some scavenging species, although the evidence is circumstantial and takes no account of historical baselines (Bicknell et al., 2013).

Aims and Objectives

At the outset of this project, Natural England wanted to gain a better understanding of whether it is theoretically possible to provision UK seabirds with offal. This requires information on relevant ecological considerations including direct and indirect effects. This project is focused on describing and quantifying the potential benefits and consequences of offal provision to seabirds under three areas of focus, identifying: (1) focal taxa most likely to benefit, and the possibility of benefiting target seabird species; (2) most appropriate time / location for disposal; (3) amounts of offal required.

Species most likely to benefit from offal provision

While a wide range of seabirds consume discards (Bicknell et al., 2013), this assemblage is dominated by large generalist species which in turn are most likely to benefit from offal provision. Quantitative information is therefore required on the seabird species considered most likely to take fish offal waste and how this varies in time and space. Consideration must also be given to maximising offal consumption by target species – i.e., how feasible it might be to subsidise only a component of a seabird assemblage, as well as what benefits this might generate.

Location / time where offal provision is likely to be most effective

Careful consideration is required to select the most appropriate location for offal provisioning. This requires information on offal availability / accessibility and appropriate seabird colonies where monitoring and offal provision could co-occur. At smaller spatial scales, consideration should be given to where offal could be provided, such as directly from fishing vessels or via feeding stations, as well as distance from focal colonies. Timing is also important. Most likely, considerations would focus on the breeding season because birds tend to be more aggregated, and impacts can be quantified at colonies. However, information is needed to determine which stage of breeding could be most beneficial for offal disposal, based on known locations of birds and potential available offal.

Estimating the amount of offal required to benefit seabirds.

Offal consumption is likely to vary as a function of the availability of alternative foods such as discards of undersize fish (Hudson and Furness, 1988, 1989) or naturally occurring foods (Votier et al., 2004). Nevertheless, despite these important caveats, estimates show that offal disposal in the North Sea in 2010 could support >1 million seabirds (Sherley et al., 2020b). It is unclear however how much offal would be required to improve the breeding success or survival of focal species (|, to quantify how many ‘extra’ birds would result per unit of offal). However, it would be possible to estimate the amount of food needed to meet the energetic requirements of the target population using a bioenergetics model (Votier et al., 2004).

Overview

For the purposes of this project, where there is limited knowledge on likely availability of offal, the optimal location and timing of offal provision is considered using the seabird colony of the FFC SPA as a case study. The work undertaken on this project is described below against two Key Deliverables (KD) linked to the objectives above:

> **KD1:** An assessment of the most appropriate target seabird species, methods to facilitate specific provisioning of those species (e.g., by reducing competition with other species) and timings and locations where offal provision could be most beneficial, including resulting relevant GIS layers.
>
> **KD2:** A bioenergetics model to assess the amounts of fish offal required to benefit focal seabirds identified in KD1, using scenario testing to test the effects of different levels of offal provision.

KD1 Assessment of target species and provisioning methods

KD1.1 Assessment of local seabird population trends

In order to assess the current state of local seabird populations found in the FFC SPA, we analysed trends in colony counts[1]. All data between 1980–2022 collected within the FFC SPA were downloaded from the Seabird Monitoring Programme database (SMP, 2022), with data available for seven species: northern gannet (*Morus bassanus)*, European herring gull (*Larus argentatus argenteus*), black-legged kittiwake, razorbill (*Alca torda*), Atlantic puffin (*Fratercula arctica*), common guillemot (*Uria aalge*), northern fulmar (*Fulmarus glacialis*) and European shag (*Gulosus aristotelis*). To ensure that data were comparable before and after the 2018 FFC SPA expansion (the inclusion of the cliffs at Filey), we used colony counts for the original Flamborough Head and Bempton Cliffs site only. Data available for this site covered a period of 1986–2022, composed of sporadic yearly colony counts for each species.

We employed Bayesian state-space models (SSMs) to model population trends in the FFC SPA. SSMs use count or relative abundance data to analyse population changes in a way that simultaneously accounts for year-to-year variation and observation or reporting errors, while also assuming a Markovian process that realistically models how animal populations can change over time (Kéry and Schaub, 2011). SSMs were implemented in ‘JARA’ (Just Another Red-List Assessment, Sherley et al., 2020a) using the ‘census’ model type option (summarised in Figure 1.1.1 and Table 1.1.1). All analyses and visualisations were conducted in R (version 4.1.0), with code and data available in supplementary material section.

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[1] It is important to note that these trends are unlikely to fully reflect the immediate or longer-term impacts of Highly Pathogenic Avian Influenza. This virus has led to widespread mortality in several species of seabirds, and its effects on the abundance of seabirds at breeding colonies may take some time to be fully revealed.

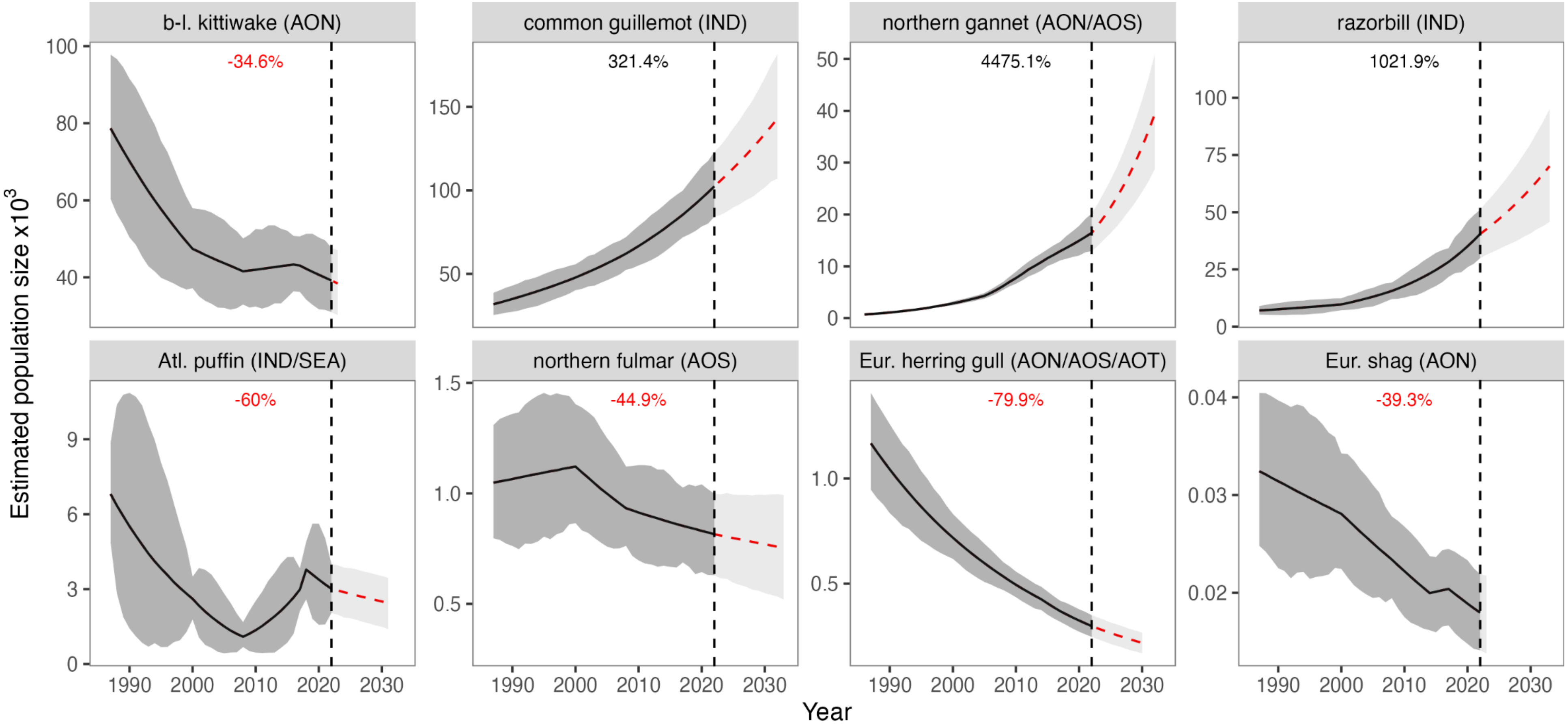

Figure 1.1.1 Population trajectories for all species monitored in the FFC SPA estimated with a Bayesian SSM implemented in JARA, with 95% credible intervals (grey polygons) for population estimates. Vertical dashed black line distinguishes the observed trajectory of data up to 2022 (solid black line) from projected trajectories (red dashed line). Projection extent varies between species according to the total duration required to assess population change over three generation lengths (for clarity all plots are clipped to a maximum of 10 years projections). Inset percentages below species names show the median population change over three generations. Acronyms after species names denote count methodology from Walsh et al. (1995) used for

census (AON: Apparent Occupied Nests; AOS: Apparent Occupied Sites; AOT: Apparent Occupied Territories; IND: Individuals on land; SEA: Individuals rafting at sea). 1 AON, AOS or AOT equate to 1 breeding pair.

The colony trends of four seabird species in the FFC SPA would be classified as 'Least Concern' (population increases or declines <30% in 3 generation lengths, GL): northern fulmar, northern gannet, razorbill, and common guillemot (Table 1.1.1). Black-legged kittiwake, European shag and northern fulmar all met the criteria to be classified as 'Vulnerable' (population declines >30% but <50% in 3GL), with their populations declining at ~1–2% per annum over all the available data (median annual change: kittiwake: −1.94%; shag: −1.68%; fulmar: –0.76%, Table 1.1.1). Atlantic puffin and herring gull both would meet the criteria to be classified as 'Endangered' (population declines >50% but <80% in 3GL), with herring gull showing annual declines of ~3.9% in both median population change and one generation change, while Atlantic puffin showed colony declines over the whole available time-series (median annual change: −2.5%) despite increases in the short-term (1GL change: +4.93%, Table 1.1.1). In terms of the FFC SPA Conservation Objectives, all species named as features of the SPA with 'Maintain' objectives have population numbers and trends in line with their local abundance targets (common guillemot: 41,607 breeding pairs; northern gannet: 8,467 breeding pairs; razorbill: 10,570 breeding pairs/21,140 individuals). However, black-legged kittiwake, which have a 'Restore' objective, show declines that put them below their abundance target of 83,700 breeding pairs.

Table 1.1.1 Median annual change (%), annual change over the last one generation length (GL) (%), and posterior probabilities (%) for the overall population change over 3GL in the FFC SPA matching the IUCN Red List categories of ‘Least Concern’ (LC), ‘Near Threatened’ (NT), ‘Vulnerable’ (VU), ‘Endangered’ (EN), and ‘Critically Endangered’ (CR). These posterior probabilities can be read as the probability that the population would meet the IUCN Red List A2 criteria for listing in each category. Species generation lengths are from Bird et al. (2020). Collision vulnerability score and disturbance risk index are both taken from Furness et al. (2013) — higher values for these columns indicate a greater degree of vulnerability/risk.

Species	Gen. Length (GL)	Median annual change	Annual change over last GL	LC	VU	EN	CR	Likely status in FFC SPA	Collision vulnerability score	Disturbance risk index
European herring gull	14.075	−3.83	−3.95	0	0	51.9	48.1	EN	1306	3
Atlantic puffin	14.230	−2.5	4.93	4.4	16	76.8	2.8	EN	27	10
Black-legged kittiwake	9.781	−1.94	−1.39	30.6	61.6	7.8	0	VU	523	6
European shag	9.257	−1.68	−1.55	18.2	69.9	12	0	VU	150	14
Northern fulmar	25.341	−0.76	−1.08	32.4	35.6	31.7	0.4	VU	48	2
Northern gannet	15.036	9.25	7.78	100	0	0	0	LC	725	3
Razorbill	16.370	5.14	6.29	100	0	0	0	LC	32	14
Common guillemot	14.772	3.37	3.52	100	0	0	0	LC	37	14

KD1.2 Local seabird vulnerability

To better understand the variable threats faced by seabirds in the FFC SPA, we gathered additional information on two pressures of key concern for species: offshore windfarm development, and high pathogenicity avian influenza (HPAI). It should also be recognised that in filtering species of concern, there are other important pressures not considered here, such as changes in food availability or severe weather events induced by climate breakdown.

We considered the degree of collision vulnerability and disturbance risk presented by offshore windfarms for each species, using information from Furness et al. (2013). Data from this paper indicated that herring gull and black-legged kittiwake (classified locally as Endangered and Vulnerable, respectively) have a high vulnerability to collision with windfarms, with herring gull having the highest calculated vulnerability score of all 38 species in the study. Northern gannet, which was classified locally as Least Concern, also had a high vulnerability score (ranked 5th of 38 species — though there is some recent evidence that they tend to avoid offshore windfarms after construction). Species' risk of disturbance by windfarms appeared to fall into two groups, with half of the eight assessed species at the low end of rankings (herring gull, black-legged kittiwake, northern fulmar, northern gannet), and the other half middle-ranked (Atlantic puffin, European shag, razorbill, common guillemot) on an index scale from 1–32 (Furness et al., 2013).

The recent epizootic of HPAI highlights the importance of assessing how seabird species may vary in their susceptibility to infection by contagious diseases. HPAI has caused significant mortality in the UK populations of great skua (*Stercorarius skua*) and northern gannet, with a range of other seabirds testing positive for HPAI, including common guillemot, black-legged kittiwake and razorbill (Falchieri et al., 2022). In northern gannets, it has been suggested that HPAI infection triggers long-distance journeys to other colonies (Jeglinski et al., 2023), putting the local FFC population at increased risk of an HPAI outbreak. Given the patterns of infection in colonies across the UK, we expect that northern gannets are the species in the SPA most likely to experience the highest levels of mortality.

KD1.3 Considering national and international red list data

To compare our assessment of the local seabird populations in the FFC SPA against each species' status on a broader scale, we considered national status classified by the British Birds of Conservation Concern list (BoCC - Stanbury et al., 2021), and global population status classified by the IUCN (2022) — see Table 1.3.1.

Table 1.3.1 Summary of local (in the FFC SPA, as taken from Table 1.1.1 above), national (Stanbury et al., 2021), EU and global status (IUCN, 2022) of seabird species found in the FFC SPA. Also included are estimates of the European population size, and approximate change in the European population size over three generations from IUCN (2022). IUCN data shared under CC-BY-NC license.

Species	Local status (table 1.1.1)	National status (BoCC)	EU status (IUCN)	Global status (IUCN)	European adult pop. (individuals × 10^3)	3GL change (Europe) [note 1]
Herring gull	EN	Red	LC	LC	1,060 – 1,220	−1 to −19%
Atlantic puffin	EN	Red	EN	VU	9,550 – 11,600	−50 to −79%
Black-legged kittiwake	VU	Red	VU	VU	3,460 – 4,410	−40%
European shag	VU	Red	LC	LC	153 – 157	−25%
Northern fulmar	VU	Amber	VU	LC	6,760 – 7,000	−50 to −79%
Northern gannet	LC	Amber	LC	LC	1,370	Increasing
Razorbill	LC	Amber	LC	LC	519 – 1,070	−30%
Common guillemot	LC	Amber	LC	LC	2,350 – 3,060	−25 to −50%

Note 1 The estimated population change over three generations for Atlantic puffin, Northern fulmar and common guillemot include a future projection

At broader scales, European population status matched local trends for all species except herring gull and European shag, which were both classified as Least Concern in the EU, while being locally Vulnerable (fulmar), and locally Endangered (herring gull) in the FFC SPA. Global conservation status for half of the species assessed matched our local population assessment (black-legged kittiwake, northern gannet, razorbill and common guillemot). Negative differences in local conservation status were observed for European shag (globally LC but locally VU), northern fulmar (globally LC but locally VU) and Atlantic puffin (globally VU but locally EN), with herring gull showing the greatest negative difference (globally LC but locally EN).

Overall assessment of FFC SPA seabird assemblage

Based on the results of our population assessments, we identify five species with local population trends that warrant conservation concern (herring gull, Atlantic puffin, black-legged kittiwake, European shag, and northern fulmar), all of which could potentially benefit from food provisioning. While northern gannet colony counts show healthy local population trends, their relatively high vulnerability to windfarm collisions (Table 1.1.1), as well as the recent drastic impact by HPAI make them an additional candidate for targeted provisioning. Importantly, the black-legged kittiwake and northern gannet populations are designated features of the FFC SPA and subject to ‘restore’ and ‘maintain’ abundance conservation objectives respectively (Natural England, 2023).

KD1.4 Literature review of seabird interactions with fishing vessels

Overview and focal species

As a bountiful foraging opportunity that carries a high risk of injury or death if bycaught in fishing gear, interactions with fishing vessels represent a double-edged sword for scavenging seabirds (Lewison et al., 2004). Despite the potential dangers, more than half of all seabird species feed to some extent on the ~9 million tons of fisheries waste produced every year by the fishing industry (Bicknell et al., 2013; Gilman et al., 2020; Oro et al., 2013). While discarded waste likely represents the primary driver behind many seabird-fishing vessel associations, there are various other types of interactions that might occur, shaped by each species’ behaviour, ecology and distribution (Le Bot et al., 2018). Seabird-vessel interactions can also be modified by a range of internal and external factors across both spatial and temporal scales (Barnes et al., 2021) including the availability of alternative prey (Clark et al., 2020). The complexity of interactions and modifying factors highlights the importance of reviewing existing research when designing effective mitigation measures involving seabirds and fisheries waste (Le Bot et al., 2018; Provencher et al., 2019).

Based on our population assessment of local seabird colonies (KD1.2), we identified five focal species of conservation concern in the FFC SPA: European herring gull, black-legged kittiwake, Atlantic puffin, northern gannet, and European shag. Northern fulmar will be included as a sixth focal species because of their importance in the seabird assemblage as an offal consumer (Camphuysen and Garthe, 1997), and despite global status of LC, their local population trend is of concern (VU). To assess the potential implications and benefits of offal provisioning for each of these focal species, we review the available literature on seabird interactions with fishing vessels, assessing several key interaction types as well as considering modifying factors and broader implications. Information is sourced primarily from Sherley et al. (2020b), supplemented by additional research published after November 2020 (including grey literature).

Species attendance and scavenging at fishing vessels

Of the six focal species identified, black-legged kittiwake, European herring gull, northern gannet, and northern fulmar are known to be a common presence around fishing vessels in the North Sea, and are observed scavenging extensively (Table 1.4.1). Alongside four other non-focal species — great skua, common gull (*Larus canus*), lesser black-backed gull (*Larus fuscus*) and great black-backed gull (*Larus marinus*), they form the main assemblage of seabird scavengers found attending fishing vessels in the North Sea (Sherley et al., 2020b). Attendance and scavenging rates by the two remaining focal species (European shag and Atlantic puffin) are markedly different to the rest of the focal species, with shag sometimes observed around vessels in small numbers (Bicknell et al., 2013), and only rarely seen scavenging (Camphuysen, 1993), while puffin have not been documented associating with fishing vessels, and are not thought to consume discards or offal (Camphuysen et al., 1995).

Table 1.4.1 Summary of fishing interactions, presence at hauls, discard and offal consumptions ranges, and foraging preference for all six focal species.

Species	Fishing vessel interactions (association | scavenging) [source 1]	Presence at hauls (%) [source 2]	Discard consumption range (%) [source 3]	Offal consumption (%) [source 4]	Discards vs. offal preference
Northern fulmar	common | extensive	100	25–80	30/50 (summer/ winter)	offal
Black-legged kittiwake	common | extensive	96	30–50 (winter only) [note 1]	25 (winter only) [note 1]	equal
European herring gull	common | extensive	55	22.5–40	10	discards
Northern gannet	common | extensive	84	8–70	0	discards
European shag	rare | rare	No data	0	0	N/A
Atlantic puffin	not recorded | N/A	No data	N/A	N/A	N/A

Source 1: Fishing vessel interactions from Camphuysen et al. (1995); Source 2: Percentage of hauls attended by each species in summer (between July-August) from Garthe and Hüppop (1994); Source 3: Discard consumption ranges from Sherley et al. (2020); Source 4: Offal consumption from Table 4.4 of Garthe et al. (1999). Note 1: Based on historical records, North Sea populations of black-legged kittiwakes shift to feeding almost exclusively on sandeels (*Ammodytes marinus*) when these become abundant in summer, making little use of discards and offal during this period (see Table 4.4. of Garthe et al., 1999).

Consumption of fisheries waste and foraging preferences

Fishing vessels produce two main types of fishery waste: ‘discards’ (defined here as whole, non-marketable fish or invertebrates), and ‘offal’ (the internal organs of processed fish) — definitions adapted from Garthe et al. (1996). When thrown overboard this waste forms an ephemeral resource patch in the wake of fishing vessels, which lasts until it is consumed or sinks. In terms of overall consumption of offal and discards by seabirds, previous studies suggest offal has the highest level of depletion (with 88% of experimentally-discarded items eaten), followed closely by discarded roundfish (79%), while consumption is generally much lower for discarded flatfish (13%) and benthic invertebrates (6%) (Camphuysen and Garthe, 2000).

Consumption rates of discards and offal can vary greatly between seabird species and across populations — in some cases forming up to 75% of an individuals’ diet (Oro et al., 2013). Most generally for seabirds in the North Sea, larger scavenger species usually consume larger discards than smaller species (Camphuysen et al., 1995). Specific preferences for discards versus offal are presumed to differ according to each species’ natural foraging niche, with pelagic piscivores tending to favour discards, and generalist foragers more likely to consume some combination of discards and offal (Camphuysen and Garthe, 2000). Scavenging preferences across the six focal species cover the spectrum of foraging behaviour from specialist to generalist (Table 1.4.1). For example, northern gannets will feed on roundfish discards (8–70% of diet), but apparently do not consume offal (Garthe et al., 1996). European herring gulls generally favour discards (22.5–40% of diet), but do also consume some offal (10% of diet) (Garthe et al., 1996). In winter, black-legged kittiwakes will make roughly equal use of discards and offal (Garthe et al., 1999). Conversely, northern fulmar by several accounts appear to specialise on offal (Camphuysen et al., 1995; Camphuysen and Garthe, 1997) — to such an extent that when they are the predominant species around a vessel they consume almost all (94%) of the offal available. This proportion drops when fulmar numbers are equal to other species (33%), and is lowest when they are in the minority (8%) (Camphuysen and Garthe, 1997).

Foraging interactions within and between species

Rates of inter- and intra-specific kleptoparasitism varies greatly between species, with experimental studies of discarding from Camphuysen et al. (1995) demonstrating that almost a third of all ‘robbery’ events were instances of intra-specific kleptoparasitism amongst northern fulmar (Figure 1.4.1). Black-legged kittiwakes also exhibited high levels of intraspecific kleptoparasitism (11.5% of total interactions). Northern gannets had lower levels of intraspecific kleptoparasitism (4.7%) but were observed regularly stealing from northern fulmar (13.6%). Northern fulmar were kleptoparasitised by the highest number of different species, with food items stolen by great skua, great black-backed gull, herring gull, and lesser black-backed gull (3.3%, 5.5%, 2.6% and 2.3% respectively), with events involving stealing from northern fulmar representing more than a quarter (27.6%) of all foraging interactions. Though the previous study did not record the species composition of flocks or age demographics of individuals observed stealing, results from other work suggest that both variables are likely to have an important impact on the ability of individuals to successfully steal prey items from hetero- and conspecifics (Bertellotti and Yorio, 2000).

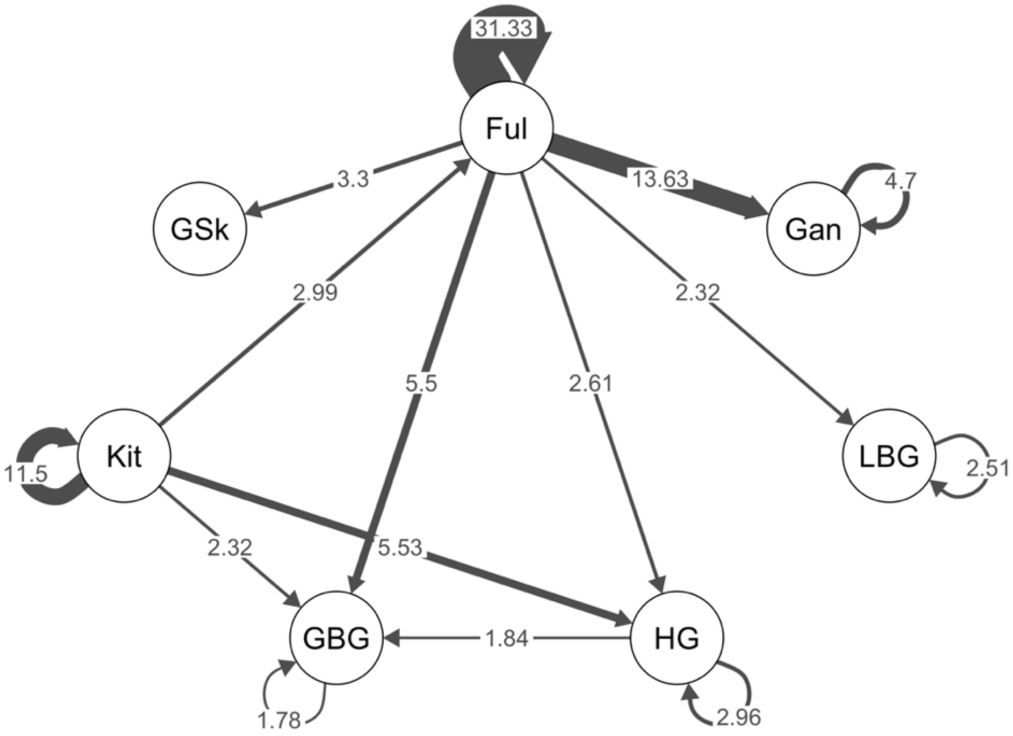

Figure 1.4.1 Foraging interaction network of the main inter- and intra-specific robbery events occurring between seabird species in the North Sea, visualised using data collected during experimental discarding (of both discards and offal) from Camphuysen et al. (1995). Ful: northern fulmar; Gan: northern gannet; LBG: lesser black-backed gull; HG: herring gull; GBG: great black-backed gull; Kit: kittiwake; GSk: great skua. Arrows show direction of robbery interaction (stolen from → stolen by), with looping arrows indicating intraspecific kleptoparasitism. Numbers for each interaction show the percentage of interactions relative to total for all observed events (e.g., intraspecific kleptoparasitism events in northern fulmars represented over 30% of all robbery interactions observed). Nodes and interactions with fewer than five robbery events were removed from totals and network, and interactions representing less than 1% of all observed events were hidden from network visualisation for clarity.

While Figure 1.4.1 shows interactions over both discards and offal combined, the frequency of kleptoparasitism between scavengers can also vary according to type of discarded item. For example, ~18–25% of flatfish, roundfish and benthic invertebrate discards are handled by at least two different individuals before being swallowed, while offal was usually swallowed immediately and only very rarely (0.7% of the time) handled by more than one individual (Camphuysen et al., 1995). Patterns of kleptoparasitism also varied between seabird species depending on the prey species involved in the interaction. For example, the "robbery index" (defined as the number of prey items stolen by a species divided by the number of prey items stolen from that species) for northern gannets were highly positive for roundfish and flatfish (indices of 18.3 and 4.0) while interactions involving offal were not recorded (Camphuysen et al., 1995). Of the two focal species with recorded kleptoparasitism interactions involving offal, black-legged kittiwakes had an index just above zero (0.1 — ie, stealing roughly as often as stolen from), while northern fulmar showed a positive robbery index of 2.2 (stealing offal more than twice as often as having it stolen). Prey-specific variation in kleptoparasitism appears to also be driven partly by size of prey items and resultant handling time, with a study on herring gull and lesser black-backed gull reporting that kleptoparasitism was lowest in a combined prey category that contained all the smallest fish species (Sotillo et al., 2014).

Facultative foraging interactions with fishing vessels

Beyond scavenging on discarded waste, seabirds may use fishing vessels for locating and accessing unpredictable, or out-of-reach prey (Assali et al., 2017; Votier et al., 2004). For example, species might use vessels as a long-distance cue for detecting patchily distributed prey shoals, or follow vessels directly to fishing grounds (Assali et al., 2017; Bodey et al., 2014; Cianchetti-Benedetti et al., 2018). Once prey are located by a fishing vessel, fishing activity can improve access to foraging opportunities, as the process of hauling fishing gear can corral shoals of fish into bait balls at the sea surface, providing a focal point for plunge-diving species (Clark et al., 2020). Even when fish are trapped in fishing gear, seabirds can either depredate prey from inside the net, wait to catch individual live prey as they escape from fishing gear, or forage on ‘slipped’ prey that are purposefully released before the catch is hauled onboard (Le Bot et al., 2018). Bait-stealing directly from hooks is regularly observed in seabird communities elsewhere in the world (most often among *Procellariformes*), but only very rare cases of this behaviour have been observed in North Sea species — primarily northern fulmars (Dunn and Steel, 2001).

Temporal variation of seabird interactions with fishing vessels

Seabird interactions with fishing vessels can show extensive variation across timescales, from yearly cycles of breeding behaviour to the daily patterns of human fishing activity (Hunt and Furness, 1996). Prey abundance for example, is a key long-term driver of interactions, as seasonal declines in prey availability often push seabirds to rely on fisheries discards as a supplementary food source (Camphuysen et al., 1995; Church et al., 2019). As a result, overall discard and offal consumption rates in the North Sea are generally lower in summer and higher in winter, ranging from 94–100% (summer % – winter %) for offal, 70–92% for roundfish discards, 10–35% for flatfish discards, and 3–17% for invertebrate discards (Table 3 – Camphuysen and Garthe, 2000). Consumption of fisheries waste can also vary seasonally for different species. For example, historic data on black-legged kittiwakes suggest they make equal use of discards and offal (representing ~50% of their diet) — but, assuming appropriately abundant prey items such as sand eels are available in summer, only in winter (Garthe et al., 1999). This pattern of increased winter discard use can also be seen in northern gannets, with smaller numbers observed feeding on discards during summer months (Camphuysen et al., 1995).

Given the increased energetic requirements of reproduction, breeding behaviour also plays an important role in seasonal variation of seabird-fisheries interactions (Searle et al., 2023).

Seasonal peaks in fish prey abundance are targeted by both the fishing industry and breeding seabirds, and as a result competition for resources can be intensified during these times (Pichegru et al., 2009). In a study of herring gulls and lesser black-backed gulls off the coast of Belgium, breeding was shown to influence both flock composition and prey selectivity, with breeding adults becoming more likely to consume or steal discarded fish items, particularly during chick rearing stages (Sotillo et al., 2014). For black-legged kittiwakes, the breeding season instigates a shift away from foraging on fisheries waste and instead targeting wild prey such as sandeels and *Clupeidae* (Garthe et al., 1999). It should be noted that the North Sea has undergone significant ecological changes over recent decades, with large reductions in sandeel biomass (Church et al., 2019), and as a result any previously documented seasonal shifts in discard use may not still be accurate. Recent historical analyses of black-legged kittiwake productivity and fishery data suggest a link between increased fishing activity and reduced breeding success (Carroll et al., 2017), with a lower proportion of 0-group sandeel in black-legged kittiwake diet (Searle et al., 2023).

Temporal patterns of fishery interactions by seabirds can also vary on shorter timescales, such as within days or over weeks. Such patterns are most often related to changes in movement and activity of fishing vessels — for example, a study on lesser black-backed gulls in the Wadden Sea showed a significantly reduced use of key fishing zones during weekends (when fleets were not operating), with tagged breeding females showing particularly intensive weekday use of fishing grounds (Tyson et al., 2015). This activity-matching behaviour (which has also been shown in urban gulls) demonstrates how some seabird species may have the capacity to flexibly respond to temporal patterns of provisioning (Tyson et al., 2015; Spelt et al., 2021).

Spatial variation of seabird interactions with fishing vessels

Seabird interactions with vessels are shaped by processes occurring over a range of spatial scales; from broad-level patterns of oceanography and distance to colony, to finer-scale patterns linked to the movement and activity of fishing vessels (Garthe, 1997).

At the broadest spatial scale, most seabirds are functionally limited by how far they naturally forage from their home colony or coastline, which during breeding is also modulated by local prey depletion (Ashmole, 1963; Weber et al., 2021). A study of 11 seabird species in the North Sea used a range of spatial and hydrographic variables to analyse important aspects of their distribution, finding that the distance to nearest breeding colony had a significant influence on the summer spatial distribution for all breeding species analysed (focal species: black-legged kittiwake, 50–80 km; European herring gull, 50–80 km) (Garthe, 1997). This study also identified two apparent clusters of species, representing an offshore group (comprised of northern fulmar, common guillemot, black-legged kittiwake, and lesser black-backed gull), and an inshore group (comprising herring gull and the six remaining species). This pattern of distribution is documented elsewhere, with Sotillo *et al.* (2014) noting the apparent substitution of vessel-attending herring gulls by lesser black-backed gulls with increasing distance from the colony. A review of tracking studies by (Woodward et al., 2019) summarised foraging ranges for breeding seabirds in the UK, with mean foraging range of focal species ranging from 15 (±8) km for herring gull, to 120 (±50) km for northern gannet (see Table 1.4.2). Recent work on guillemots (*Uria* spp.) demonstrated how the distribution of foraging ranges scales with colony size, and is consistent across colonies varying in size over multiple orders of magnitude (Patterson et al., 2022).

Table 1.4.2 Adapted version of Table 1 from Woodward et. al (2019), summarising breeding foraging ranges in kilometres estimated from tracking studies, filtered to only include focal species in the FFC SPA. Error is presented as ± 1 SD, and sample sizes are shown in parentheses. 'Confidence of assessment' assigns a confidence level to each foraging range based on the number of tracking studies available as well as a visual and statistical assessment of variability (ie, >5 tracking studies and 'Highest' suggest low variability between sites; >5 tracking studies and 'Good' suggest wider variability between sites).

Species	Maximum foraging range	Mean maximum foraging range (number of studies)	Mean foraging range (number of studies)	Confidence of assessment
Northern gannet	709	315.2±194.2 (21)	120.4±50 (19)	Highest
Northern fulmar	2736	542.3±657.9 (16)	134.6±90.1 (11)	Good
Lesser black-backed gull	533	127±109 (18)	43.3±18.4 (16)	Highest
Black-legged kittiwake	770	156.1±144.5 (37)	54.7 ± 50.4 (37)	Good
Herring gull	92	58.8±26.8 (10)	14.9±7.5 (7)	Good

At a local scale, seabirds use a wide variety of visual and olfactory cues to detect actively fishing vessels, and much research has been directed to studying the way fishing vessels influence seabird movement and foraging behaviour (Votier et al., 2013). A study of northern gannets estimated the spatial range of this influence to be roughly 11 km, with some results suggesting that individuals are also able to modify their behaviour depending on vessel type and activity (Bodey et al., 2014). Similarly, in a tracking study of northern fulmars, it was estimated that over half of tagged individuals associated with fishing vessels while they foraged, and persistent commercial fishing effort was found to be a significant spatial predictor of foraging behaviour – performing better than several other environmental covariables (Darby et al., 2021). For lesser black-backed gulls tracked near Helgoland, over a third of foraging trips overlapped with fishing vessel movements, and when within 5 km of a vessel individuals flew slower and changed direction more — indicative of scavenging behaviour (Sommerfeld et al., 2016).

Fine-scale spatial patterns of seabirds around fishing vessels can also be heavily influenced by discarding strategy; a recent experimental study of *Procellariiformes* in the Southwest Atlantic demonstrated how a ‘batch’ release method (discards stored and periodically dumped) greatly reduced the number of birds observed around fishing vessels (Kuepfer, Sherley, et al., 2022). Discarding while vessels are travelling at full steam can even put some less manoeuvrable species at a disadvantage; northern fulmars for example struggle to forage behind fast-moving vessels as they are unable to pick up items on the wing (Camphuysen et al., 1995).

Implications of avian influenza

During the breeding seasons of 2021–22 an outbreak of high pathogenicity avian influenza (HPAI) caused mass mortality across many north Atlantic seabird colonies adding a novel threat to some species sustainability and an unforeseen dynamic to understanding ecosystem benefits of offal provisioning. Although the impacts are not fully understood, there have been severe negative impacts on gannets (Lane et al., 2023) and positive tests of HPAI from five other species which are part of this study (herring gull, common guillemot, great black-backed gull, black-legged kittiwake, and Atlantic puffin). Therefore, any potential ecosystem benefits from offal should be viewed through the lens of this disease with due consideration given to whether attracting large numbers of birds to baiting/discarding locations could increase contact rates and therefore the potential spread of HPAI.

Previous work has shown how anthropogenic food subsidies can potentially lead to disease propagation (Oro et al., 2013), but it is unclear whether this may be the case here. Indeed, many seabird species are characterised by foraging in large groups because food is often aggregated in the marine environment, therefore interactions while foraging would appear to be commonplace.

Key conclusions for prospective offal provisioning project

Species considerations

Given the propensity for northern fulmars to scavenge large proportions of available offal (particularly when they are the dominant species present), placement of any offal provisioning sites should carefully consider proximity to fulmar colonies and areas likely to be frequented by large numbers of fulmars. Provisioning from vessels moving at full steam may also be a viable way to restrict offal depletion by fulmars (if this was desirable) given their inability to scavenge on the wing (Camphuysen et al., 1995)

Spatial considerations

Provisioning sites should attempt to avoid large colonies of non-target gulls and northern fulmar as mentioned above (spatial overlap and colony range will be assessed further in KD1.5). Provisioning sites located a long way offshore (50–80 km) appear less likely to be utilised by generalist *Larus* gull species (Garthe, 1997). If sites are located away from gull colonies but still inshore, it is likely that non-target species will still be able to change their distribution to match provisioning locations (though the timeframe over which this could occur is not clear).

Temporal considerations

To maximise chances of success, provisioning could target periods of the year when target species experience increased energetic stress, such as during chick-rearing, or when natural prey are seasonally less abundant. For species such as black-legged kittiwakes that may be less likely to consume offal during the breeding season if prey items such as sandeels are available, more active hand-feeding methods could be considered (Whelan et al., 2020). Methods should also try to avoid times of days when large gulls show high levels of movement and foraging activity, whilst being aware of the capacity for some species to learn regular weekly patterns of human activity (Tyson et al., 2015).

Suitability of offal as a provisioned food source

Several aspects of offal make it well-suited for provisioning to smaller seabird species: offal is often in pieces small enough to be consumed quickly with little opportunity for kleptoparasitism, and is preferentially eaten by black-legged kittiwakes, while apparently targeted by relatively few other species (primarily fulmar). The outlined provisioning approach does have some unknown elements, as the energetic content and nutrition of offal can vary depending on the composition of tissue types, and assimilation may differ across scavenging species relative to their body size and digestive tract length (Hilton et al., 2000). The primary unknown is that there is a lack of clear information on the energetic, survival and breeding implications of a diet dominated by offal, and even less so for chicks provisioned with offal.

Provisioning method

Provisioning should deliver offal in a way that minimises opportunities for kleptoparasitism (ie by fulmars and larger gulls), via i) reducing the size of food pieces to minimise handling time and thus shorten kleptoparasitism window (Sotillo et al., 2014), ii) physically blocking entry to non-target species using custom designed floating apparatus at sea, or iii) provisioning directly at nesting sites (Whelan et al., 2020). Offal could also be sorted by quality (e.g., retaining energy-dense organs) — though this assumes sufficient availability of offal and feasibility of sorting method.

KD1.5 Identifying core use areas as spatio-temporal opportunities for offal provisioning

Data collation

Given the importance of space-use in seabird ecology, it is prudent to consider where best to locate provisioning sites to maximise access to target species and minimise competition from non-target species. We aimed to achieve this goal by a) using real tracking data to simulate the distribution of seabird movements from known colony sites, b) relate this distribution coarsely to colony size as per Patterson et al. (2022), and c) look for potential times and places where target and non-target species do not overlap (or overlap the least).

Public tracking data from individuals inside the FFC SPA was only available for black-legged kittiwake via the FAME and STAR dataset (Wakefield et al., 2017), which comprised data for 154 individuals tracked over five years (2010–2015). We also utilised the FAME and STAR dataset for northern fulmar (43 individuals tracked over four years from 2010–2014), though these individuals were tracked from several sites on the east coast of Scotland.

Methods

Raw tracking data was processed using the ‘nestR’ package (Picardi et al., 2020) to detect the most likely nest locations, and movements outside of a 250m buffer around nests that lasted more than 30 minutes were classified as trips. We filtered data to the first complete trip (where tracks started and ended at the same nest location). For species with smaller tracking datasets (specifically northern fulmar), we retained the first three trips to ensure adequate source data for simulation replicates.

Using this processed and filtered tracking data, we fit correlated random walk, continuous-time state-space models (SSM’s) using the ‘aniMotum’ package (Jonsen et al., 2023). Derived SSM model parameters were used to simulate 50 new central place foraging tracks per trip, and incorporated a weak potential function to avoid simulated locations on land (Brillinger et al., 2012). For species tracked outside of the FFC SPA, simulations were adjusted to initiate at the Lighthouse colony site at Flamborough Head (which we arbitrarily designated as the central colony location of the FFC SPA).

All simulated tracks were then filtered to include only the top 20% of tracks with greatest ‘similarity’ — calculated following Hazen et al. (2017) as the sum of normalised differences in net angular displacement between the SSM path and the simulated path. To remove any remaining unrealistic tracks, we ran a final spatial intersection filter to remove tracks where more than 5% of points were on land.

Observed activity patterns

To analyse the temporal activity patterns of our focal species, we plotted the temporal density distribution of raw data points weighted by their speed (Figure 1.5.1). While an unweighted temporal distribution plot would show how the amount of data collected varies over time (which for GPS data should remain relatively constant), weighting each tracking data point with travel speed means the same temporal distribution now highlights periods of high-speed movement as peaks, and slow-movement or stationary periods as troughs. The resulting visualisation represents an approximate daily activity profile for each species. Given the similarity in latitude and tracking periods of the two datasets, seasonal differences in photoperiod are likely to have only minimal effect on the strength of activity patterns observed.

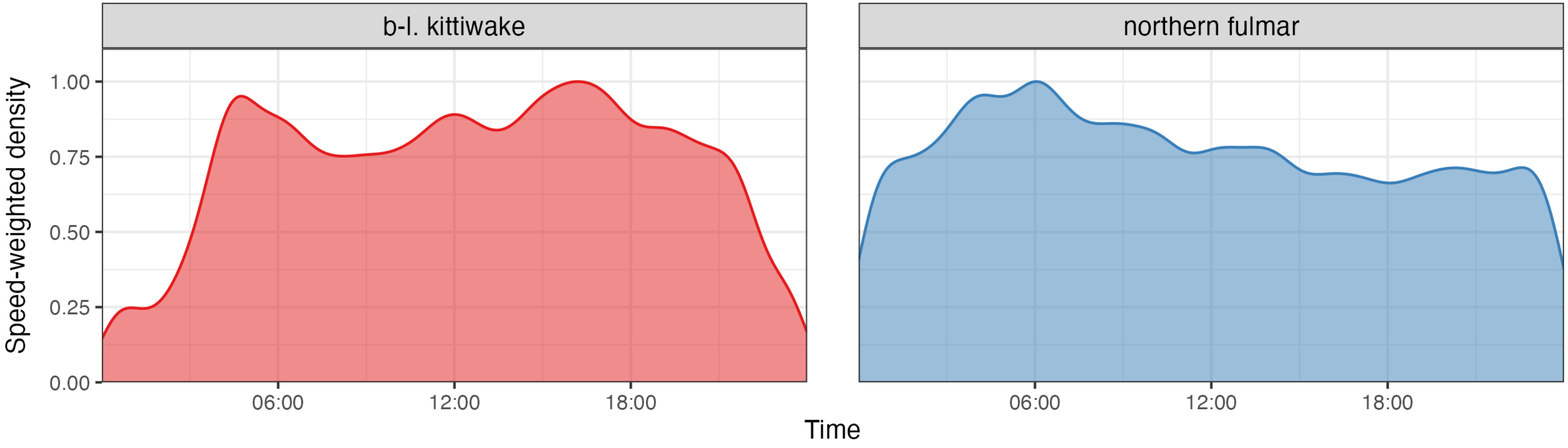

Figure 1.5.1 Speed-weighted density distribution of movement activity faceted by focal species (density axis is scaled for ease of comparison between species).

Overall, black-legged kittiwakes exhibited primary peaks in activity around 05h00 and 17h00, with depressed activity levels between 21h00 and 04h00 (presumably for roosting or incubation). This coarse pattern of activity for black-legged kittiwakes in the FFC SPA reflects activity patterns of birds tracked on the Isle of May (Daunt et al., 2002). By comparison, northern fulmar appears to show little diel variation in activity, with a small peak in activity around 06h00, followed by a shallow decline in activity level over the rest of the day, levelling out at around 18h00.

Simulated spatial distributions

We used kernel density estimation (KDE) to map the spatial distribution of simulated movements for focal species (Figure 1.5.2). Bandwidth for KDEs was estimated per species using a univariate plug-in bandwidth selector (Wand and Jones, 1994), implemented with the ‘eks’ package (Duong, 2023). 50% and 95% KDEs were chosen as the standard for visualising distributions of animal movements.

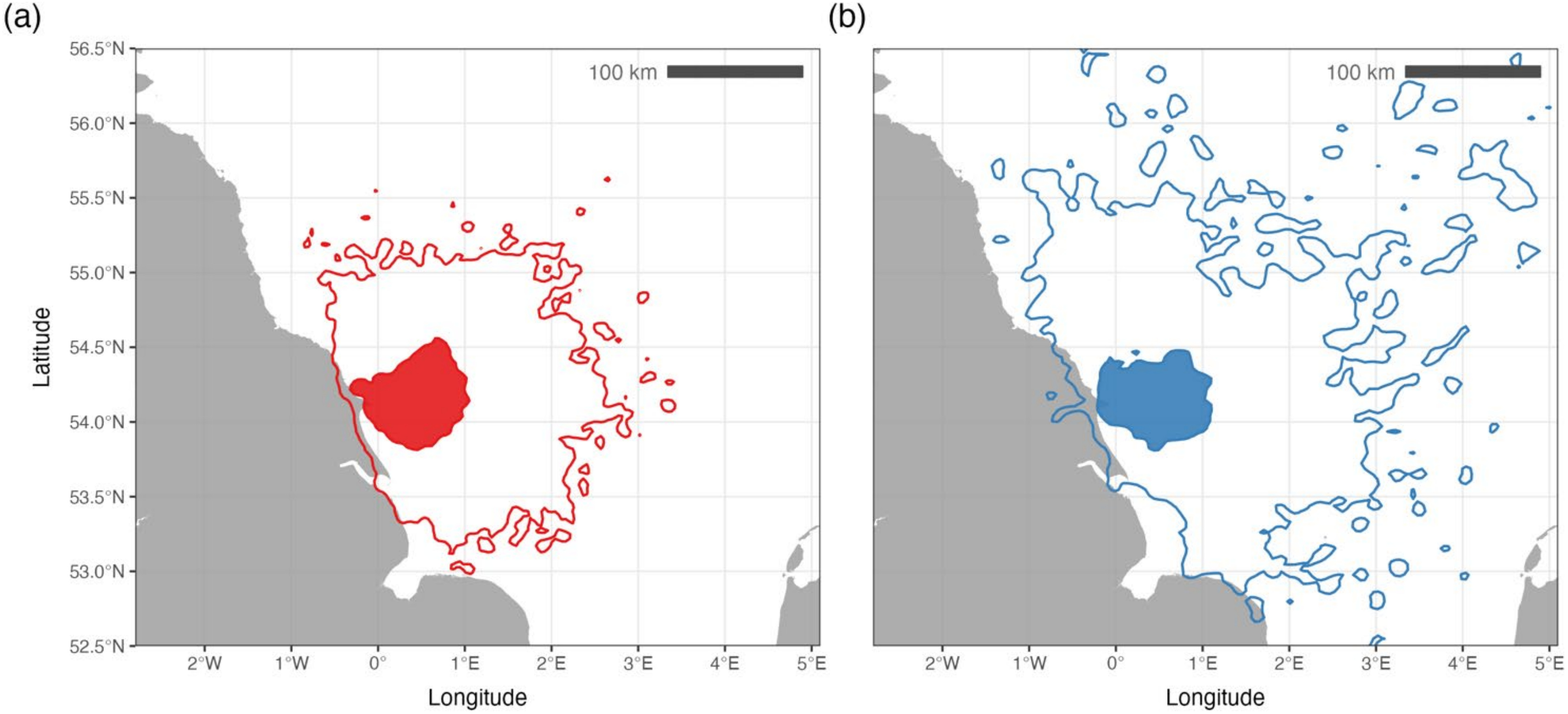

Figure 1.5.2 Kernel density estimates for distribution of focal species, derived from simulated tracking data of a) black-legged kittiwakes (919 simulated tracks from first trips of 145 individuals) and b) northern fulmar (404 simulated tracks from first three trips of 38 individuals). The 50% KDEs are denoted by coloured filled polygons, while the 95% KDEs are denoted by coloured lines.

Spatial analyses suggest longer-range trips made by northern fulmar cause the 95% KDE to encompass the entire spatial extent of the simulated black-legged kittiwake distribution, with core areas (50% KDEs) for each species also largely overlapping. Correlated random walk simulations appeared to accurately represent the 95% KDEs of real seabird movements, validating our choice of track simulation parameters (see supplementary figure S1.4.1 for comparison of real and simulated distribution of black-legged kittiwake).

Conclusions

Temporal analyses show little opportunity for provisioning black-legged kittiwakes alone, as northern fulmars appear to be consistently active throughout the day and night, with only minimal variation in activity. Comparison of temporal activity patterns suggest there may be a small window of opportunity in the late afternoon and early evening worth exploring further (Figure 1.5.1). This is mirrored in the analyses of spatial distributions, with the simulated 95% distribution of northern fulmars encircling much of the simulated kittiwake distribution. Considering the focal species not modelled, provisioning sites could be located near the maximum extent of the 50% KDE for black-legged kittiwakes, as this will likely reduce the speed at which larger gull species (herring and lesser-black backed) are able to discover provisioning sites (see species foraging ranges summarised in Table 1.4.2).

The spatial analyses presented do have some caveats, due to both data and methodological limitations. First, while we made use of the relevant species included in the FAME and STAR datasets (black-legged kittiwake and northern fulmar), several gull species found in the FFC SPA (notably the European herring gull), do not have freely available tracking data. The lack of tracking data in the FFC SPA could be problematic, as several species exhibit site-specific variation in foraging ranges, and may potentially overlap with black-legged kittiwake and northern fulmar (see Table 1.4.2). Tracking data for three relevant gull species (herring, great black-backed and lesser black-backed) have been collected in a study conducted within the East Caithness Cliffs SPA (Archibald et al., 2014), though additional time was needed to secure permissions to use these tracking data. Second, using simulated tracks to model species distributions (particularly for species not tracked within the FFC SPA) are likely to be a poor representation of behaviour of local individuals. This is especially true given that the simulations used are not given any environmental information other than a gradient raster for avoiding land. Some additional tracking data for the FFC SPA have been collected by the RSPB (e.g., Wischnewski et al., 2017) but additional time and resources (in particular person hours at RSPB) would have been necessary to secure permissions to use these tracking data here. A specific collaboration with the RSPB Centre for Conservation Science and additional tracking studies to assess spatial behaviour of individuals from the local population could improve our understanding, particularly for species not yet tracked as recent work suggests that even one year of data can be sufficient to characterise the local distribution of each species (Beal et al., 2023). In addition, combining local tracking data with environmental covariables derived from remote-sensing would allow a more accurate simulation model to be built that includes resource selection functions, providing distribution estimates that are more closely linked to local environmental variation (Boyd et al., 2015).

KD1.6 Literature review on seabird bycatch mitigation

Given that any offal provisioning method used is likely to involve the entire local seabird assemblage foraging at a provisioning site, we need to consider how to deter non-focal species without also discouraging the species targeted for provisioning. To this end, in this section we summarise the anti-bycatch measures developed by the fishing industry to deter, block, or otherwise reduce the chance of scavenging seabirds from becoming entangled in fishing gear (Williams et al., 2019), and assess whether any of these methods could be co-opted for blocking non-target species from foraging at provisioning sites.

Blocking access to baited hooks

One primary way of reducing seabird bycatch is to prevent access to the fishing gear itself (Maree et al., 2014). One of the most common approaches is to use hook-shielding devices that cover baited hooks and only open when they have reached a sufficient depth — out of reach of plunge-diving scavengers (Sullivan et al., 2018). Blocking access to baited hooks can also be achieved by setting nets underwater, using weighted nets or bait, or using thawed (rather than more buoyant frozen) bait to ensure that baited hooks sink quickly (Klaer and Polacheck, 1998). While these methods have been shown to greatly reduce seabird bycatch when used, they have little relevance to offal being provisioned on the sea surface.

Physical and acoustic deterrents

Mitigation methods that deter species from fishing gear while above water have better utility for preventing access to a sea-surface offal provisioning site. One common form of seabird deterrent are bird-scaring lines (also termed ‘streamer’ or ‘tori’ lines), which have been shown to have high effectiveness when used to deter seabirds from interacting with longline fisheries gear (Maree et al., 2014; Williams et al., 2019). Bird exclusion devices such as ‘Brickle curtains’ can be used to similar effect when hauling in demersal longlines (Reid et al., 2010). Exclusion devices may have some utility for discouraging non-target species away from provisioning sites, though it may be challenging to stop such methods from also deterring target species.

Several acoustic methods exist that could be used to deter seabirds from interacting with fishing gear. For example, gillnets fitted with acoustic alert devices called ‘pingers’ have been shown to cause significant reductions in the number of seabirds bycaught (Melvin et al., 1999). Previous studies have suggested that acoustic deterrents may have limited feasibility due to negligible responses in several tested seabirds, as well as the high probability of habituation if sounds are played too regularly (Brothers, 1999). Minimal information available from seabird species suggests more research is needed into which sound types, frequencies and delivery methods are needed to make them effective seabird deterrents.

Alternative discarding methods

Given the strong attraction of seabirds to fisheries waste, another key form of bycatch mitigation relates to how discards and offal are discharged from vessels. For example, this can involve discarding on the opposite side of the vessel to fishing gear, which reduces seabirds crowding in high risk areas around fishing vessels (Bull, 2006). As mentioned in KD1.4, using a 'batch' release method — where discards are stored and then dumped periodically — has been shown to significantly reduce the number of birds observed around fishing vessels, which again reduces proximity to fishing gear (Kuepfer, Sherley, et al., 2022). While batch discarding works well to keep seabirds aways from vessels, this approach may favour access to discards for species that can dive over those that feed on the surface.

Spatial and temporal avoidance measures

One simple approach for minimising seabird bycatch is put out fishing gear at night. This is thought to have a combined reduction of seabird bycatch because fewer seabirds are likely to be active, and those that are may struggle to see baited hooks in low light (Bull, 2006). Night-setting in this way has been shown to be a successful method for reducing seabird bycatch (Fernández-Costa et al., 2016; Jiménez et al., 2019), and is thought to be particularly beneficial for fishing types that use slow-sinking bait (Bull, 2006). It should also be noted that not all species avoid foraging at night — for example red-legged kittiwakes in the Bering Sea are known to forage nocturnally on bioluminescent *Myctophidae* fishes, potentially to avoid interspecific-competition with sympatric black-legged kittiwakes (Kokubun et al., 2015).

Selective feeders

Transponder-activated selective feeders have been used to great success in study systems of songbirds (Firth et al., 2016). While the use of transponders with seabirds may not be feasible, it is conceivable that a selective feeder could be designed that uses a simple camera input and machine learning to classify target species and provide access to a food source (Hentati-Sundberg et al., 2023). Analogue selective feeders with specifically sized holes that prevent access to certain seabirds with larger heads may also be feasible, though both selective feeder designs would likely require extensive research, development, and testing.

Conclusions

Many of the commonly used methods for bycatch mitigation are broad-spectrum approaches, and likely to deter both target and non-target species alike. Testing of chosen methods will be required to establish if selective approaches used are both functional and feasible for implementing at the scale required for this project.

KD2 Bioenergetics modelling to assess offal provisioning requirements

KD2.1 Assessing local offal availability

To model more accurately the current and potential offal usage by seabirds around the FFC SPA, we made use of discard data collected by Poseidon (see parallel NE report — Archer et al. 2024). This raw data is comprised of catches by UK commercial fishing vessels, summarised (alongside other spatial and temporal variables) by the ICES division and rectangle in which fish were caught. As per the methodology used by Archer et al. (2024), offal tonnage was estimated by subtracting the landed weight of each catch from the live weight, yielding an approximate value of offal removed from fish during processing. Offal tonnages were then grouped into ICES rectangles of catch origin (Figure 2.1.1). All subsequent spatial analyses using these data are built on the assumption that for each catch, offal was discarded in the same ICES rectangle in which fish were landed.

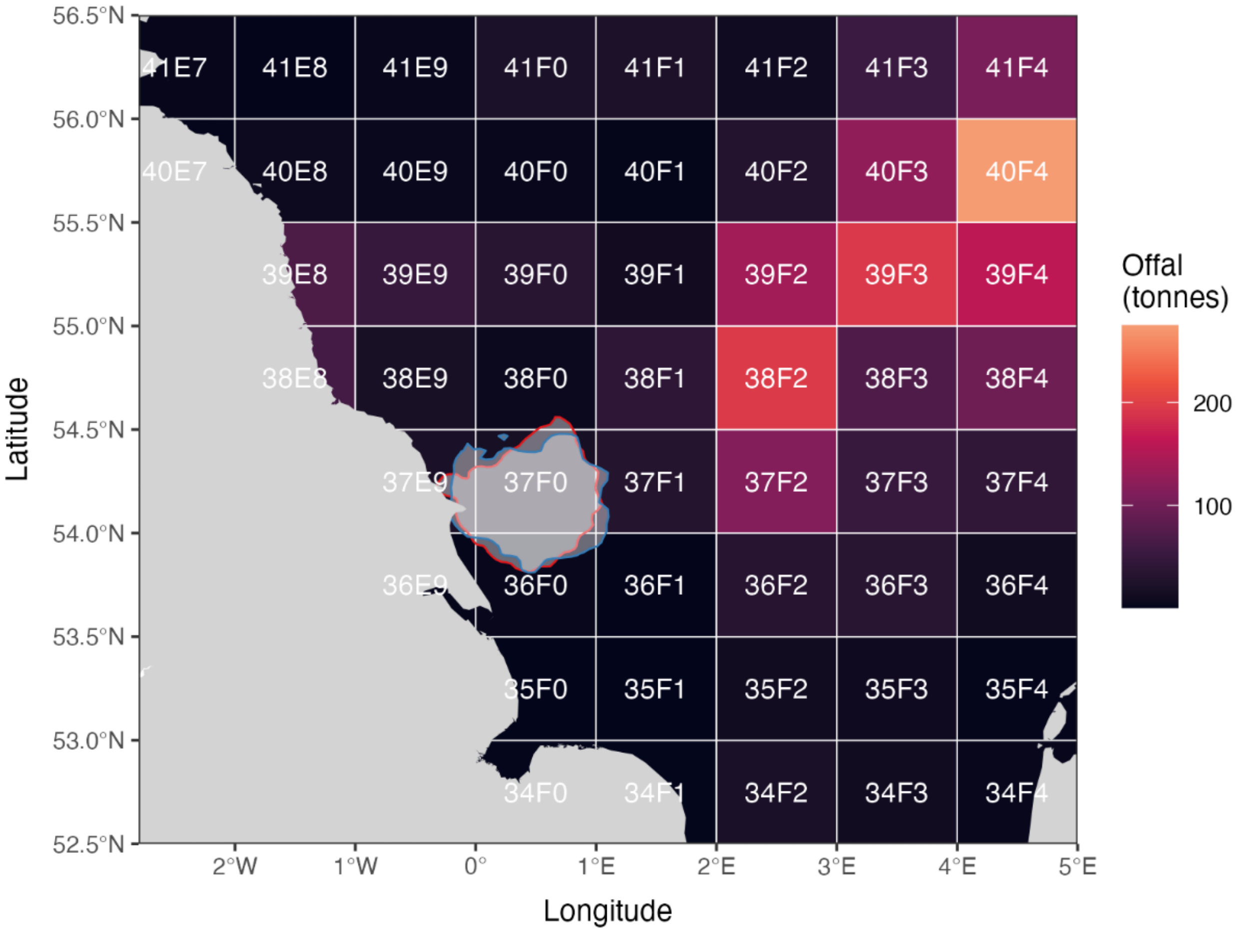

Figure 2.1.1 Cumulative spatial distribution of offal discarded in the North Sea, summarising data collected from 2016 – 2021. Of the rectangles shown, 40F4 appears most likely to have the highest intensity of offal discarding, with more than 275 tonnes discarded over the five-year period. Also shown are the 50% KDEs for black-legged kittiwake (red-bordered polygon) and northern fulmar (blue-bordered polygon)

from Figure 1.5.2, which are included for reference. See Figure 2.2.2 for temporal distribution of this same data.

KD2.2 Outlining offal availability scenarios

To parameterise a model that reflects realistic offal availability scenarios for each species, we combined the estimated offal discarded in each ICES statical rectangle (shown previously in Figure 2.1.1) to outline three possible scenarios of offal availability. For approximating the current ‘natural’ foraging paradigm, ***scenario i)*** includes offal from all rectangles that overlap or are adjacent to the spatial distribution of focal species. To capture a realistic provisioning approach, ***scenario ii***) uses offal from rectangles within 185 km of the edge of the focal species’ 50% spatial distribution — this distance equates to 100 nautical miles, which we use as an approximation of the maximum daily travel distance for a fishing vessel. To capture the maximum extent of potential provisioning, ***scenario iii)*** uses all offal from the entire ICES statistical area 27.4.b (also termed ‘IVb’). The sets of ICES rectangles used in scenarios ***i*** and ***ii*** are visualised in Figure 2.2.2.

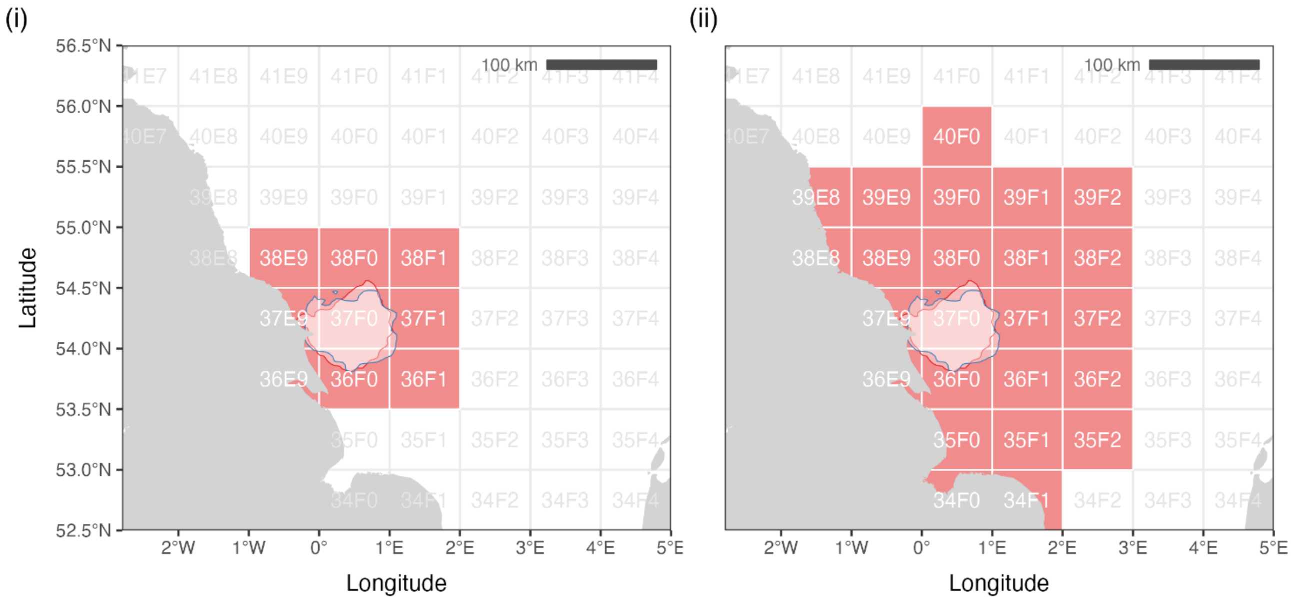

Figure 2.2.1 Visualisation of the ICES statistical rectangles used for the first two offal availability scenarios. The first scenario i) uses rectangles either overlapping or adjacent to species simulated 50% KDE, while the second scenario ii) uses all rectangles within 100 nautical miles of the 50% KDEs of focal species’ simulated spatial distribution. Also shown are the 50% KDEs for black-legged kittiwake (red-bordered polygon) and northern fulmar (blue-bordered polygon) from Figure 1.5.2, which are included for reference. Non-overlapping ICES rectangles (greyed out) can be referenced in Figure 2.1.1, which uses identical grid extents.

Calculating quantities of offal available

With data summarised by year for all rectangles, we estimated the yearly mean tonnage of offal discarded within sets of ICES rectangles covered by the three outlined scenarios

(Table 2.2.1), and calculated the approximate 95% confidence intervals (lower: 2.5%; upper 97.5%) using the mean ± 1.96 x SE. Calorific value of discarded offal was calculated by multiplying offal estimates by an energetic equivalent value of 9.0 kJ/g, following Garthe (1996). To assess offal availability for seabirds within the FFC SPA for breeding, we also calculated the mean annual tonnes and calorific value of offal discarded during the summer, from April to August (Table 2.2.1).

Table 2.2.1 Summary of three scenarios of offal availability, with sea coverage of rectangles, estimated annual mean and estimated summer (April–August) annual mean quantities of offal available, equivalent calorific value of summer offal discards. 95% confidence intervals (CIs) for offal quantities and energetic values are shown in brackets.

Scenario	Sea coverage (km^2)	Mean annual tonnes of estimated offal discarded (95% CIs)	Mean summer annual tonnes of estimated offal discarded (95% CIs)	Calorific value of estimated summer offal discards (kJ x 10^6)
Scenario i **(Overlapping 50% KDE)**	78,393	22.4 (9.8–34.9)	12.3 (3–21.6)	110.6 (27–194.2)
Scenario ii **(Within 185km of 50% KDE)**	207,336	142.2 (60.2–224.2)	90.6 (32.8–148.4)	815.3 (295.3–1,335.4)
Scenario iii **(Entire 27.4.b ICES area)**	916,459	706.2 (407.5–1,005)	377.6 (255.1–500.1)	3,398.3 (2,295.6–4,501)

We estimate that the current annual quantity of offal available to our focal seabird species in the FFC SPA (ie, scenario i) is in the region of 22 (10–35) tonnes, of which approximately 12 (3–22) tonnes would be available to birds in summer — equivalent to 111 (27–194) million kJ of energy. Expanding to include all rectangles in scenario ii, the estimated annual amount of offal available increases to 142 (60–224) tonnes, with a summer availability of 91 (33–149) tonnes, and an energetic equivalent of 0.8 (0.3–1.3) billion kJ. In the broadest range of rectangles, covered by scenario iii, annual offal discarding sits at 706 (408–1,005) tonnes, with a summer availability of 378 (255–500) tonnes, equating to 3.4 (2.3–4.5) billion kJ of energy. In addition, we also visualised the total monthly tonnage of offal discarded in the North Sea between 2016 and 2021 (Figure 2.2.2). Offal discarding exhibits an annual cycle, falling to its lowest levels around January, and peaking around June-July. From the data available, annual offal discards appear to show a general downward trend. May 2021 showed unusually high levels of offal discarding compared to previous years.

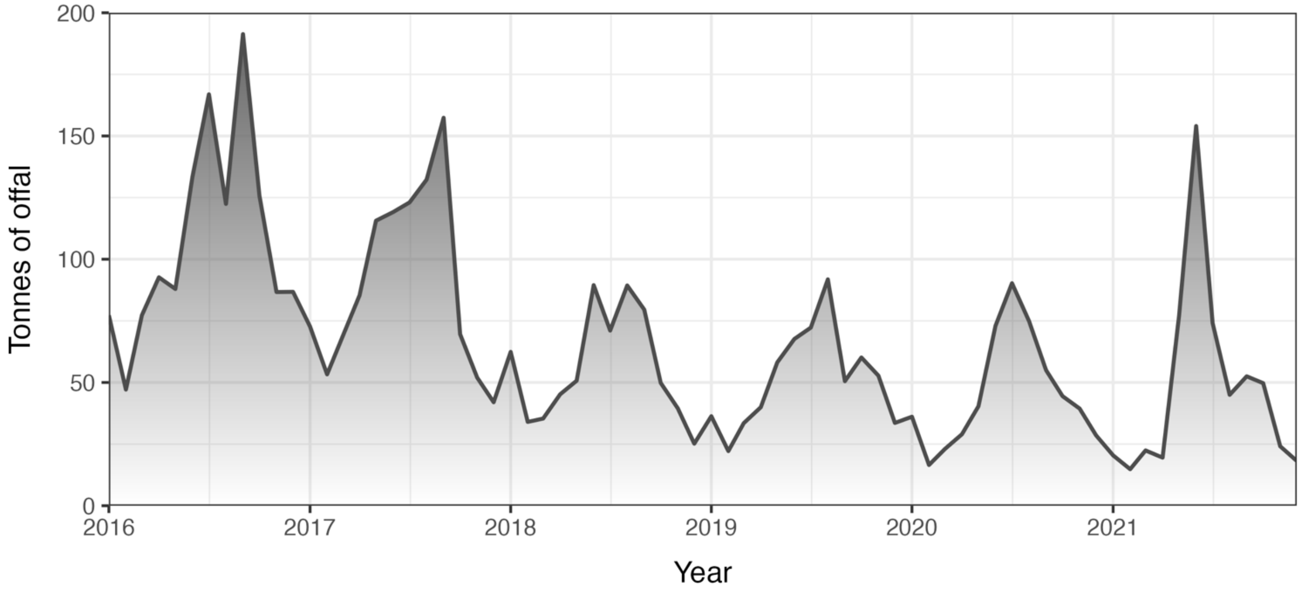

Figure 2.2.2 Visualisation of monthly variation in quantity of offal discarded in the North Sea (from demersal species landed within ICES Division IVb). See figure 2.1.1 for spatial distribution.

KD2.3 Bioenergetics modelling under offal availability scenarios

Bioenergetics modelling was implemented in JAGS (Plummer, 2003) following the methodology used by Sherley et al. (2020b). This Bayesian modelling approach combines information on fisheries waste (quantity, energy, and assimilation efficiency per type) and seabirds (relative abundance, field metabolic rates during breeding and non-breeding seasons, and diet composition per species), to estimate the number of individuals of each species that could be supported by a given amount of discards/offal. Using the 2010 version of the discard model from Sherley et al. (2020b) as a starting point, we adjusted the input variables by removing seabird species largely absent from the FFC SPA (great skua and common gull) and rescaling the remaining seabird species abundances. To reflect the major reduction in the amount of discarding occurring in the North Sea under the current landing obligations, all discard categories in the original model excluding offal (roundfish, elasmobranch, flatfish, and other marketable fish) were reduced to one tonne of each discard type. These arbitrary discard quantities were multiplied by their energetic equivalents during modelling, and helped to account for slippage and other forms of fisheries waste not recorded in the available data. Finally, we ran three iterations of the model, each time replacing offal discard quantities with the estimates from each of the three offal availability scenarios (Table 2.2.1) and combined the three resulting datasets for comparison. Each model output included estimates of total individuals supported annually, along with number of individuals supported during each respective species' breeding and non-breeding phase. To focus on individuals using the FFC SPA as a breeding site, we used these breeding season values for analyses[2].

Number of seabirds supported under each scenario

After accounting for assimilation efficiency and consumption rates (see Table S2.3.1), we estimate that 123 (56-212) million kJ in discards were available annually in the FFC SPA (ie, scenario i), supporting just over 200 breeding seabirds, including 38 (12–99) black-legged kittiwakes and 37 (12–93) northern fulmar (Table 2.3.1 and Figure 2.3.1). When increasing offal availability to include rectangles covered in scenario ii, 0.7 (0.3-1.3) billion kJ annually could support more than a thousand (453–2,532) breeding individuals, including 230 (68–607) black-legged kittiwake and 226 (68–571) northern fulmar. At maximum offal availability, the 3.7 (1.8–5.9) billion kJ of energy available in scenario iii could support an estimated 6,079 (2,554–11,674) breeding individuals, comprising 1,136 (374–2,894) black-legged kittiwake and 1,115 (377–2,711) northern fulmar (Table 2.3.1 and Figure 2.3.1).

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[2] While coarse data on energy available from discards during the breeding season (April-August) under each scenario can be found in the final column of Table 2.2.1, these values are not suitable for direct comparison to model-derived estimates of breeding individuals supported, as they do not account for species-level differences in breeding period and relative abundance.

Table 2.3.1 Estimated number of individuals from each species potentially supported by offal in the breeding season under the three offal availability scenarios, (including 95% credible intervals), with 2022 population estimates taken from KD1.1.

Species	Scenario 1	Scenario 2	Scenario 3	FFC SPA 2022 census (method)
Northern fulmar	37.3 (12.1–92.8)	226 (67.9–570.5)	1,115.4 (377–2,710.7)	815 (AOS)
Northern gannet	10.3 (2.9–28.1)	62.2 (16.4–172.9)	308.1 (89.4–833.2)	16,481 (AOS)
Lesser black-backed gull	75.2 (24.3–192.9)	454.9 (136.3–1,186)	2242.8 (755.7–5,621.8)	No data
European herring gull	40.9 (12.2–106.3)	247.8 (68.6–653.9)	1222 (378.7–3,120.5)	298 (AOS)
Great black-backed gull	1.8 (0.6–4.7)	11.1 (3.4–28.8)	54.9 (18.6–137.4)	No data
Black-legged kittiwake	38.2 (12–99)	230.4 (67.8–606.7)	1136.3 (373.5–2,893)	39,090 (AON)
Total	203.7 (81.6–408.8)	1,232.5 (453–2,532.2)	6,079.5 (2,553.6–11,673.6)	56,684 (AON)

The number of supported individuals can also be related back to local population estimates. For black-legged kittiwake, the mean numbers of supported individuals represent 0.1% (scenario i), 0.3% (scenario ii) and 1.5% (scenario iii) of the local kittiwake population (Table 2.3.1). For northern fulmar, supported numbers equate to 2.3% (scenario i), 13.9% (scenario ii) and 68.4% (scenario iii) of the local population. Not accounting for data gaps in population counts and the smaller local population sizes for some species, the total number of individuals supported by the three scenarios represents 0.2% (scenario i), 1.1% (scenario ii), and 5.4% (scenario iii) of the ~57 thousand seabird pairs censused in the FFC SPA (Table 2.3.1).

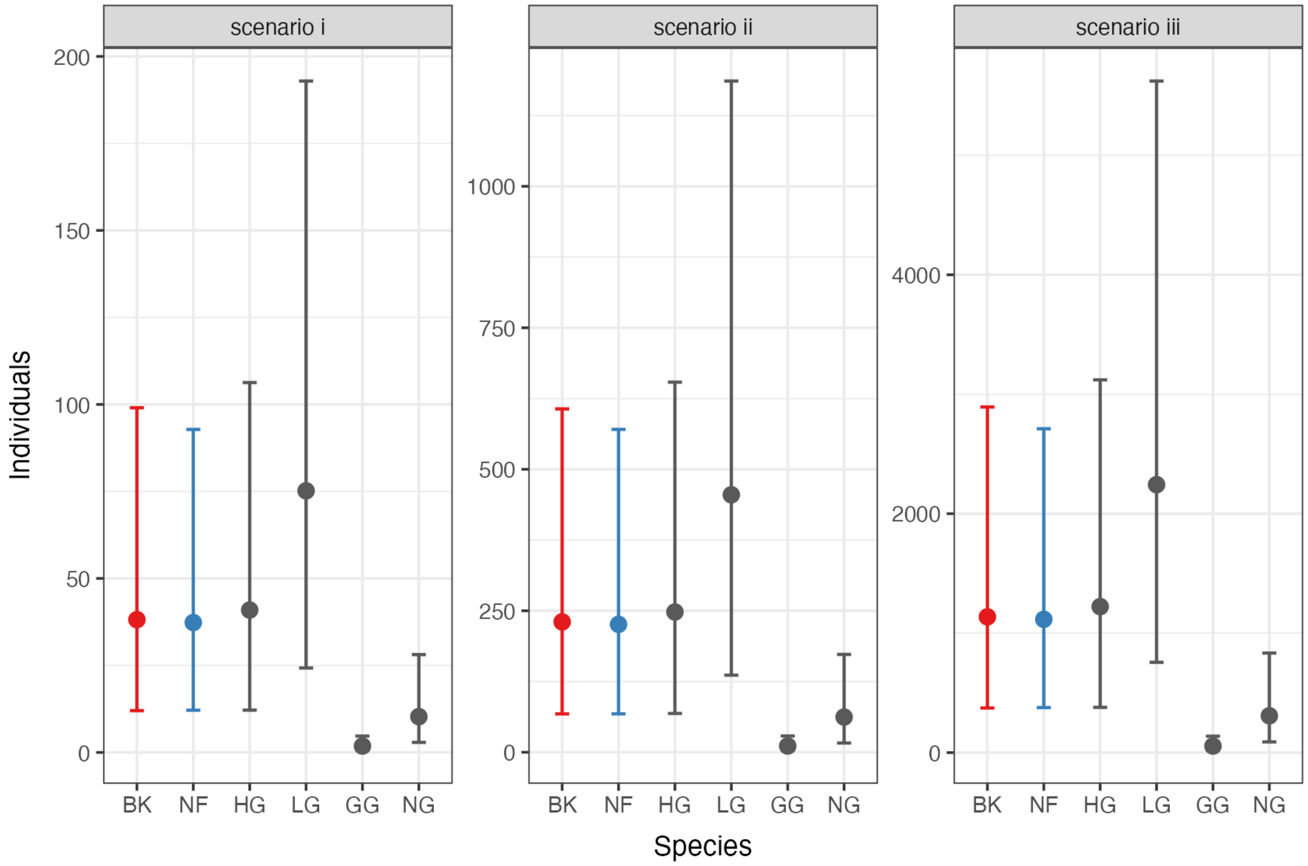

Figure 2.3.1 Posterior means (points) and 95% CI (whiskers) for the estimated number of individuals consuming discards in the breeding season under each of the offal availability scenarios, by species present in the FFC SPA (focal species in colour): BK, black-legged kittiwake (red); NF, northern fulmar (blue); HG, herring gull; LG, Lesser black-backed gull; GG, great black-backed gull; NG, northern gannet.

After assessing the number of individuals supported under each offal availability scenario (Figure 2.3.1), we also attempted to extrapolate the relationship between offal quantity and the number of individuals supported during the breeding season. We used mean values from Figure 2.3.1 to fit and extrapolate a simple linear model between each of the three data points for each species (Figure 2.3.2). Extrapolation suggested that every additional tonne of offal supports approximately 3 black-legged kittiwakes, 3 northern fulmars, 3 herring gulls, 6 lesser black-backed gulls, <1 great black-backed gull, and 1 gannet. The previous figures all assume that offal is provisioned at sea, that competitive interactions will occur resulting in species only accessing a proportion of all available offal (based on the consumption rates in Sherley et al. 2020b), and that dietary compositions remain unchanged (see also more limitations below). Accordingly, the extrapolations in Figure 2.3.2 should be treated with caution and with due consideration of the large uncertainties associated with the estimates in Figure 2.3.1.

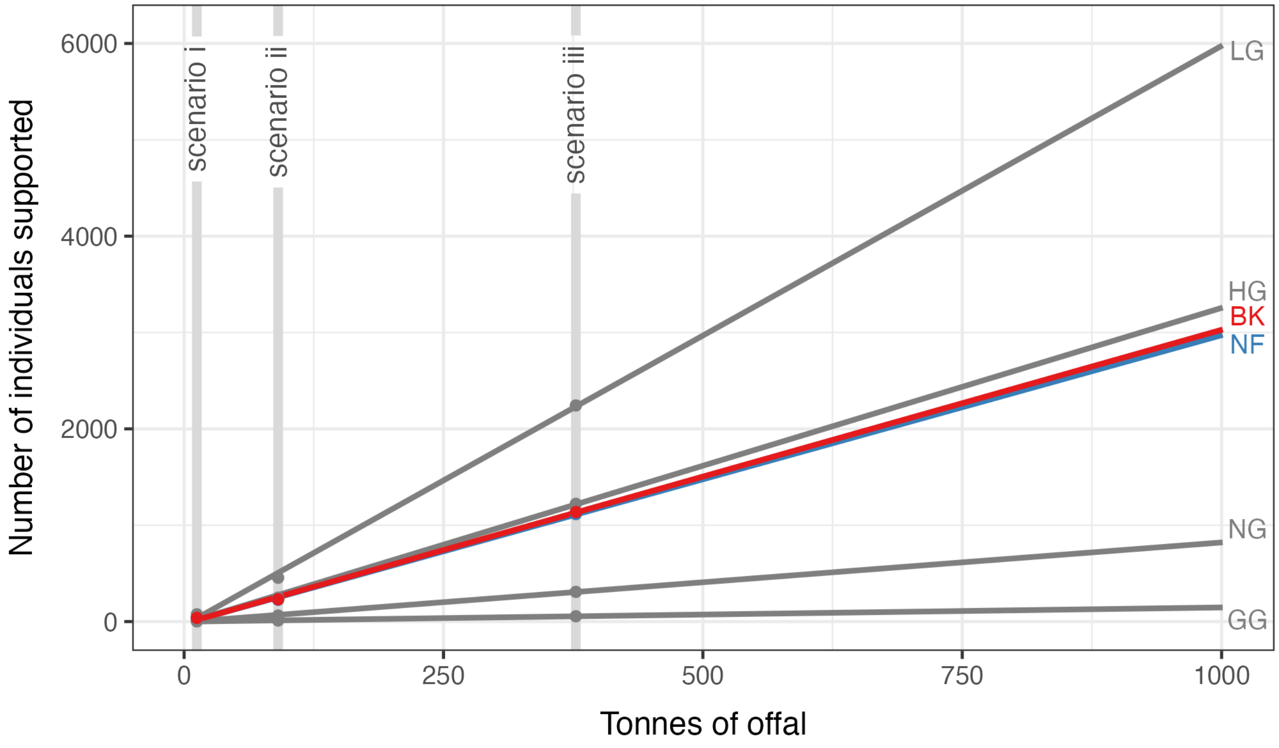

Figure 2.3.2 Approximate extrapolation (lines) of posterior means (points) for the estimated number of individuals consuming discards in the breeding season under each of the offal availability scenarios (vertical grey lines) for all species present in the FFC SPA (focal species in colour): BK, black-legged kittiwake (red); NF, northern fulmar (blue); HG, herring gull; LG, Lesser black-backed gull; GG, great black-backed gull; NG, northern gannet.

Limitations of bioenergetics modelling

While the bioenergetics modelling yields an estimate of the number of seabirds supported by different offal availabilities, the approach used does not estimate the impact of provisioning offal on individual survival or reproductive output — both of which would be necessary for projecting population growth under each provisioning scenario. It is also important to acknowledge that the original 2010 model was parameterised using dietary data that carries a large amount of uncertainty. Particularly for a small-scale study like this, there may be local specialisation on fisheries waste not accurately captured by the current parameters of the model, with species either over- or under-utilising different discard types. Additional work to assess seabirds' use of discards (either observationally or experimentally) is likely to be valuable for both future energetic modelling work and as an effective tool for monitoring the population-level impacts of changing discard practices (Sherley et al., 2020b).

KD2.4 Reviewing effect of offal consumption on seabird energetics, breeding and survival

While many seabird populations do generally appear to benefit from consuming dumped fisheries waste — as demonstrated by the artificially-inflated populations of species across the globe (Furness, 2003) — the long-term impacts of discard and offal consumption on survival, breeding, behaviour, and demography are not fully understood (Bicknell et al., 2013; Oro et al., 2013). Given that the provisioning will be comprised of predominantly offal, we need to also consider the ramifications of an offal-rich diet for both adult seabirds and their chicks.

Positive implications of offal provisioning

While it has often been assumed that easy access to fish offal may reduce the energetic costs of foraging (Votier et al., 2010), recent work on gannets suggests that individuals foraging on either discards or natural prey have very similar energy expenditure (Clark, 2020). In a provisioning context where food is predictable, there is likely to be an increase in foraging efficiency and reduction in path length, as individuals will spend less time searching, and more time making direct trips to and from a known provisioning site (Bartumeus et al., 2010; Fagan et al., 2013). This reduced search time may be especially valuable during the breeding season, as consistency of food intake for chicks is likely to improve growth and survival, which could be especially important during early chick development (Regular et al., 2014).

Negative implications of offal consumption

Having access to a reliable source of food may be invaluable to a range of seabird species, but this impact is likely to be modulated by the nutritional quality and energetic content of the food source provided. An important consideration around any discard foraging scenario relates to the ‘junk food hypothesis’, which states that fisheries waste has a lower energetic and nutritional value than natural prey, with the potential to negatively affect an individual’s fitness (Piatt and Anderson, 1996). However, these impacts may well be species and/or discard-type specific. For example, adult northern gannets and Cape gannets show higher foraging effort and lower body condition when discards are prevalent in the diet and their prey is not (Cohen et al., 2014; Le Bot et al., 2019). While in contrast herring gulls and great black-backed gulls wintering on Helgoland had better body mass when feeding on cod fisheries discards than when fisheries were absent around the island (Hüppop and Wurm, 2000).

During the breeding season, some provisioned food consumed by adults is likely to be fed to chicks, and any potential detrimental effects passed onto young. For example, Cape gannet (*Morus capensis*) chicks fed discards tend to have slower growth rates and reduced survival compared with natural prey diets (Hüppop and Wurm, 2000), a finding that is supported by experimental feeding studies of black-legged kittiwakes (Romano et al., 2006). Several species including the Black-browed albatross (*Thalassarche melanophris*) have been shown switching to feeding their chicks on discards when natural prey are less available, with negative implications for breeding success (Kuepfer, Votier, et al., 2022). This pattern of prey switching has also been shown in northern and Cape gannets with individuals apparently making use of discards after unsuccessful foraging trips (Le Bot et al., 2019) or in years when natural prey are scarce (Cohen et al., 2014; Grémillet et al., 2008).

Unknown implications of an offal-rich diet

Critically, we need to consider the potential negative consequences of seabirds feeding on a greater proportion of offal, but while historically studies have looked at use of fisheries waste by seabirds, the vast majority involved waste that was comprised of both whole discards and offal (Camphuysen et al., 1995; Garthe et al., 1996) As a result, there is a distinct lack of information on how offal-only foraging scenarios might differentially affect seabirds. Without even the basic information on the nutritional content of fish offal, we are prevented from conducting simple assessments of the potential health implications for both adults and chicks. Further, seabirds consuming only offal are also likely to experience increased exposure to contaminants, because fish organs (notably the liver) contain the highest deposits of heavy metals such as mercury (Arcos et al., 2002). While Arcos et al. (2002) find that epipelagic fish have lower mercury concentrations than demersal species, there does not appear to be any equivalent assessment of heavy metal contaminants in North Sea fish populations.

Wider implications on trophic ecology

The effect of discards on trophic ecology of seabird communities has been well studied, with research demonstrating how reductions in discarding triggered an increase in predation of small seabirds by great skua (Furness, 2003; Votier et al., 2004). While seabird ecology should be carefully considering alone, as both the introduction and removal of offal provisioning is likely to have some type of localised effect on the local food web (Heath et al., 2014). With large loads of offal being dumped in a single batch (compared to a more constant rate of disposal from vessels actively fishing), there is also the potential for a trophic cascade to occur in benthic communities, as the huge amounts of offshore energy are brought inshore, and uneaten material falls to the seafloor. This could cause unexpected increases in benthic communities of invertebrates and other detritivores, with unforeseen implications for the local coastal ecosystem (Groenewold and Fonds, 2000).

Limitations and recommendations

For future application of the insights provided, here we outline important limitations in the approaches used, and provide future recommendations guided by the findings of this work.

Practical feasibility

Provisioning offal to local seabird populations in the FFC SPA appears practically feasible, with two species showing local declines (black-legged kittiwake and northern fulmar, KD1.1), appearing most likely to make use of offal discards (KD1.4). As suggested by spatial modelling (KD1.5), placing an offal provisioning site 25-50 km offshore could be used to target these focal species that travel longer distances from the coastline. Offshore provisioning could be combined with a well-tested selective feeder (KD1.6) to prevent wider-ranging species (such as lesser black-backed gull) from gaining access to provisioned offal.

Effectiveness

To ensure that offal provisioning supports a meaningful number of seabirds (for example to offset the annual population declines in the FFC SPA), several hundred tonnes of offal would have to be assembled from the local area (KD2.2). We estimate that all the offal discarded during summer in the 916 thousand km^2 of ICES rectangles outlined in scenario iii could support ~5% of the seabird population in the FFC SPA (KD2.3), including ~1% of the local population of black-legged kittiwakes.

Ecological implications

Moving hundreds of tonnes of offal inshore represents a substantial ecological manipulation, with potential impacts on both seabirds and the entire local ecosystem. Due to a lack of research the long-term impacts of an offal-rich diet on the individual fitness and breeding success of seabirds is largely unknown, but generalising from studies of discard provisioning it appears that both adults and chicks can experience detrimental effects (KD2.4). Moreover, bringing large amounts of biomass into inshore ecosystems may have unknown cascading impacts on seabird and benthic scavenger communities (KD2.4)

Data limitations

The seabird tracking data used was limited in term of species available and local relevance (KD1.5). While simulations are a valuable tool for assessing potential species distributions, they are unable to accurately represent the fine-scale habitat selection likely exhibited by individuals found in the FFC SPA. Similarly for the bioenergetics modelling, parameterisation for UK-wide data carried a large degree of uncertainty, and local dietary specialisation by seabirds in the FFC SPA may not be accurately represented by the model parameters used. For each scenario we present the number of individuals supported during the breeding season, while also providing the number of individuals supported annually (see supplementary material section S2.3). It should be noted that all energetic modelling assumed a constant rate of offal through the year, equating to the estimated annual totals per scenario. As such, models do not account for within-year variation in offal availability, which given the peak in offal availability during summer (Figure 2.2.2) means there may be some under-estimation of the number of breeding individuals that could be supported.

Existing knowledge gaps and suggested additional research

Building on the assessments and limitations previously mentioned, we propose four pieces of additional research that could be conducted to better inform future planning for an offal-provisioning project:

1. To fill gaps in our modern understanding of discard consumption by seabirds, we recommend using a series of field observations to investigate the current consumption rates of discard/offal and assess dominance interactions of seabirds within the FFC SPA (KD1.4).
2. To maximise targeted provisioning, we suggest some time and funding be directed towards designing and experimentally testing a selective feeder capable of restricting access to non-target species (KD1.6) if provisioning at sea is to be the preferred option.
3. To gather fine-scale patterns of local habitat use, we suggest collecting additional tracking data within the FFC SPA from wider range of species (KD1.5).
4. To fill critical knowledge gaps in our understanding of the energetic and nutritional content of offal, we suggest conducting chemical analyses of samples of discards and offal (can also look for presence of local contaminants) (KD2.4).

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Supplementary Material

Data and R code for reproducing all analyses shown in this report can be found in the following GitHub repository: https://github.com/sketchkey/NE-discards-project

Additional queries regarding analyses can be directed to the authors: (r.sherley@exeter.ac.uk, s.d.j.Lang@exeter.ac.uk, s.votier@hw.ac.uk).

S1.1 Species assessments

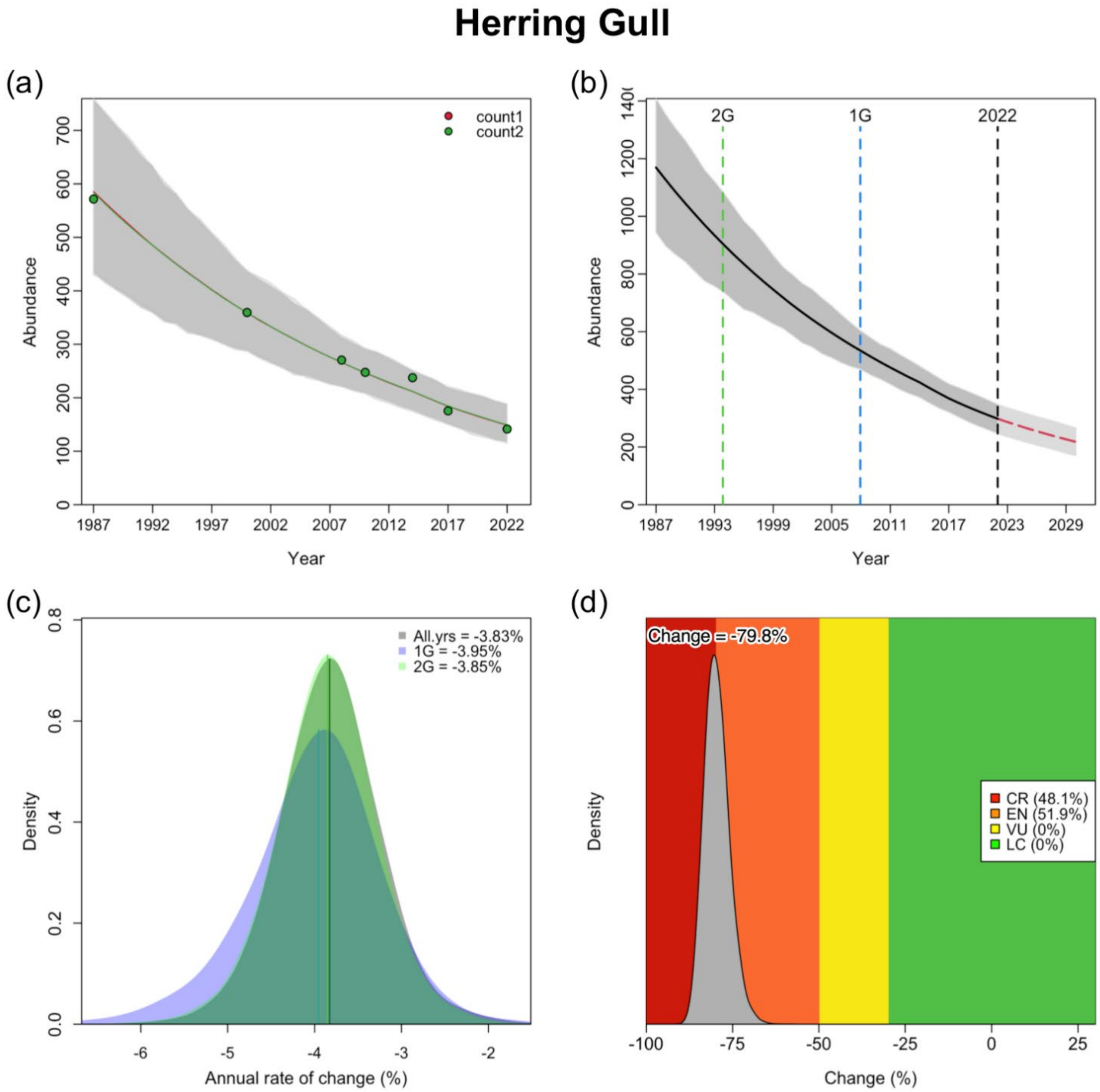

Figure S1.1.1 IUCN-style plot of local population assessment for European herring gull colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts ('count1' and 'count2' points overlap as a result of single counts being

evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

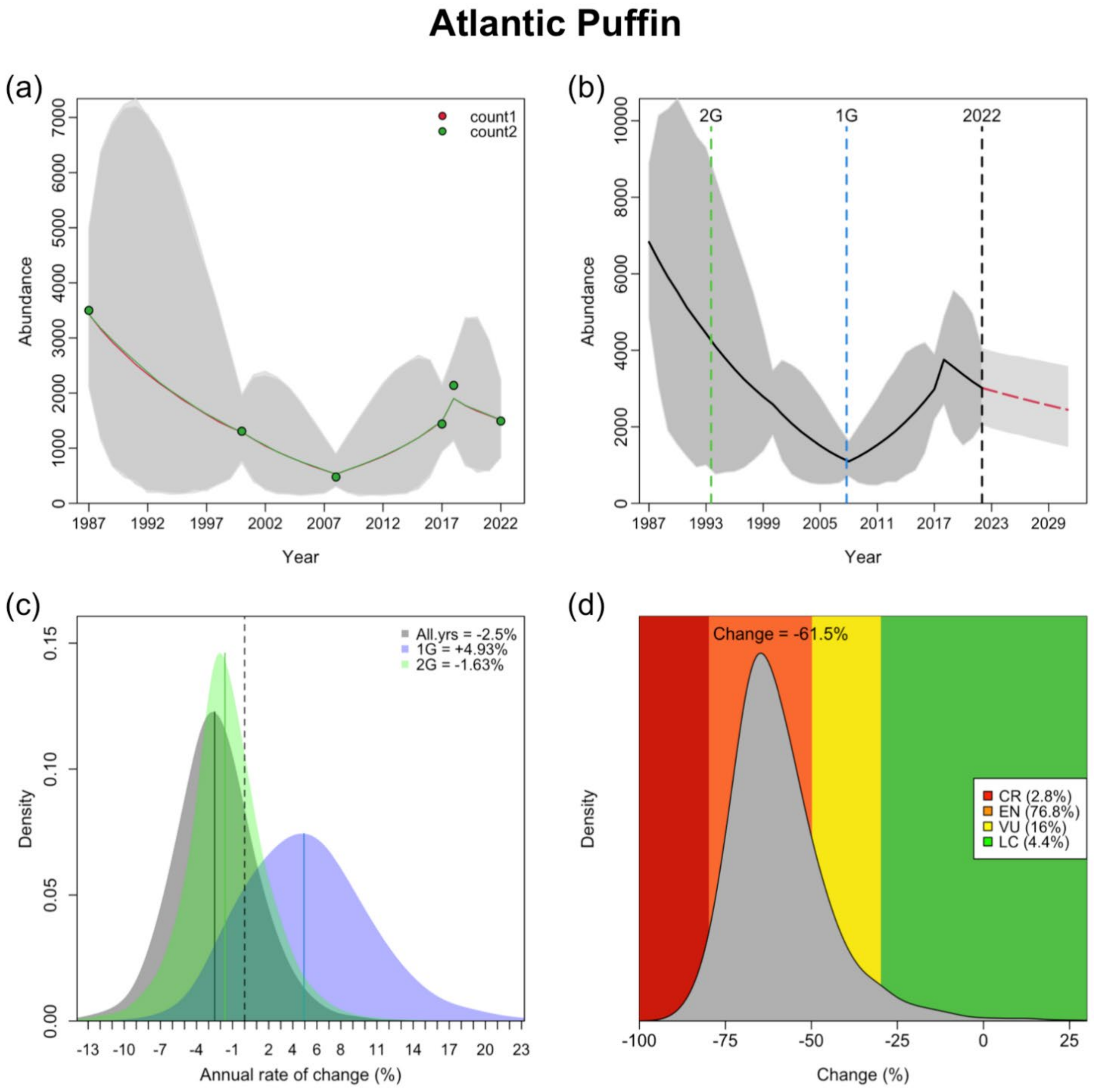

Figure S1.1.2 IUCN-style plot of local population assessment for Atlantic puffin colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts (‘count1’ and ‘count2’ points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c)

the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

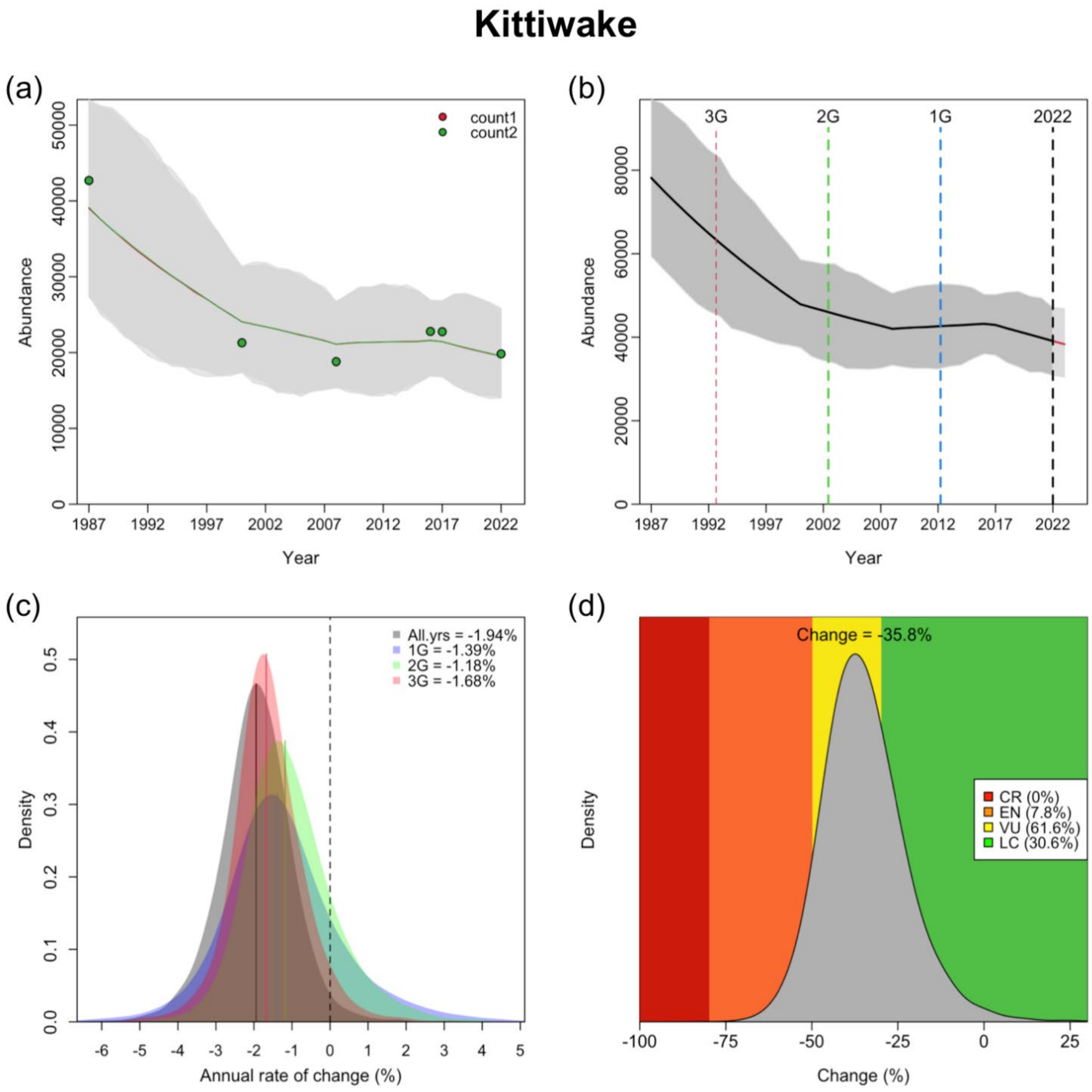

Figure S1.1.3 IUCN-style plot of local population assessment for black-legged kittiwake colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts ('count1' and 'count2' points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three

generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

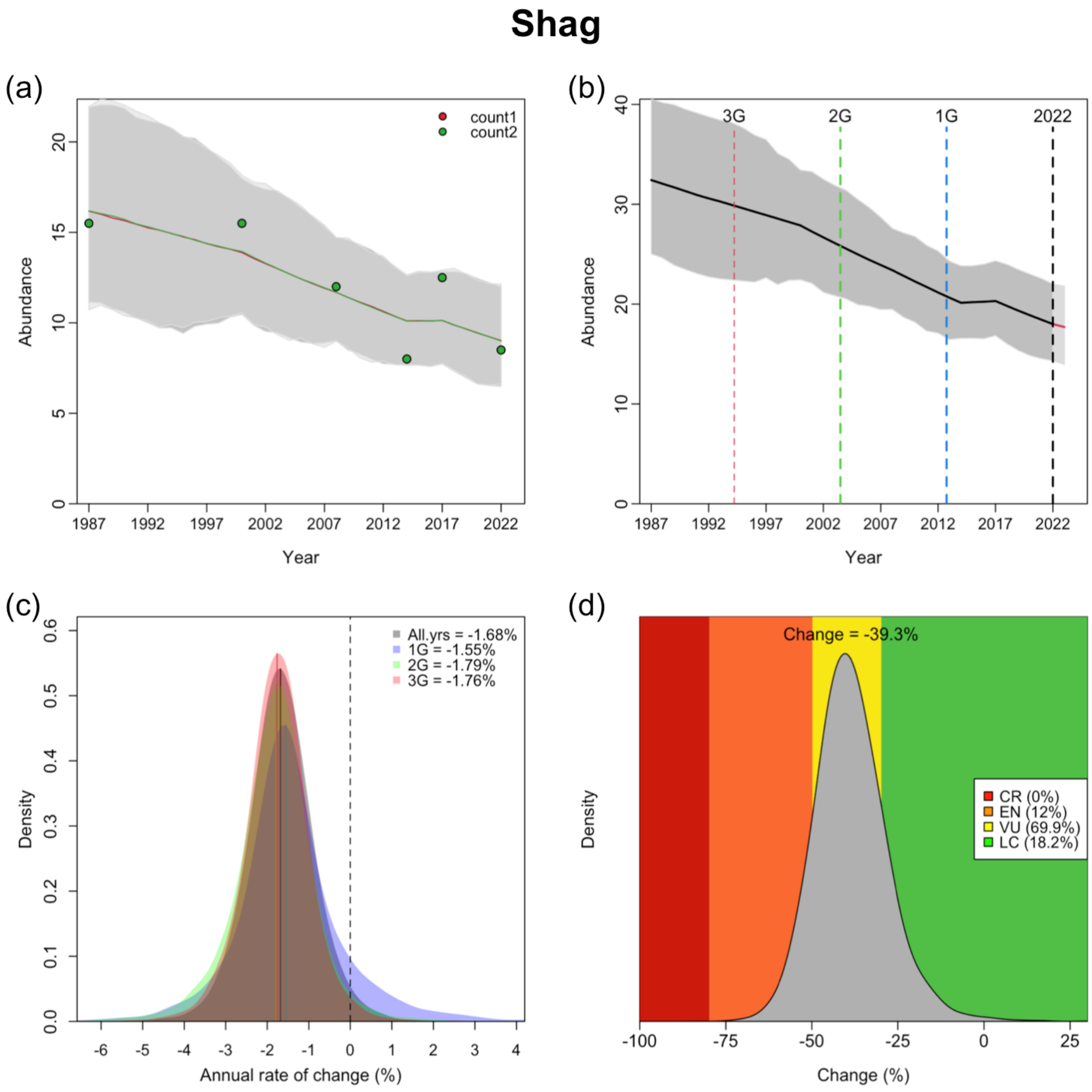

Figure S1.1.4 IUCN-style plot of local population assessment for European shag colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts (‘count1’ and ‘count2’ points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data

(coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

Fulmar

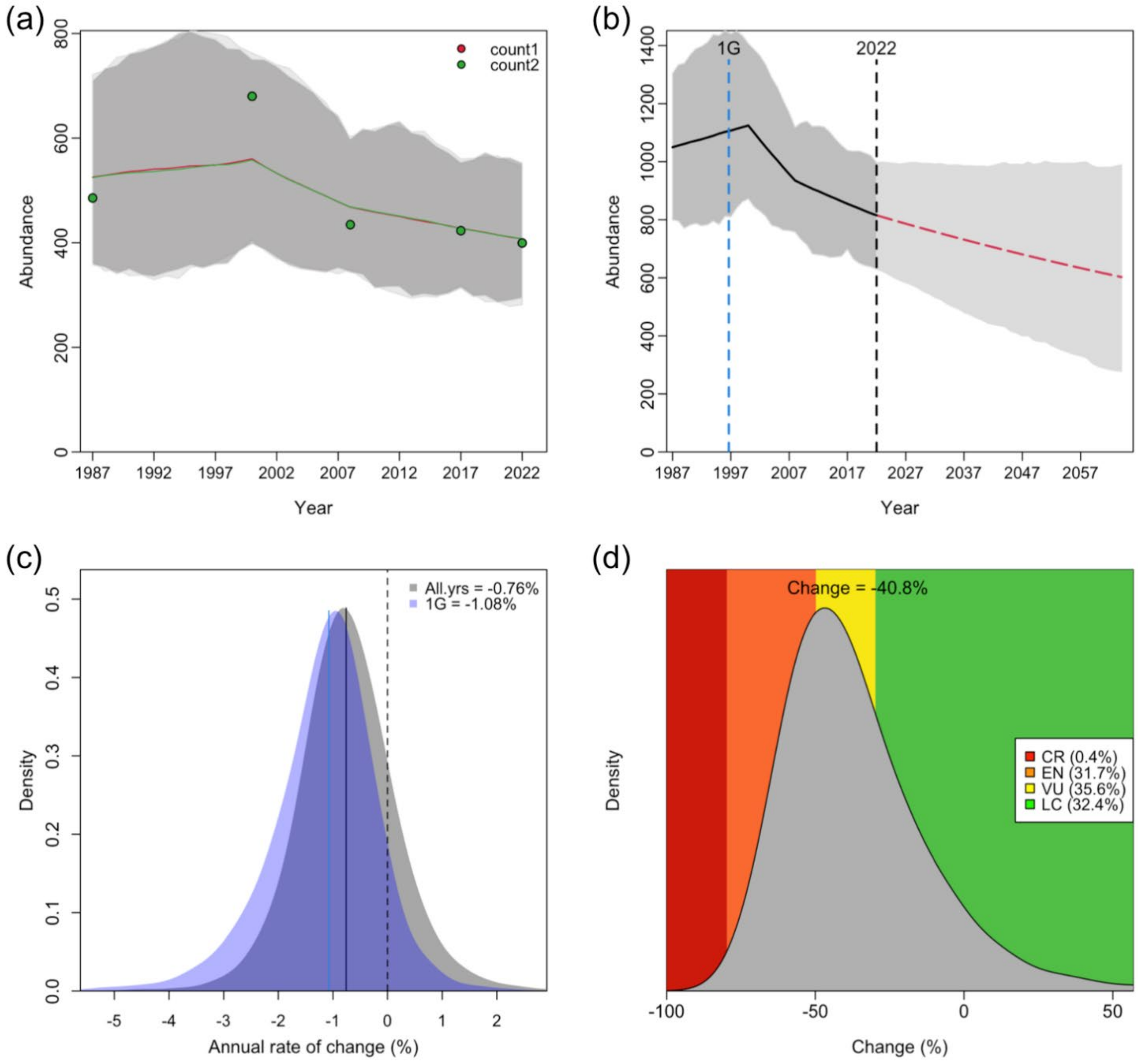

Figure S1.1.5 IUCN-style plot of local population assessment for northern fulmar colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts (‘count1’ and ‘count2’ points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

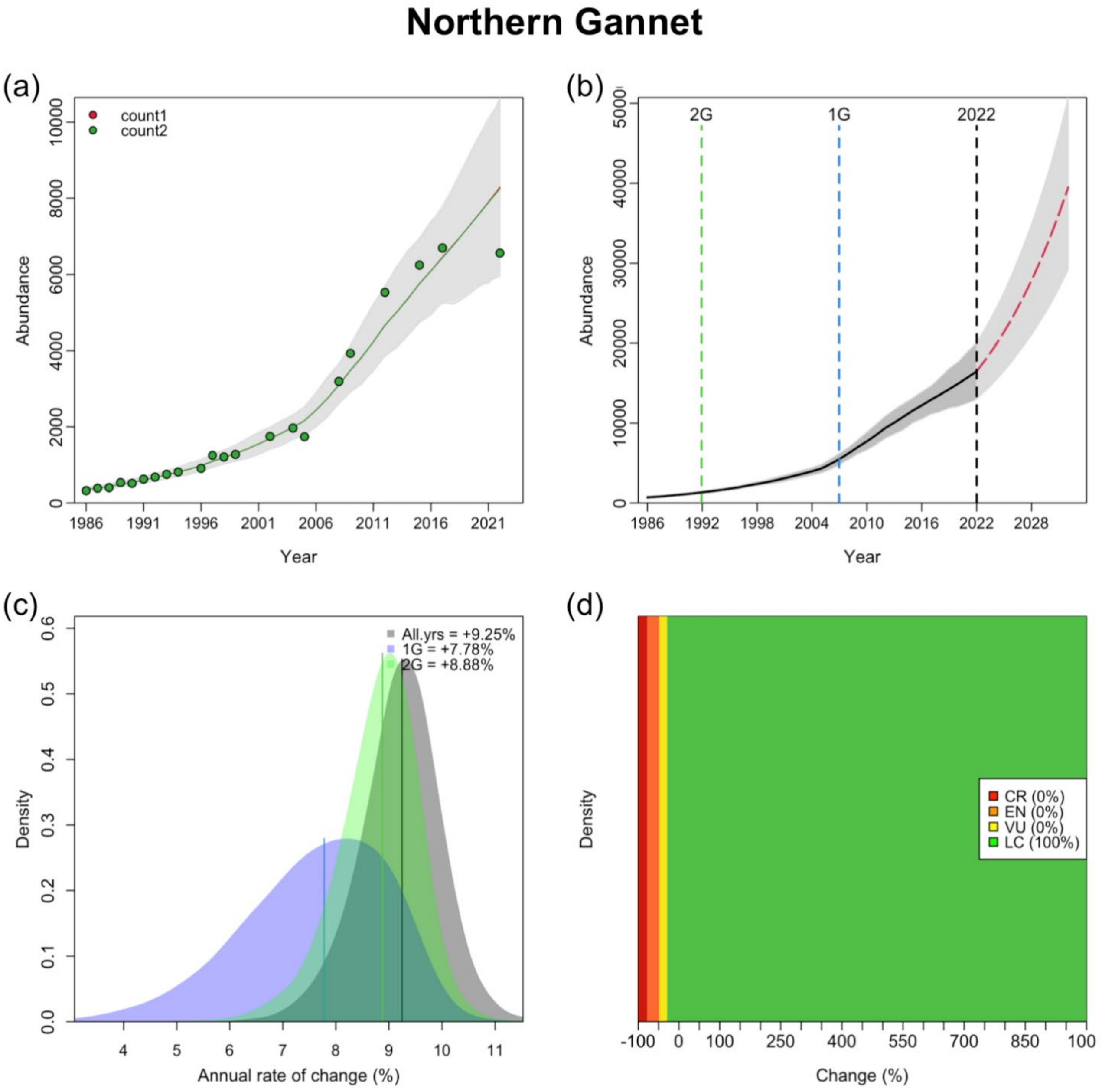

Figure S1.1.6 IUCN-style plot of local population assessment for northern gannet colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts (‘count1’ and ‘count2’ points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria. NB: sub-figure d shows no probability curve because population change is greater that 1000%.

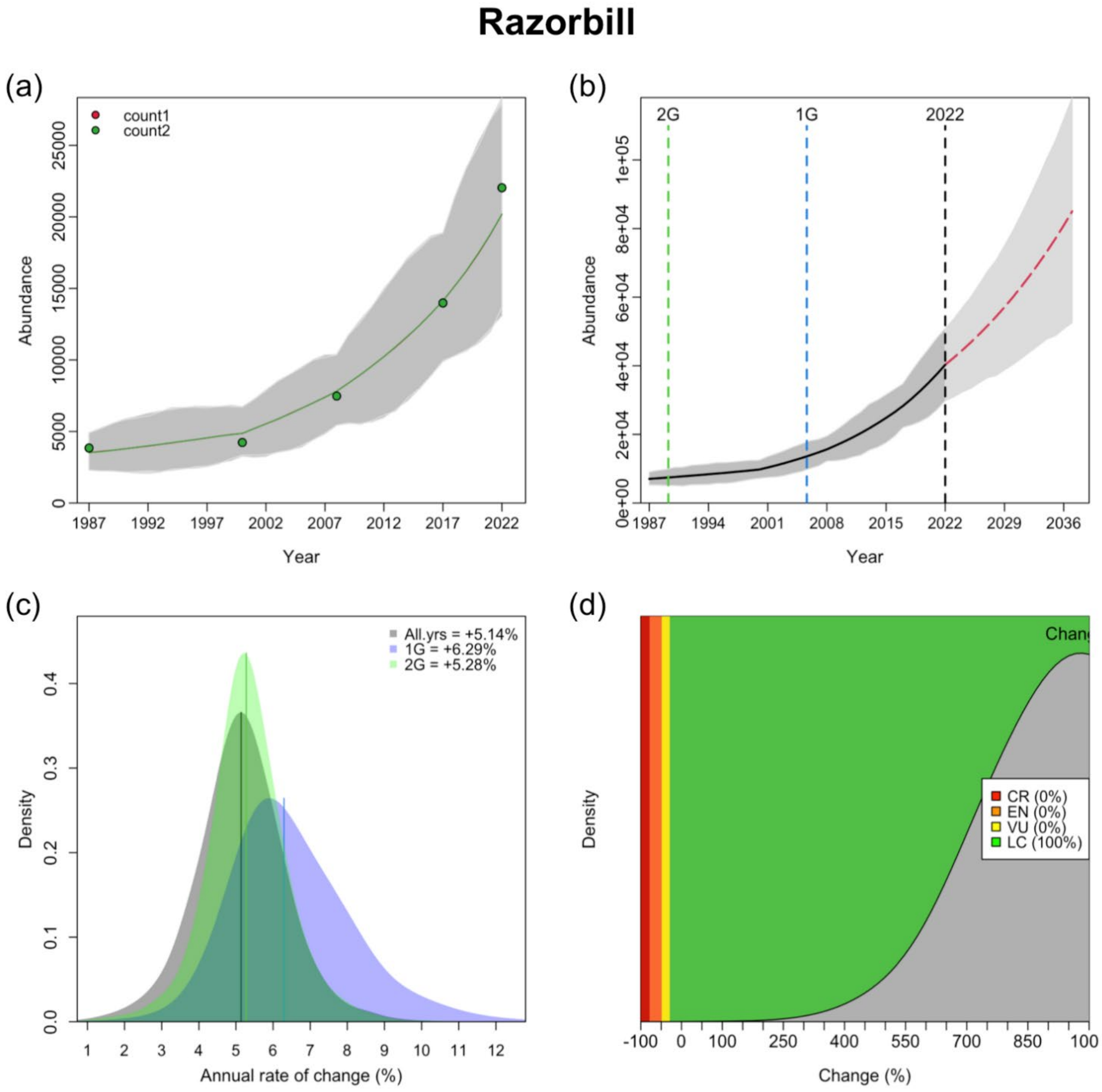

Figure S1.1.7 IUCN-style plot of local population assessment for razorbill colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts (‘count1’ and ‘count2’ points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

Common Guillemot

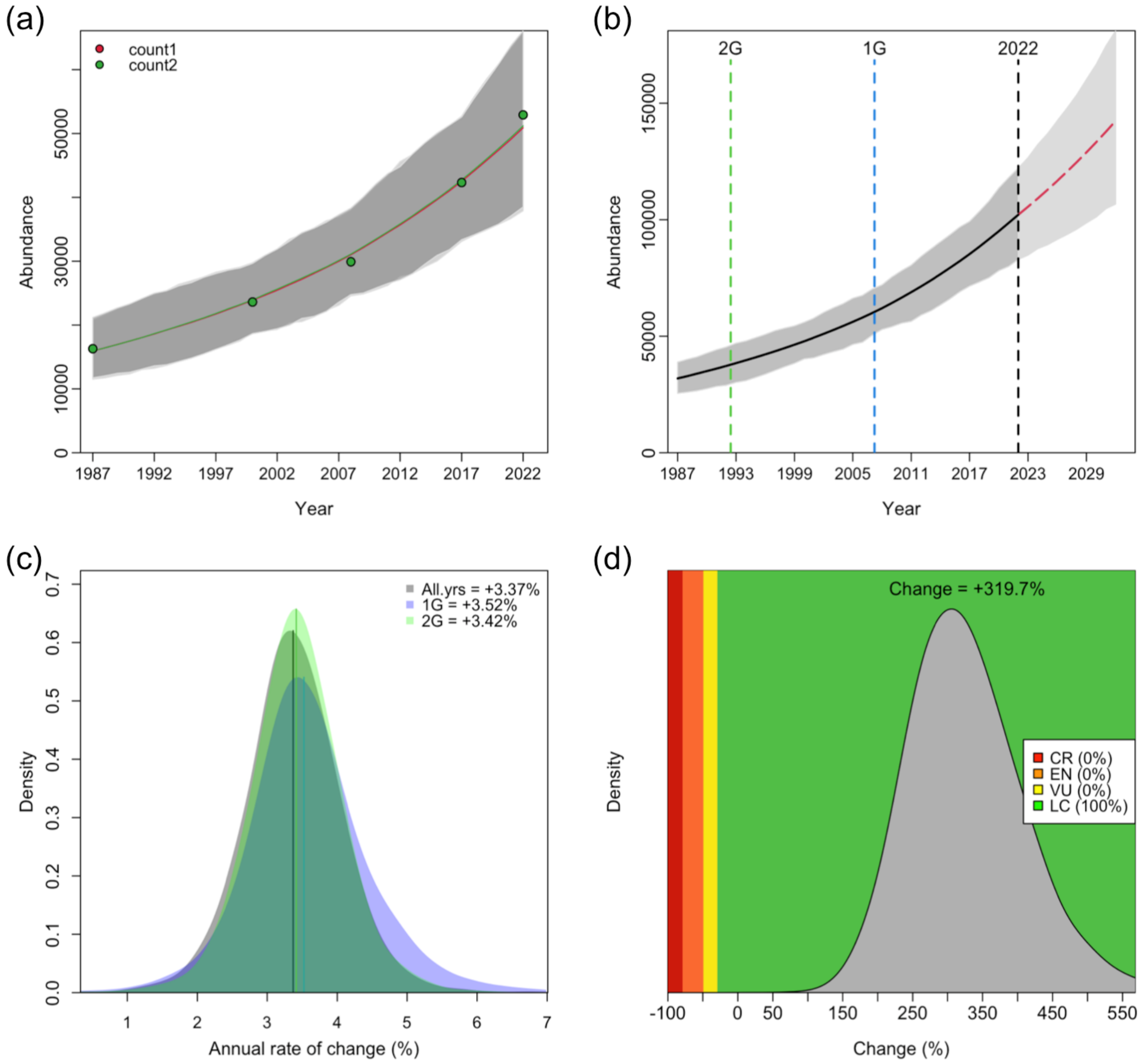

Figure S1.1.8 IUCN-style plot of local population assessment for common guillemot colony numbers in the FFC SPA. (a) JARA fit to the observed time series of colony counts (‘count1’ and ‘count2’ points overlap as a result of single counts being evenly divided to provide the two counts per timestep required for JARA), (b) the observed (black line) and predicted (red line) population trajectory over three generations, (c) the posterior probability densities for the percentage annual population change calculated from all observed data (grey polygon), from previous generations of data (coloured polygons), with generation means (solid coloured lines) shown relative to a stable population (% change = 0, dashed black line), and (d) median change over three generation lengths and corresponding probabilities for rates of population decline falling within the IUCN threat criteria.

S1.4 Spatial assessment of species distributions

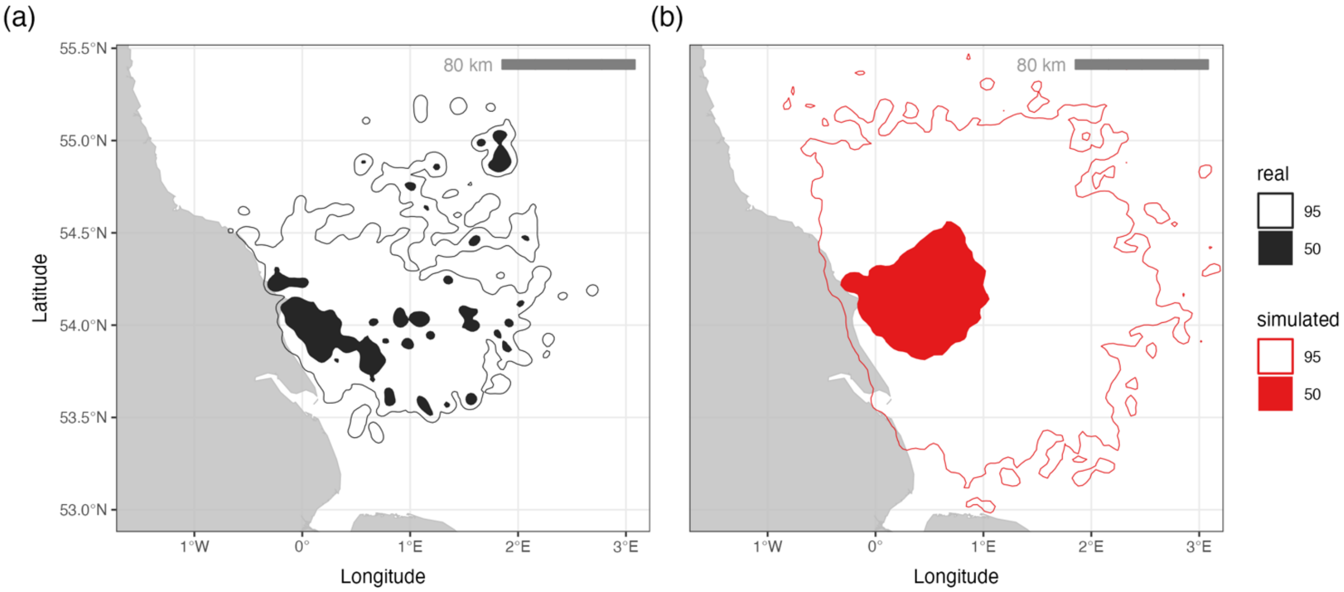

Figure S1.4.1 Comparison plot of kernel density estimates for black-legged kittiwake distributions using: a) real tracking data (grey polygons), compared with b) simulated tracks derived from same tracking data (red polygons). 50% and 95% KDEs are represented by darker and lighter shades of each colour (legend for simulation data included above for clarity). Raw data presented was processed and filtered to first complete trip per individual, and this filtered dataset was used for SSM's and subsequent simulations.

S2.3 Bioenergetics modelling under each offal availability scenario (annual)

Table S2.3.1 Estimated annual energy available in offal (as per Table 2.2.1), energy available in total discard biomass (all discard types) and energy that can be assimilated (accounting for variable assimilation and consumption rates), for the three availability scenarios. 95% confidence intervals are show in brackets.

Measure	Scenario i (kJ x 10^6)	Scenario ii (kJ x 10^6)	Scenario iii (kJ x 10^6)
Total energy available in offal	201.3 (104.5-329.2)	1279.1 (650.9-2120.7)	6356.4 (3953.7-9317.8)
Total energy available in discard biomass	230.8 (133.4-359)	1308.6 (680.5-2150.1)	6385.9 (3983.2-9346.6)
Total discard energy that can be assimilated	123.3 (55.8-211.5)	746.1 (308.3-1321.7)	3678.9 (1752.5-5873.4)

Table S2.3.2 Estimated number of individuals from each species potentially supported by annual offal under the three offal availability scenarios, (including 95% credible intervals), with 2022 population estimates taken from KD1.1.

Species	Scenario 1	Scenario 2	Scenario 3	FFC SPA population (2022)
Northern fulmar	150.8 (54.1–353.2)	912.1 (302.2–2,164.3)	4505.3 (1,691.6–10,248.7)	815
Northern gannet	30.8 (9.3–81.4)	186.2 (52.4–503.4)	921.5 (288.5–2,418.6)	16,481
Lesser black-backed gull	198.7 (67–497)	1203.4 (375.3–3,070.8)	5928 (2,085.5–14,564)	No data
European herring gull	203.2 (64.7–511.2)	1231.6 (365.3–3,139.2)	6067.5 (2,004.5–14,994.8)	298
Great black-backed gull	58.3 (20–144.7)	352.8 (112–891.8)	1743.1 (628.6–4,250)	No data

Black-legged kittiwake	268.3 (88.4–683.1)	1620.6 (496.6–4,182.4)	7991.9 (2,755–19,961.2)	39,090
Total	910.1 (373.8–1,779.9)	5506.7 (2,078.8–11,007.4)	27157.3 (11,668.6–50,651)	56,684

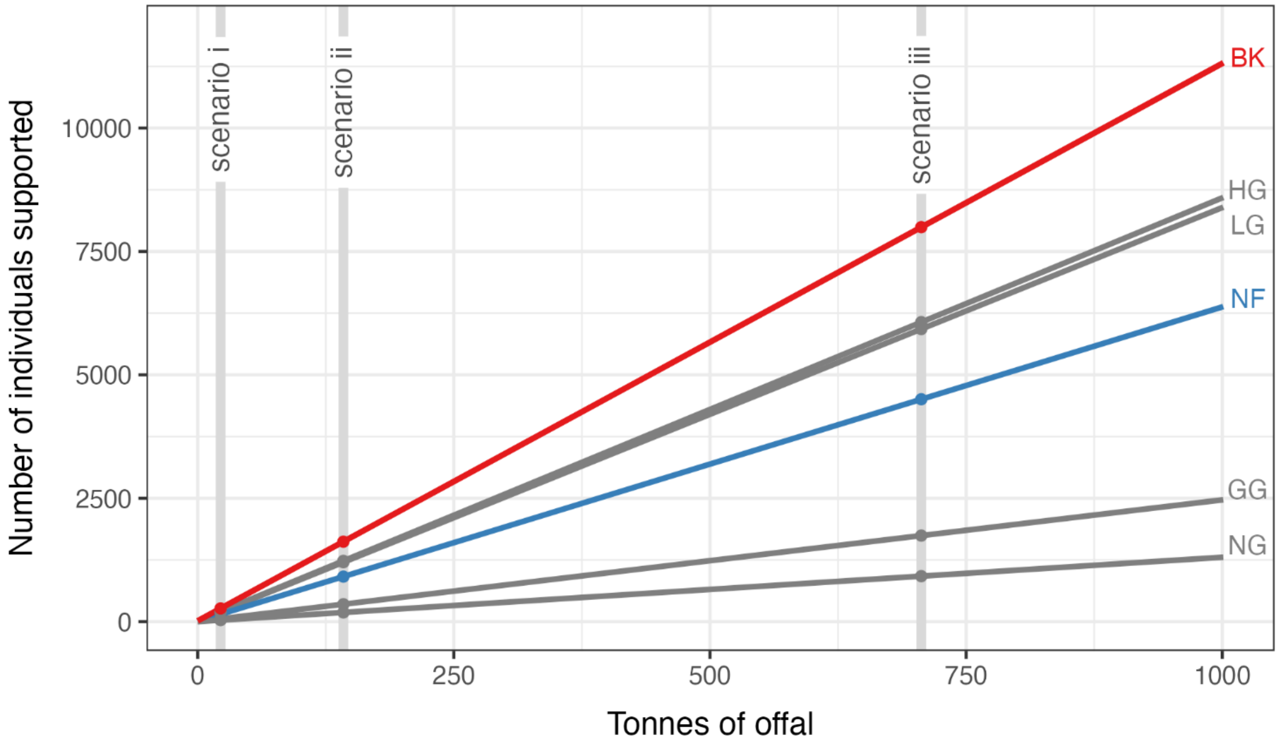

Figure S2.3.2 Extrapolation of posterior means (points) for the estimated number of individuals annually consuming discards under each of the offal availability scenarios (vertical grey lines) for all species present in the FFC SPA (focal species in colour): BK, black-legged kittiwake (red); NF, northern fulmar (blue); HG, herring gull; LG, Lesser black-backed gull; GG, great black-backed gull; NG, northern gannet.

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